# South Dakota School of Mines

BULLETIN NO. 12 —13

(Departments of Geology and Chemistry)

# The Occurrence, Chemistry, Metallurgy and Uses of Tungsten

With Special Reference to the Black Hills
of South Dakota

By

J. J. RUNNER and M. L. HARTMANN

Including

## A Bibliography of Tungsten

By M. L. HARTMANN

RAPID CITY, SOUTH DAKOTA
September, 1918

# LETTER OF TRANSMITTAL

South Dakota School of Mines,
Rapid City, March 15, 1918.

Sir: I have the honor to transmit herewith a paper by Professor J. J. Runner of our Department of Mineralogy and Petrography and Professor M. L. Hartmann of our Department of Chemistry, entitled "The Occurrence, Chemistry, Metallurgy and Uses of Tungsten with Special Reference to the Black Hills of South Dakota" including "A Bibliography of Tungsten" by Professor M. L. Hartmann. The paper is an important one and should prove of value to all who may be interested in the occurrence and uses of tungsten.

I submit the paper with the recommendation that it be published as Bulletin No. 12 of the South Dakota State School of Mines.

Respectfully,
CLEOPHAS C. O'HARRA, President.

HON. T. W. DWIGHT,
President Regents of Education.

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## PREFACE

For some time past and especially during the last three years, the South Dakota State School of Mines has received numerous requests from citizens of the state, and from many others, for information regarding tungsten and tungsten deposits. These inquiries have been for data upon a wide range of subjects, including the chemistry, metallurgy, uses, minerals, and geologic occurrence of tungsten in other localities, as well as in the Black Hills. The general field was partially covered by brief articles on various phases of the subject, published in the Tungsten Number of the School of Mines Magazine, The Pahasapa Quarterly, in February 1916, but the limited supply of this publication was soon exhausted. The issue of this number of the magazine has resulted in stimulating the demand for more information.

This bulletin is written in the attempt to bring together pertinent information concerning the general subject of tungsten. Some of this material has already appeared in the literature, but is not readily accessible to many persons interested in the subject. Other parts, especially those relating to the deposits of the Black Hills, are the result of field work and laboratory research by the authors.

It was the original intention to make the chapter on the geologic occurrence of tungsten very complete, but the appearance last year of an excellent treatment of this subject in U. S. Geological Survey Bulletin 652, on Tungsten Minerals and Deposits by Mr. Frank L. Hess, seems to render a thorough treatment of this subject quite superfluous. In Chapter 1, however, some data have been included not found in Hess' bulletin, that may prove to be of value to many readers. In this chapter the data presented by Hess have been freely used in order that they might be available to some not in possesssion of his publication.

The authors wish to express their thanks to ex-Supt. Richard Blackstone, and to Supt. Bruce C. Yates of the Homestake Mining Company, and to Messrs. A. J. Clark, W. J.

Sharwood, A. J. M. Ross, and Patrick Hayes, of the same company for information regarding the Homestake deposits; to Mr. Ed Manion for information regarding the Wasp No. 2 and Bismarck deposits; and to Mr. Otto Ellerman, and Mr. George Coats for data on various properties.

We wish also to express our appreciation of the generous services rendered by Miss Della M. Haft and Messrs. W. C. Bochert, and W. W. Waldschmidt in preparing the manuscript, and in various other ways.

Finally we desire to record our gratitude to Pres. C. C. O'Harra and to the Regents of Education for making possible the publication of this report, and to Pres. O'Harra also, for his hearty co-operation and his valued suggestions upon numerous phases of the work.

# INTRODUCTION

About the middle of 1915, after the war had been in progress for nearly a year, the war industries awoke to the fact that no rapid tool steel was to be obtained because Germany had forseen the situation and had secured a monopoly on the tungsten ore production. A violent sepeculative rise in the price of tungsten stimulated intensive search for new sources of the ores, and as a result many new deposits were opened, and increased production was reported from nearly all fields.

Dr. C. G. Fink says that every age has had its "key" substance, on the existence of which its civilization has largely depended. In the stone age the tribe which controlled the best flint deposits had the upper hand until some other tribe discovered bronze. Bronze as "key metal" was displaced by steel, which in turn gave place to lead for use in bullets. Still later, copper became the key, because it made possible the percussion cap. Tungsten is the key metal of today, because by the use of tungsten steel, modern manufacturing methods have been revolutionized. "To deprive a nation of tungsten is to cripple its military power in time of war, and its industrial power in time of peace. Without high speed steels, machine tools could not be produced nor operated in sufficient quantity to make the 'seventy-five' and its thousands of shells, the rifle and machine gun and its millions of cartridges. Nor could automobiles, farm machinery, ships, or engines be replenished after the sword has been happily sheathed—it may some day well be said that tungsten made democracy possible."

Popular interest in tungsten has also been developed by its common use in incandescent electric lights, which with an efficiency over five times as great as the old carbon filament lamps, have added much to the comfort, convenience and welfare of man.

In 1916, the United States produced more tungsten than any other country. Burma ranked second and Portugal third. Then followed Australia, Bolivia and Argentina.

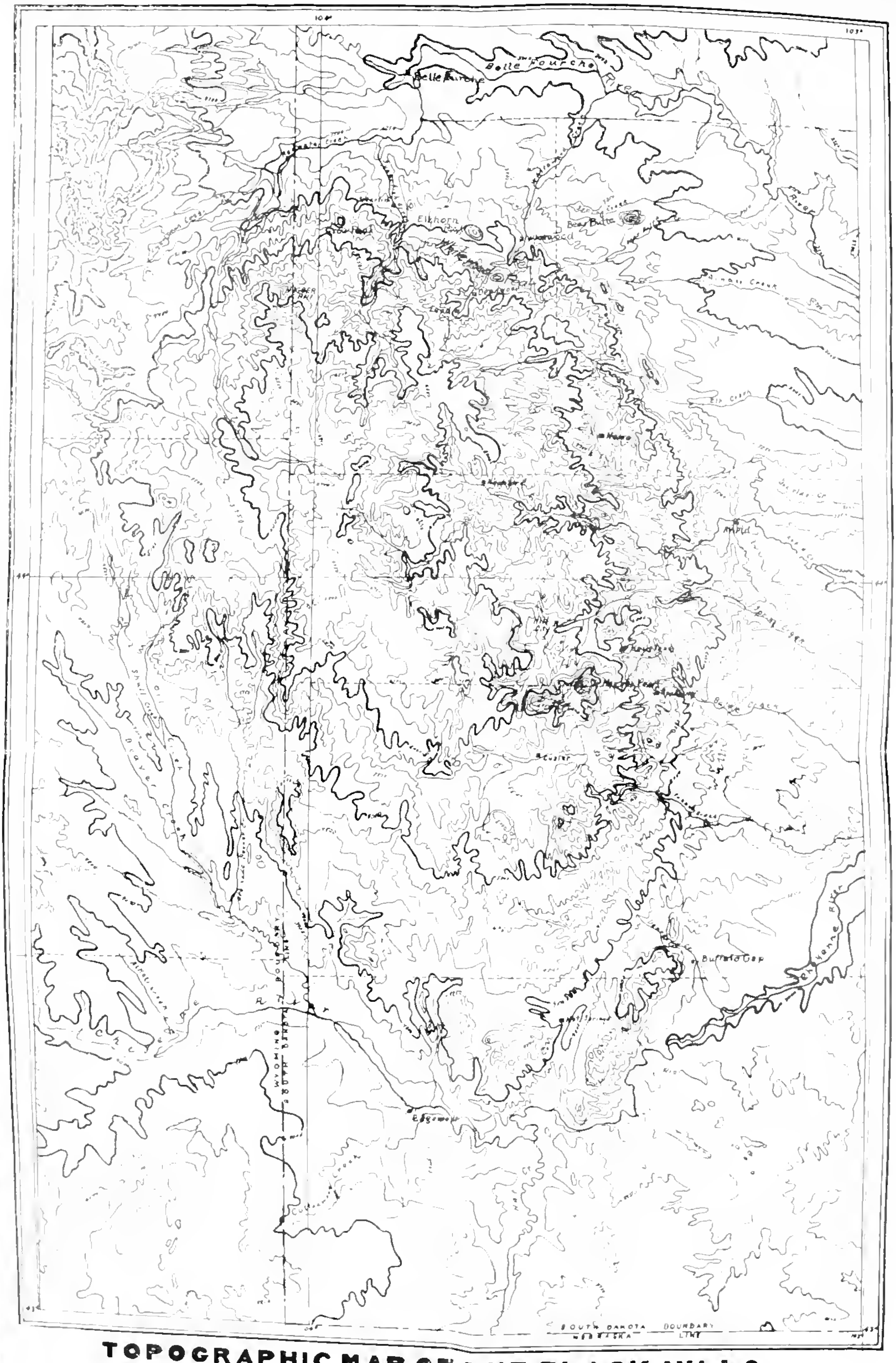
In the United States, Colorado is the largest producer, followed closely by California, with Nevada and Arizona about even for third place, then in order, South Dakota, Idaho, Utah and Missouri.

The Black Hills of South Dakota have already produced over a million dollars worth of tungsten ores, and many of the deposits are as yet not thoroughly developed. There is considerable promise of increased production in the future.

# PART I.

# GEOLOGICAL OCCURRENCE OF TUNGSTEN WITH SPECIAL REFERENCE TO THE BLACK HILLS

BY J. J. RUNNER



TOPOGRAPHIC MAP OF THE BLACK HILLS

SCALE
5 0 5 10 15 20 MILES
CONTOUR INTERVAL 250 FEET

**GE**

# PART I.

## CHAPTER I.

## THE GEOLOGICAL OCCURRENCE OF TUNGSTEN

In nature tungsten has not been found as a metal, but always in combination with other elements. It is certainly known combined with other elements, in but eleven minerals, a relatively small number when compared with the number of minerals in which many of the other metals occur. It is, however, the chief constituents, by weight, of nearly all of the tungsten-bearing minerals. Many metals, such as iron and calcium, occur in traces as impurities in a large number of minerals; tungsten on the other hand, has been identified in relatively few minerals, even among those with which it is commonly associated in pegmatites and quartz veins. In its natural occurrences the element is not a base forming one, and therefore does not act as a true metal in any of its mineral compounds.

In certain types of ore deposits, tungsten minerals are of frequent occurrence and have a wide distribution, but in the aggregate, the amount of the metal present is usually small. It might be said, therefore, to occupy the apparently paradoxical position of being a somewhat rare metal of comparatively common occurrence.

### Tungsten Minerals.

The following are the known tungsten minerals:

The wolframite series—
    Ferberite (80% to 100% $FeWO_4$) (20% to 0% $MnWO_4$)
    Wolframite (80% to 20% $FeWO_4$) (20% to 80% $MnWO_4$)
    Hubnerite (20% to 0% $FeWO_4$) (80% to 100% $MnWO_4$)
Scheelite $CaWO_4$.
Powellite $Ca(Mo,W)O_4$.
Stolzite $PbWO_4$. (Tetragonal)
Raspite $PbWO_4$. (Monoclinic)
Cuprotungstite. $CuWO_4.2H_2O$.
Tungstite $WO_3.H_2O$ (Tungstic ocher)
Ferritungstite $Fe_2O_3.WO_3.6H_2O$.
Tungstenite $WS_2$.

Reinite ($FeWO_4$) is given by Dana as a separate species, but is now regarded as ferberite pseudonmorphous after scheelite.

The wolframites have been shown by Hess* to form a complete series, with an infinite number of members from $FeWO_4$ to $MnWO_4$ so that he has proposed the following definition:

"Ferberite should be considered as an iron tungstate ($FeWO_4$) contaminated by not more than 20 per cent $MnWO_4$, a proportion equivalent to 4.69 per cent MnO, or 3.63 percent Mn, in the pure tungsten mineral."

Hubnerite should be considered as manganese tungstate ($MnWO_4$) contaminated by not more than 20 per cent $FeWO_4$, a proportion equivalent to 4.74 percent FeO, or 3.69 percent Fe.

Wolframite should cover the ground between the limits above indicated. That is, wolframite should be considered a mixture of iron and manganese tungstates containing not less than 20 per cent nor more than 80 per cent of either."

Hess further states:

"Except the light colored hubnerites, most of these mixtures cannot be distinguished by the eye or by simple tests, and in the absence of analyses it is therefore convenient to refer to the dark minerals of the series as wolframites."

Ferberite and wolframites when pure are black. When partly oxidized they may appear brownish, from the presence of iron oxide. Hubnerite is characteristically brown. Some specimens are yellowish, others reddish, while some are nearly black.

The members of the wolframite series are all monoclinic in form and the crystallographic constants of the end members have not been found to show any characteristic differences. Ferberite, however, seems to show a greater tendency to form well defined crystals than do the other members. Crystals of ferberite and wolframite are frequently wedge shaped and usually small. Such forms are common in ores where the crystals have grown in open cavities. Such crystals are shown in Plate III B. Boulder county, Colorado, ferberite,

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*U. S. Geol. Surv. Bull. 652, page 22.

often crystallizes in cuboid and elongated rhombic forms. In quartz veins wolframite seldom shows good crystal boundaries, but occurs in tabular or irregular masses. (See Plate II A.) Hubnerite exhibits a strong tendency to form radiating groups of thin, bladed crystals, such as the hubnerite from Two Bit Creek, Lawrence Co., S. D., shown in Plate IV A. Dense, fine-grained aggregates of closely packed crystals that have interfered with each other in growth, and show only irregular boundaries, frequently occur. When such masses are broken they may exhibit small shiny, cleavage surfaces, which may be mistaken for crystal faces. An example of such an occurrence may be seen in Plate III A.

In hardness, all members of the wolframite are a little over 5, and can be scratched with the point of a knife. Their specific gravities range from 7.2 or 7.3 in hubnerite, to 7.5 in ferberite, with wolframite intermediate.

Crystals of all members of the series split readily along very perfect planes in one direction. The plane of cleavage is at right angles to the plane of elongation in the tabular forms. This relation of cleavage to the form of the mineral is well shown in Plate II A. On newly broken cleavage surfaces of the unweathered mineral, the luster is brilliant metallic. Crystal faces are usually duller and their luster ranges from sub-metallic to dull. When the mineral is crushed fine, or is drawn over a surface of rough porcelain a powder is produced that differs somewhat from the color of the mineral. This powder, or the streak of the mineral, as it is frequently called, is dark brown to nearly black in the case of ferberite, dark brown to reddish brown for wolframite, and is brownish red or even greenish yellow in hubnerite.

Scheelite is calcium tungstate, or is sometimes spoken of as lime tungstate. In color scheelite is usually white, light gray, or honey yellow. Less commonly it is bright yellow, greenish yellow, brown or reddish brown. Its luster is often greasy, or may be simply glassy. Frequently specimens are found that are slightly translucent, but seldom are clear transparent ones seen.

Good crystals of scheelite are very rare. It is commonly found in granular masses, or irregular lumps of a coarser texture. In the Black Hills it is frequently seen coating wolframite in small botryoidal masses resembling drops of honey.

The hardness of scheelite is a little less than 5, so that it may be scratched easily with the point of a knife blade. Its specific gravity is approximately 6, which is less than that of the members of the wolframite series. It possesses four directions of fairly good cleavage, that may be seen in freshly broken massive specimens.

Scheelite frequently occurs as a secondary mineral, while the wolframites apparently, rarely do. Scheelite occurs in small quantities in nearly all wolframite veins, while wolframites are rare in the scheelite veins.

Tungstite ($WO_3H_2O$) or tungstic ocher, is a bright yellow powdery mineral, formed by the decomposition of the other tungsten minerals. It commonly occurs associated with oxides of iron or manganese, coating surfaces or filling cracks in scheelite or the wolframites. It is very rarely found in sufficient quantities to be of commercial importance.

Powellite, stolzite, raspite, cuprotungstite, ferritungstite and tungstenite, are very rare, and hence of little economic importance, therefore seem to merit no description here. For information regarding them the reader is referred to the standard texts on mineralogy.

### Minerals For Which Tungsten Ores are Frequently Mistaken

Among minerals which have been frequently mistaken for the wolframites may be mentioned; specular hematite, magnetite, cassiterite, columbite, spahalerite, tourmaline, manganese dioxide, and even graphite. In one instance that came to the author's attention, a prospector had mined and hand sorted several tons of quartz containing black tourmaline. In another case a large mass of black sphalerite was exhibited and placarded as assaying 70% $WO_3$. In the field, "especially rich ore" has been seen that was mostly graphite. Numerous specimens of the other minerals listed above have been received at the South Dakota State School of Mines to be assayed for tungsten. Such mistakes are, of course, natural among prospectors in new fields, and in fact

Plate II A.
WOLFRAMITE—HILL CITY

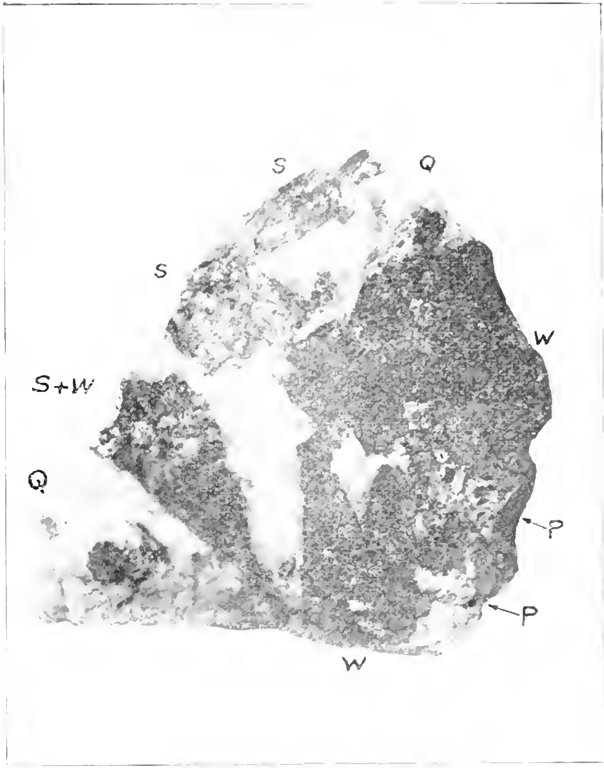

Plate II B.
TUNGSTEN ORE—ROBINSON CLAIM, SPOKANE, S. D.
P, Pyrite; Q, Quartz; S, Scheelite; S & W, Sheelite and Wolframite; W, Wolframite.

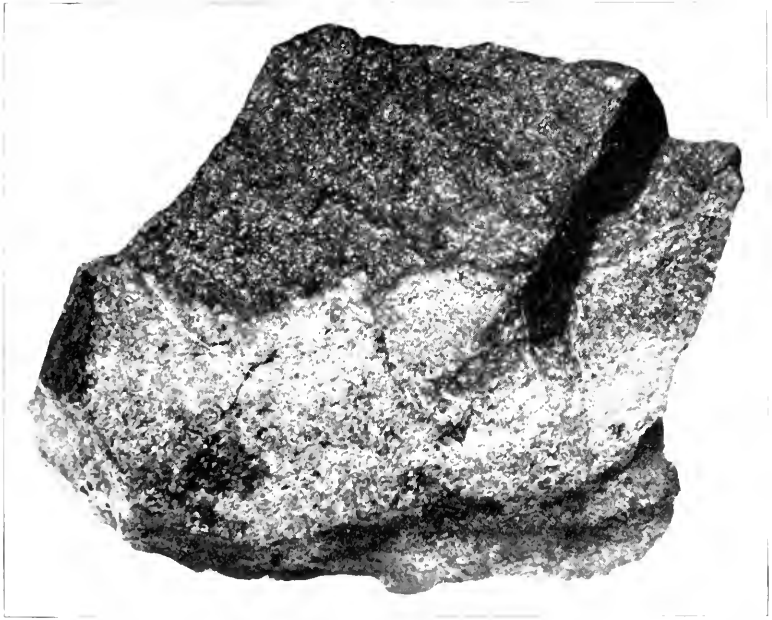

Plate III A.
GRANULAR WOLFRAMITE REPLACING DOLOMITE. HOMESTAKE MINE, LEAD, S. D.

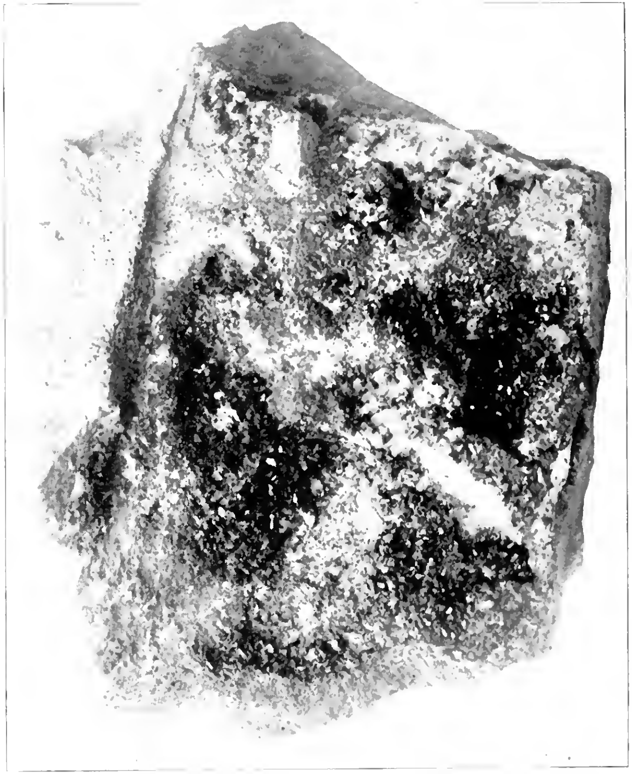

Plate III B.
WEDGE SHAPED CRYSTALS OF WOLFRAMITE GROWN IN OPEN CAVITIES. HOMESTAKE MINE, LEAD, S. D.

Plate IV A.

RADIATING GROUP OF BLADED CRYSTALS OF HUBNERITE, TWO BIT CREEK, LAWRENCE COUNTY, S. D.

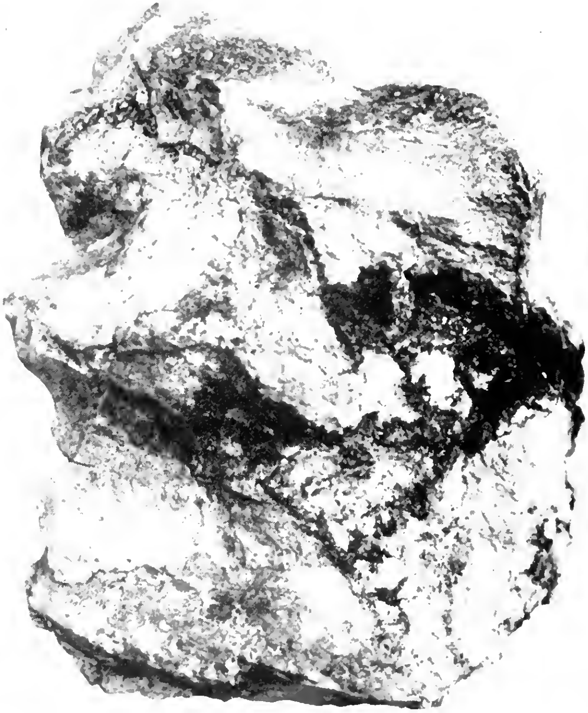

Plate IV B.

CRYSTALLINE WOLFRAMITE IN CAVITIES AND SEAMS OF RHYOLITE PORPHYRY, HENAULT CLAIM, NEAR LEAD, S. D.

are not unknown among technically trained mining men. Some of the larger companies have shown a very commendable spirit in furnishing specimens of their ore to the prospectors for comparisons. It is to be highly recommended to the man unacquainted with tungsten minerals, that he collect specimens for study before doing much prospecting, even should he be able to get determinations of his mineral finds made free of charge.

Magnetite, cassiterite, columbite, tourmaline, and manganese dioxide, can usually be readily distinguished from the wolframites by their lack of good cleavage, which the tungsten minerals possess to a high degree. The cleavage of the wolframites may be readily recognized by their flat, shiny surfaces produced upon breaking the minerals. Micaceous hematite flakes off in thin, shiny leaves, that may be mistaken for the cleavage of wolframite. Its reddish brown streak, furthermore, is not unlike that of some of the wolframites. Its color, however is more of a steel blue, while that of the wolframites is dark brown or black, and the cleavage flakes of the micaceous hematite are usually very much thinner than can readily be obtained from any of the tungsten minerals. Tourmaline lacks cleavage, is much harder than any of the tungsten minerals, and has more of a glassy than a metallic luster. It is, furthermore, commonly in long, slender crystals, with a rounded triangular cross section. Graphite is so soft that it soils the fingers. Sphalerite, tourmaline, graphite and manganese dioxide differ from the wolframites in being much lighter in weight and can with a little practice be readily distinguished by this property.

Cases in which scheelite has been mistaken for other minerals, or in which a variety of other minerals have been thought to be scheelite have come to the author's attention. The more common errors have been in connection with calcite, garnet, quartz, apatite, amblygonite, barite, and feldspar. Of these minerals, quartz, and garnet are much harder and will readily scratch glass, whereas scheelite can be easily scratched with the point of a knife blade. Feldspars are scratched with great difficulty with a knife and furthermore always cleave readily along smooth planes, while scheelite does not show good cleavage surfaces, barite has a superior cleavage and is much softer than scheelite. Amblygonite has a perfect cleavage in one direction and is with difficulty scratched with a knife. Calcite has three perfect cleavages and is much softer than scheelite. Apatite, as well as all the other minerals here mentioned, has a specific gravity decidedly less than that of scheelite and in a majority of cases, can be distinguished from it because of this fact.

Tungstite and yellow, hydrous iron oxide are often confused. The most satisfactory method of distinguishing these minerals, and it might be added, the most conclusive test for any of the tungsten minerals, is a chemical one.

A simple, and usually a very satisfactory test is to boil the finely powdered mineral in hydrochloric acid, when if tungsten is present, a bright yellow powder ($WO_3$) will be formed. Upon the addition of metallic zinc or tin the yellow powder will be changed to a blue and finally to brown.

In case the yellow powder and blue color do not appear, when treated as given above, fuse the finely powdered mineral with sodium carbonate, or sodium bicarbonate and then dissolve the fused mass in hydrochloric acid, and add tin or zinc. If any tungsten is present the indigo color will appear.

## Mineral Associates of Tungsten in the Ores

Inasmuch as tungsten ores most commonly occur in veins, closely associated with granites, acid porphyries and pegmatites, a list of the minerals most commonly associated with tungsten ores in reality, becomes a partial list of acid pegmatites and deep vein minerals. Upon reviewing the literature describing the most important deposits of the United States and foreign countries, the author has found the following to be the more common associates of tungsten; quartz, muscovite, cassiterite, molybdenite, pyrite, arsenopyrite, topaz, tourmaline, fluorite, chalcopyrite, gold and silver; and to a lesser extent feldspars, biotite, beryl, apatite, bismuth, bismuthinite, sphalerite, columbite, graphite, sylvanite, and many less common ones.

In general there seems to be a greater variety of minerals in the wolframite veins than in the scheelite veins. Scheelite veins are, perhaps, more commonly associated with gold ores than with ores of silver or the base metals. Minerals of copper, lead, zinc, tin, silver, nickel,cobalt, arsenic, antimony, and bismuth, are apparently more common in wolframite veins than in scheelite veins.

### Rocks Associated With Tungsten Ores

Among rocks, granites, acid pegmatites, and acid porphyries, are by far the most common igneous associates of tungsten deposits. These rocks are all characterized by an excess of silica, that has crystallized in the form of quartz, and quartz is easily the most common mineral associate of the tungsten ores. In some cases the ore bodies lie wholly within the igneous rocks, in other cases they extend into slates, quartzites and other rocks at the sides, or lie at the contact of the igneous rocks and sedimentaries, but in a great majority of cases igneous rocks of the acidic type are to be found nearby. Tungsten deposits are frequently within, or in close proximity to metamorphic rocks, such as slates, schists, or crystalline limestones, for the very intrusion of the igneous rocks themselves have in many cases brought about the metamorphism.

### Types of Deposits

The known deposits of tungsten of the world may be conveniently classified according to their mode of occurrence as follows: (1) segregation deposits; (2) pegmatites; (3) veins; (4) replacement deposits; (5) contact metamorphic deposits; (6) placers. Of these types the vein and placer deposits have furnished much the greater part of the product.

(Segregation Deposits.) During the crystallization of an igneous magma it sometimes occurs that minerals of one kind will be concentrated within a limited space and there separate out in greater amounts than are in the average of the rock as a whole. In the Whetstone Mts., Cochise County, Arizona, is an occurrence of this kind where wolframite occurs in portions of a granite in quantities sufficient for a small production. In the Henault property near Lead, South Dak., crystals of wolframite have been found intergrown with the feldspar and quartz, of a rhyolite porphyry, that has apparently segregated out from the magma and concentrated near the margin of the dike.

(Pegmatites.) As a molten mass of igneous material from below the outer crust of the earth rises, it comes into contact with relatively colder rock and begins to solidify. Those materials least soluble under the existing conditions of temperature, pressure and concentration separate first, leaving a solution that continually becomes richer in the more fluid materials. The fluidity of the residual solutions is greatly increased by the presence of certain substances known as mineralizers, or as one might say, fluxes. Among the mineralizing agents, are water; boric, hydrochloric, and hydrofluoric acid; and compounds of phosphorus, sulphur, arsenic, lithium, beryllium, cerium, niobium, tantalum, and tungsten. During a later stage of the solidification of the parent magma, the liquid portions find avenues of escape outward through the cracks, formed as a result of the shrinkage of the solidified portions as they crystallized and cooled, and are forced into these openings and even out into the surrounding rock along planes of weakness, where they finally solidify in dikes, sills, or pipe-like masses. The resulting rocks in the case of a parent, acid magma, are characterized by quartz, alkali feldspars, muscovite, biotite, lepidolite, topaz, tourmaline, fluorite, apatite, beryl, columbite, cassiterite, spodumene, amblygonite, tungsten minerals, monazite, and frequently a small amount of arsenides and sulphides of the base metals. Such rocks are the acid pegmatites. In case the tungsten content of the original magma were sufficiently high the pegmatite forms an ore-body from which the tungsten may be profitably recovered. Such pegmatites are always associated with deep seated rocks of the acid type and often may be traced into granites by insensible gradations. From their mode of origin it may be readily seen that the pegmatites will frequently be found at the outer margins of the granite masses. Often, however, they have differentiated in place and may be found in irregular masses within the granite, and not separated from it by sharp boundaries.

On the whole the pegmatites are more commonly found in dikes, but frequently they occur in sills and irregular pipe-like forms. Whether in dikes, sills or pipes, their forms and sizes are extremely variable. Few of them maintain a uniform thickness and direction for more than short distances. The distribution of the minerals within is likewise very erratic. Rich spots of ore intervene with barren stretches, suddenly and frequently, and there seems to be no method of predicting the character of the body a few feet distant from the exposed portion. In general the pegmatites seem to be less favorable for ores of tungsten than the veins.

The deposits of Cornwall, England, Torrington, N. S. W., and some of the Queensland deposits are perhaps the most important occurrences of tungsten in pegmatites. Tungsten bearing pegmatites occur near Hill City in the Black Hills of South Dakota.

(Veins.) The relations of the quartz-tungsten veins to the pegmatites, or to other acidic rocks, is very similar to the relation of the pegmatites to the granite rock, i. e. they are products of the separation and solidification of the more soluble parts of the original solution. In the pegmatites of the Black Hills the author has noted numerous cases of the occurrence of wolframite in the quartz-rich portions of the pegmatite. In some cases these quartz-rich portions are in the form of local segregations of irregular form, in others they are in the form of veins. Some of the veins have extended beyond the pegmatites and into the surrounding schists, and it is in these veins that the richest ores exist. So that it is true that the more promising deposits occur in vein area beyond the pegmatites just as many of the richer pegmatites lie at the border of the granite area. Tungsten minerals and quartz, perhaps in aqueous solution, appear in this case to have been the most fluid portions of the original magma and to have separated most completely and to have travelled farthest. Cassiterite appears to have been less soluble and crystallized more commonly in the pegmatites.

On the whole the minerals of the quartz-tungsten veins are very similar to those of the pegmatites. They, however, contain a much smaller percentage of silicates, except perhaps tourmaline and muscovite; phosphates; columbates and tantalates; lithia minerals; and a greater percentage of native metals; sulphides of iron, copper, zinc, lead, molybdenum, silver, and antimony; arsenic minerals; and tungsten minerals. Furthermore the veins frequently contain carbonates which are not found in the pegmatites.

Tungsten veins may occur singly, or in zones of rock permeated by many parallel or anastomosing veins. Veins frequently branch, pinch and swell. Some are lense shaped, others thin, sheet-like forms, and some are thick, plug-like masses. The greater number cannot be traced far along the strike or dip, but some persist for great distances and are remarkably uniform in thickness. Sudden changes in direction are common. The mineral content is as variable as the other physical features.

The veins are the chief source of tungsten at the present time. The ferberite veins of Boulder County, Colorado; the scheelite veins of California; the wolframite veins of Burma, the Malay Peninsula, Portugal, and South America, have furnished much the greatest part of the world's production of tungsten, and bid fair to continue their output for years to come.

(Replacement Deposits.) Where ore bearing solutions encounter soluble rocks, they may react with them removing the original material, and leaving in its place the silica and ore minerals of the solution. In many cases the intimate structure of the original rocks is preserved, although completely changed in composition. In the act of solution cavities are frequently formed that later may be lined with crystals of the ore. Carbonate rocks are especially favorable for replacement, apparently on account of their greater solubility.

Perhaps the best known and most important deposits of this type occur in the Northern Black Hills of South Dakota, where a dolomitic limestone has been partially replaced by silica and wolframite. The ore solutions ascended through vertical cracks in the dolomite until they reached an impervious shale and were forced to spread laterally, and here formed horizontal lenses of rich ore.

(Contact Metamorphic Deposits.) Where molten magmas come into contact with other rocks the high temperature, and the solutions and gases emanating from the magma, frequently cause intense mineral changes. Especially is this true in the carbonate rocks. The carbon dioxide is driven off and the lime, magnesia, and iron of the carbonates, reacts with silica, alumina, and other materials of the magmatic solution, causing the destruction of the original rock, and the development in its place of an aggregate of new minerals, chiefly silicates of calcium, magnesium and iron. Among the minerals characteristic of contact metamorphism are, garnet, vesuvianite, epidote, tremolite, actinolite, wollastonite, diopside, axinite, and many others. The magmatic solutions, as in the case of veins and replacement deposits, frequently bear metallic ores and these are precipitated in the zone of metamorphism.

The tungsten deposits near Bishop, Inyo County, California, are of this type. A description of this occurrence will be found below.

(Placers.) As the chemical and mechanical agents of weathering act upon an ore body exposed at the surface, it is gradually disintegrated and carried away. The materials easily dissolved are removed in solution, while the more resistant ones are washed down by running water, or may be gradually removed by gravity to stream beds, where they are sorted by the stream. The heavier materials of the gravel bed gradually work toward the bottom and there become concentrated. Tungsten minerals, for the most part are resistant to chemical weathering, and on account of their high specific gravity readily concentrate in rich placers.

Deposits of this type have furnished a large amount of the tungsten production of Burma and the Malay Peninsula. Placer production in the United States has been small, but locally some rich gravels have been worked in California, Arizona, and Nevada.

## Persistence of Tungsten Deposits in Depth

The persistence of tungsten deposits in depth, and the maintenance of values, are questions of vital importance to those interested. Unfortunately but few deposits have been developed far enough to determine their true nature, so that we have not a sufficient amount of real data upon which to base definite conclusions.

Geologists are fairly well agreed that granites are rocks formed at considerable depth below the surface of the earth. The association of tungsten deposits with granite and their occurrence in veins and pegmatites with such minerals as tourmaline, topaz, beryl, muscovite, and others believed to be formed only at high temperatures, seems to point fairly clearly to the formation of most tungsten deposits at considerable depths. This would seem to imply conditions of more or less uniformity, within a comparatively large zone bordering the granitic mass, so that although tungsten veins might not form everywhere, they are likely to form anywhere, within this zone. The evidence seems clearly to indicate that a great number of pegmatites and associated quartz veins, were suddenly and under great pressure forced into the surrounding rocks. Such a mode of origin would likely produce irregularity in their forms.

Among tungsten deposits we frequently find veins of very limited extent vertically as well as horizontally with irregular swelling and pinchings, and yet some are known, such as the Boulder County, Colorado, veins, that seem to persist for considerable distances along the strike and for at least 900 feet vertically. In one of the Atolia mines the greatest quantity of ore was found below a depth of 400 feet, and the mine has good ore at a depth of over 500 feet, which is over 1000 feet along the dip of the vein. A deposit of scheelite in Halifax County, Nova Scotia, is reported to have been followed three miles along the strike of the vein. The deposits of scheelite and the genetically related gold reefs of Hillgrove, N. S. W. are believed to persist vertically for upward of 1500 feet.

It would seem therefore, that despite the characteristic bunchiness of so many tungsten bearing lodes and of their sudden termination, there are lodes that maintain their values over a considerable distance along the strike and along the dip. The development of one vein of limited extent might easily lead to the discovery of others, and the opening of these to still others. At least it seems that other lodes are likely to be found within the zone of known deposits.

No authenticated case of secondary enrichment to any important extent, in tungsten deposits, has yet been described. It appears improbable, furthermore, that any of the wolframite, hubnerite, or ferberite in the more important deposits are secondary, so that there is no apparent reason for believing that some of the rich deposits have become so because of secondary enrichment, and that for this reason would grow poor in depth.

Below is given a brief description of some of the more important deposits of tungsten in the United States and in foreign countries. A description of the important deposits of Japan and of some other countries, as well as some within the United States, that otherwise would have been included, were omitted because of the meager information on them obtainable in the literature.

## Important Tungsten Deposits of the United States

(Colorado.) The principal tungsten producing district of Colorado occupies a strip approximately 4x20 miles in southwestern Boulder County and northern Gilpin County. The rocks of the district comprise sedimentary gneiss and schist, and intrustive gneissic-granite of pre-Cambrian age; all of which are cut by later dikes ranging in composition from limburgite to granite pegmatite. On the northwest and southwest sides of the tungsten area are gold and silver bearing veins having the same trend as the tungsten veins. These are believed to be a continuation of the gold belt of Clear Creek and Gilpin Counties. The tungsten veins are in many ways similar to the gold veins of the district and seem to have a close connection with them in genesis. The gold veins bear sylvanite, pyrite, molybdenite, roscoelite, barite, adularia, and chalcedony. The mineralogy of the tungsten veins, is similar to that of the gold veins, but they carry in addition several other minerals. Both gold and tungsten veins occupy sheeted zones characterized in places by brecciation. A close relationship between the tungsten veins and the pitchblend veins of Gilpin County lying in the same belt, has also been noted.

The tungsten bearing veins are to be found largely in the pre-Cambrian granite, in the sedimentary gneiss and at the contact of the two. The schistose parts of the gneiss have proven less favorable for ore bodies. In places veins follow dikes of granite pegmatites, and occur both within them, and at their borders. In other places veins are to be found in the dikes and masses of the later fine grained granite. In places the veins turn sharply from the dikes of pegmatite and granite and enter the surrounding rocks. In general the ore bodies seem to follow no regular system, but in the Nederland-Beaver Creek area they follow approximately the direction of trend of the tungsten bearing area as a whole. The veins dip for the most part steeply, and rarely as low as 45°. In width the lodes vary from a fraction of an inch to as much as 14 feet, averaging perhaps, between 2 and 4 feet. In length, width, direction of strike, persistence in depth, and quality, the veins vary considerably.

In physical characteristics the ores are of three types: (1) crystals of ferberite occur in crusts, vugs, and open breccias; (2) fine grained and massive ore filling the seams in the wider and less brecciated portion of the vein; and (3) highly siliceous ores in which fine grained ferberite occurs in various quantities, scattered through chalcedonic silica. In association with the ferberite, which is the principal ore mineral, are to be found some wolframite and scheelite, also sphalerite, galena, chalcopyrite, molybdenite, pyrite, sylvanite, magnetite, hematite, adularia, hamlinite, chalcedony, quartz, silver, and gold. The ores are notable for their lack of cassiterite and tourmaline and the very small percentage of quartz.

(California.) The most important tungsten prooducing district of California extends from near Atolia in northwestern San Bernardino County, to near Ransburg in eastern Kern County. A second area of considerable importance lies in Inyo County near Bishop in Owen's Valley.

The Atolia-Randsburg district occupies an area approximately 2½x10 miles in extent. The country rock is largely a gnessic grano-diorite cutting hornblend and mica schists. In the grano-diorite, intrusive igneous dikes occur in places. Adjacent to the grano-diorite occur also limestones, quartzites and slates. The ores consist of scheelite in quartz veins, chiefly in the grano-diorite; but also cutting the schists; at the margins of the intrusive dikes; and to some extent at the contact of limestones and schist. The veins follow zones of shearing, and in general are well defined. Some are mere lenses, while others are persistent over a considerable range, both along the strike and along the dip, and have been followed to depths of over 500 feet. In places they have a thickness of three feet or more. The material of the veins consists of crushed grano-diorite, that is in places partially replaced by silica; quartz; calcite; siderite; scheelite; and a little wolframite. Some of the veins are gold bearing. Placers of scheelite derived from the veins have proved very profitable locally.

In the Inyo County tungsten area the rocks are granite, inclosing masses of various sediments including limestone. The principal ore bodies follow the bedding of the sedimentary strata inclosed in the granite and contain scheelite, garnet, epidote, quartz, calcite, hornblend, pyroxene, apatite, magnetite, and traces of various sulphides. Other ores occur with a considerable amount of phlogopite mica. The $WO_3$ content of the ores varies on the average, from 1.5 to 2 per cent. The ore bodies are known to have a vertical range of at least 700 feet. This occurrence is of considerable scientific interest inasmuch as it is a contact metamorphic type of deposit, which is not a common one among tungsten deposits.

(Arizona.) Tungsten deposits are of very wide distribution in Arizona. The most important deposits in this state are, perhaps those of the Dragoon and Whetstone Mountains in Cochise County; of the Guijas Mountains in Pima County; of the Acquarius and Yucca districts of Mohave County; and of Eureka, Tip Top, and Tule Creek districts in Yavapai County.

In the Dragoon Mountains numerous quartz veins occur cutting granite, that bear hubnerite, scheelite, pyrite, chalcopyrite, and fluorite. Many of the veins have proved rich but of rather limited extent. Rich placer deposits derived from the veins have proved rich.

In the Whetstone Mountains wolframite and scheelite associated with pyrite, bornite, chalcopyrite, and mica occur in quartz veins cutting granite, and on the contact of granite and schist. Wolframite also occurs in the granite as a primary constituent.

At Arivaca in the Guijas Mountains of Pima County, hubnerite, wolframite and scheelite occur in quartz veins cutting granodiorite, and acid porphyry dikes. In places the veins occur singly, in others the lodes are composed of vertical zones of country rock permeated by a great number of thin seams of quartz. Associated with the tungsten minerals are chalcopyrite, pyrite, galena, and gold.

In the Acquaris district of Mohave County wolframite occurs in quartz veins cutting granite. Some of the lodes are fissure veins from 1 to 3 feet thick and have been followed for upward of 2000 feet along the strike. In the Yucca district of the same county wolframite and scheelite occur in quartz veins in schist, at the contact of limestone and schist, and at the contact of limestone and granite. Associated with the tungsten minerals are molybdenite and copper sulphide.

In the Eureka, Tip Top and Tule Creek districts of Yavapai County hubnerite and wolframite occur in quartz veins associated with granite. Some of the veins were formerly worked for their rich silver content and the tungsten minerals discarded as worthless. In recent times many of the old mine dumps have been worked for their tungsten content with good results.

(Nevada.) The tungsten production of Nevada has come largely from the deposits in the Snake Range of eastern White Pine County. The rocks of the tungsten area are Cambrian quartzites and argyllites and intrusive granite porphyry. Hubnerite and a little scheelite occur in quartz veins with pyrite, fluorite, gold and silver. The veins range from a few inches to three feet in thicknesss and dip steeply. The ore minerals occur irregularly scattered through the vein material, in fine disseminated grains and in irregular masses. In places the hubnerite has been concentrated along the vein walls.

### Foreign Occurrences

(Burma, Siam, and the Federated Malay States.) From the southern Shan States of Eastern Burma there extends an area of metamorphic rocks and intrusive granites southward through Lower Burma, the Siamese Malay States, and the Federated Malay States to the extremity of the Malay Peninsula. A continuation of the same granite appears on the islands to the south as far as Banka and Billiton. This area furnished the majority of the world's tin and has been, for a number of years a region of foremost importance in the production of tungsten. The geologic conditions under which the tungsten occurs throughout this great area, are sufficiently uniform to permit of a general description of the deposits rather than to necessitate a considerable number of more detailed ones. Both tin and tungsten are obtained from lode as well as placer deposits, closely associated with the granite in distribution and genesis.

The granite is a coarse rock commonly bearing feldspar, quartz, biotite, tourmaline, and in places, some cassiterite. At contacts with the schists, granite is frequently porphyritic. In the granite, at the contact of granite and schists, and, to some extent, in the schists, occur quartz veins bearing wolframite, cassiterite, pyrite, chalcopyrite, arsenopyrite, molybdenite, bismuthinite, muscovite, and tourmaline. In places the veins are richer in wolframite in the schists and richer in cassiterite within the granite, as though the cassiterite had been precipitated at a higher temperature than the wolframite. In the veins the muscovite is often concentrated along the walls. The wolframite is very unevenly distributed. It occurs in places in bunches of massive ore, and again in fine needles and small crystals with intervening barren spaces. The lodes are composed of single veins, of zones of parallel veins and of stockworks, and are variable in extent and thickness. Some quartz veins bearing scheelite in association with fluorite, have been found near areas of limestone.

For the most part, the mining has been in the oxidized zone, where the ores were easily removed and little knowledge has been gained as to the continuity of the lodes in depth.

In the valleys below the lodes occur rich placers from which a considerable percentage of the production has been derived.

(Portugal.) In Portugal, the largest of the European producers of tungsten, the greater part of the output comes from the northern provinces of Tres-Os-Montes and Beira Baixa. The area is underlain largely by a granite that occurs extensively over western Spain and northern Portugal. In the province of Tres-Os-Montes the ore occurs in quartz veins in the granite or at the contact of the granite with sedimentary rocks. The veins are very irregular and the distribution of the wolframite within them is very erratic. In some veins cassiterite accompanies the wolframite, but there is a general lack of other minerals than quartz in most of the veins. In the Panapqueira district of Beira Baixa the ore occurs in quartz veins, in schists. Associated with wolframite in the veins are pyrite, arsenopyrite, cassiterite, mica, and carbonates of copper. No igneous rock occurs in association with the ores but granites outcrop at a distance of about 11 kilometers.

(Bolivia.) In Bolivia tungsten comes largely from the departments of Oruro, LaPaz, and Potosi, where it is closely associated with ores of tin, and occasionally with silver. Wolframite occurs in quartz veins cutting sedimentary rocks for the most part, in the neighborhood of rhyolites, and trachytes that are believed to have given rise to the ores. Associated with wolframite in the veins are arsenopyrite, chalcopyrite, bismuth, cassiterite, and sometimes silver, niobium and tantulum minerals. Some of the veins are extensive and rich and have produced a large amount of ore.

(Argentina.) Among the most important deposits of tungsten in Argentina are those of the Cerro del Morro in the province of San Luis, and those of the Sierra de Cordoba. In the Sierra del Morro granites have invaded and metamorphosel sediments of Silurian age. Later followed intrusions of andesite. The acid intrusives comprise aplite, pegmatite, and micaceous quartz-veins, some of which bear tourmaline. The tungsten occurs in wolframite in the quartz veins and is frequently accompanied by apatite and fluorite. Some of the pegmatites carry a considerable amount of magnetite, and hematite pseudomorphous after magnetite. The tungsten veins are from 2 to 4 feet wide and in them the wolframite occurs irregularly, the richer portions rarely exceeding a length of 12 feet along the vein. In the Sierra de Cordoba, quartz veins bearing wolframite and secondary scheelite occur cutting granites and crystalline schists. Associated with the tungsten minerals are copper sulphides, molybdenite, sericite, apatite, fluorite, tourmaline, and a little topaz.

(Peru.) The chief deposits of Peru are located in the departments of Ancachs and La Libertad. Wolframite and hubnerite occur in quartz veins on the contact of granite with slates and quartzites and within the sedimentary rocks. The tungsten ores are associated with others of copper and silver.

(England.) For a number of years a few hundred tons of tungsten concentrates have annually been produced from the celebrated mines of Cornwall, England, best known for their tin and copper ores.

On the Cornish Peninsula occur sedimentary strata of Cambrian, Ordovician, Silurian, and Devonian age, that were intruded by granite, probably during late Carboniferous times. The granite appears in five large, and several small bosses that are probably connected below, inasmuch as the granite surfaces extend downward at low angles and have been encountered at many places below the sediments. The granites have pronounced metamorphic effects on the surrounding sedimentary formations near their contacts. From the granites extend apophyses of quartz and felsite porphyry, known as "elvans." The elvans vary in thickness from 1 to 100 meters, and some have been followed along the strike for a distance of 20 kilometers. The lodes occur along the margins of the elvans, partly within the granite itself, and partly in the surrounding metamorphosed slates. Some ore bodies occurring at the surface of the slates have been followed downward into the granite. The lodes in places follow joint planes in the granite, forming impregnated zones and stockworks, also they occupy tectonic zones characterized by brecciated structure. The ore minerals are chiefly cassiterite and some stannite; chalcopyrite, boronite, and chalcocite; wolframite and scheelite; arsenopyrite and other arsenic minerals. Of lesser importance are tetrahedrite; sphalerite; bismuthinite; silver, cobalt, and nickel minerals; pitchblende; and various secondary minerals of iron, manganese, copper, and lead. As gangue minerals quartz, chlorite, tourmaline, fluorite, and kaolin are abundant, while topaz and axinite occur sparingly. The copper ores prevail near the surface, while the tin and tungsten ores occur chiefly at greater depths, and often are confined to lodes in the granite.

(Queensland.) In Queensland the important tungsten deposits are uniformly associated with granite but occur also in greisen, felsite, quartz porphyry, schist, slate, and quartzite. The deposits are of various types, consisting chiefly of fine quartz veinlets; large masses and lenticular bodies of quartz; irregular masses of quartz, chlorite, and mica; and impregnations of granite and greisen. The lodes are irregular in form and size and exhibit a marked tendency toward suddenly pinching out. The mineral associates of the wolframite are molybdenite, and minerals of bismuth, tin, copper, uranium, cerium, iron, manganese, zinc, and lead. The chief gangue minerals are quartz, topaz, fluorite, tourmaline, beryl, muscovite and biotite.

(New South Wales.) In New South Wales the most important tungsten deposits are the wolframite deposits of the Mole Tableland, or Torrington district and the scheelite deposits of the Hillgrove district.

In the Torrington district clay slates have been invaded by granites and pegmatites, causing silicification and induration of the host rock. Wolframite occurs in the pegmatites and in quartz veins in the granite and metamorphosed slate. Associated with the wolframite are bismuth, molybdenite, chalcopyrite, arsenopyrite, cassiterite, ilmenite, monazite, fluorite, topaz, beryl, smaltite, and lithia-mica. A large number of deposits have proved erratic in form, size and in tungsten content.

In the Hillgrove district quartz veins bearing scheelite cut granite and slates. Accompanying the veins are dikes of granite porphyry and diorite. Some of the veins appear to be true fissure veins while others occupy contraction joints in the granite. The tungsten lodes or "reefs" accompany gold reefs, and in places valuable ores of gold have been mined in conjunction with the scheelite. In places a considerable amount of stibnite accompanies the scheelite. Many of the veins have proved very thin and the ore irregular in its occurrence, yet some are known to be persistent over a vertical distance of 1600 feet.

(New Zealand.) In New Zealand valuable scheelite deposits occur, accompanied in the majority of cases by gold ores. The veins traverse schists for the most part, where they are, in some cases, of the bedded type, and in others of the fissure type. The scheelite occurs irregularly in pockets and in lenticles in quartz, and is accompanied by pyrite and arsenopyrite.

# CHAPTER II.

## GEOLOGY OF THE BLACK HILLS

**Topography.** The Black Hills occupy an area, elliptical in outline, having a length of about 100 miles from northwest to southeast and a maximum width of about 50 miles. The hills rise rather abruptly from the surrounding plains to elevations of more than 7,000 feet above the sea. The central area may be compared to an elevated basin, elongated from north to south, and with a plateau rim of varying width. Rising above the floor of the basin are ranges of hills attaining for the most part, altitudes slightly less than that of the rim, but containing one elevation, Harney Peak, that is the highest point in the entire hills area. The larger streams, that drain the central basin, head near its western margin and flow eastward through broad park-like valleys until they reach the central, or the eastern portion of the basin, where they enter narrower depressions, and finally find their way northward, eastward, and southward through the plateau and flanking ridges, by way of deep canyons. The plateau surrounding the central area is broad on the west, where the dip of the rocks is gentle, and narrow on the eastern side where the formations dip more steeply. Its surface conforms to that of the massive, resistant Pahasapa limestone. In it streams have carved numerous deep gorges, flanked by nearly vertical walls of gray limestone. On the outer flanks of the limestone plateau occurs the Red Valley, a race-track like depression, completely encircling the main hills area. The slopes of the Red Valley on the inner side toward the limestone plateau, are paved with the gently-dipping, hard Minnekahta limestone. On its outer margin it faces the steep, truncated edges of the outward-dipping, resistant sandstones of the Lakota and Dakota formations, that form the prominent hog-back ridge on the outskirts of the hills. The outer slopes of the hog-back ridge descend gently with the surface of the Dakota sandstone to the plains, that present broad expanses of rolling prairies.

**General Geologic Relations.** Occupying the central area are crystalline metamorphic rocks and granites of pre-Cambrian age. Surrounding them, occur in sequence outward, the formations of the Paleozoic and Mesozoic groups, and finally the Cenozoic formations. The latter formations overlap in places the upturned and eroded edges of the older rocks but mostly lie at the surface of the plains beyond. In the northern portion of the area are numerous dikes, sills, and laccoliths of early Tertiary age, intrusive into the pre-Cambrian, Paleozoic, and Mesozoic formations. Structurally the Black Hills uplift is a somewhat elongated dome. The sedimentary formations dip outward in all directions from the central axis and disappear beneath the younger formations of the plains.

**Pre-Cambrian Formations and History.**—(Rocks of Sedimentary Origin.) The oldest formations exposed within the Black Hills Uplift consist for the most part of a group of alternating beds of schists, slates, gneisses, quartzites, and lesser amounts of quartzite conglomerate, limestones, and iron formations of sedimentary origin. These sedimentary rocks are believed by the author to belong to two systems separated by an unconformity that appears along the eastern margin of the crystalline area in the vicinity of Nemo on Box Elder Creek.

The older system covers much of the larger part of the area of crystalline rocks in the central region of the hills. In it rocks originally argillaceous are perhaps in greater abundance, while arenaceous beds are of slightly less importance. In places, much of the argillaceous rock is also calcareous and in other places graphitic. As a result of the great pressure accompanying the folding of these rocks they have been changed to slates and phyllites. Near granite intrusions they have been metamorphosed to garnetiferous, staurolitic, and tourmalinic-mica schists. Arenaceous rocks have been metamorphosed to quartz-mica schists and where less pure, to gneisses and graywackes. Of less importance quantitatively but of great value in deciphering the pre-Cambrian history are rocks once dominantly calcareous. These present material for exceedingly interesting studies in metamorphism on account of the great variety of rocks that have been derived from them. Near Nemo the original limestones have, in places, been dolomitized and today remain as normal dolomites while in other places the dolomites have been altered to talcose schists. Some of the original limestones in the same region have been silicified so completely as to resemble normal quartzites, while others have been replaced partly by iron oxide and partly by silica forming banded quartz-hematite, and quartz-magnetite rocks. In contact with the intrusive granites, near Custer, the original limestones have been altered to an aggregate of actinolite and phlogopite which grades away from the contact into crystalline dolomitic marble. Near Rochford and Lead, where affected presumably by thermal solutions bearing silica and iron, and probably of igneous origin, calcareous rocks have been partially recrystallized with the production of quartz and cummingtonite at the expense of the original carbonates, garnet, chlorite and mica. This hydro-thermal metamorphism followed the period of dynamic metamorphism by pressure which had resulted in a development of garnet and of flakes of mica and chlorite in parallel position and had given the rock a fair cleavage. The crystals of cummingtonite developed during the second period of metamorphism penetrate the original cleavage in radiating groups but themselves show no tendency toward parallel orientation. Calcareous shales and possibly other rocks in the Lead and Rochford areas have been metamorphosed to chlorite and mica schists.

The exact delimitations of the younger system and the trend of the unconformable contact are, as yet, matters of some doubt so that no exact description can be made of this system. So far as interpreted, however, the younger system comprises a thick basal conglomerate containing pebbles and boulders of the iron formation and quartzite with which it is in contact, and a siliceous and ferruginous dolomite similar to those of the older system. The evidences for the unconformity will furnish the subject of a paper to be published at a later date and will not be discussed here.

Although repeated by folding to an unknown extent, the total thickness of the pre-Cambrian sedimentary systems is probably very great and is to be measured by several tens of thousands, and perhaps many tens of thousands of feet rather than in units of a lesser order.

(Intrusive Igneous Rocks.) Into the sedimentary formations were intruded at different times, but largely before, or during, the period of principal dynamic metamorphism, numerous basic igneous rocks in the forms of sills, dikes, and possibly laccoliths. These different intrusives show varying amounts of dynamic metamorphism but universally exhibit a certain amount of parallelism of biotite, chlorite and amphibole crystals that produces a fair cleavage parallel to the cleavage of the deformed sediments. The amount of contact metamorphism produced by these rocks seems to have been small on the whole. In places where in contact with calcareous rocks, little or no changes have resulted. The basic intrusives are widely distributed throughout the pre-Cambrian sediments and their total mass must be very great.

In the valley of Little Elk Creek in the northeastern part of the crystalline area, outcrops a considerable mass of granitic gneiss. This rock is very probably a flow-granite and probably was intruded after the main deformation of the pre-Cambrian sediments had been accomplished. The gneissic banding parallels the direction of dominant cleavage in the neighboring schists. This gneiss may be a phase of the Harney Peak granite described below.

In the southern part of the area, centering about Harney Peak, occurs a mass of coarse pegmatitic granite, that is intrusive into the sediments and basic igneous rocks of the pre-Cambrian. Within an area four miles in length from north to south and perhaps half as wide, granite containing numerous inclusions of schist is the predominant rock. Passing outward from the central granite area the scists become more abundant, until finally they predominate, but contain numerous dikes of granite and pegmatite lying for the most part, in directions nearly parallel to the strike of the original folds in the sediments (approximately N.-S.) the area within which the granite occurs is an elliptical one, probably exceeding by a little a total length of 25 miles from north to south and a width of 15 miles from east to west.

It is thought likely that the Harney Peak granite may underlie a large portion of the Black Hills area, for rock of precisely similar character has been brought to the surface by the Tertiary intrusives, in the vicinity of Whitewood Peak, three miles east of Deadwood, and again in the Nigger Hill uplift, fifteen miles west of Lead, and in the Bear Lodge Mountains twenty miles farther to the northwest. The metamorphism of calcareous rocks to form cummingtonite and chlorite schists in the Lead and Rochford regions furthermore, point to the presence beneath, of some agent of hydrothermal alteration. In the Lead area intrusive igneous rocks of Tertiary age occur in considerable abundance but are believed not to be the agents of the metamorphism that produced the schists, for the Cambrian dolomites show no such changes and hence the alteration is thought to have been produced in pre-Cambrian times. In the Nemo region the pre-Cambrian basic intrusives are in places in contact with dolomites that show no such alteration, while in the Rochford district, where cummingtonite rocks are so prevalent, there is no apparent relation between the basic intrusives and the cummingtonite. Cummingtonite rocks have developed throughout this area wherever calcareous rocks occur, but basic intrusives, although abundant, are by no means found where the calcareous rock exists, and furthermore, exhibit only a very inconsiderable tendency to produce metamorphic effects at contacts. It would seem more probable, therefore, that the Harney Peak granite is of wide extent below the surface and is part of a large batholith.

Mineralogically the Harney Peak granite consists in general of orthoclase, anorthoclase, albite, and oligoclase; quartz, biotite or muscovite, tourmaline, and small amounts of garnet, apatite, and other minor accessories. Much of the rock shows a coarse graphic intergrowth of quartz and feldspar and a perthitic intergrowth of orthoclase and oligoclase. The texture even at the border of the central mass is very coarse. Feldspar masses weighing several pounds, mica plates as large as one's hand and tourmaline crystals two or three inches long are not at all uncommon. In some of the dikes the texture is much finer, while in those dikes and masses containing lithia minerals, such as spodumene and amblygonite, the texture is very coarse. These pegmatites will be described further in another place.

(Structure and Metamorphism.) The pre-Cambrian group of sediments has been closely compressed throughout into a number of steeply pitching isoclinal folds. The axial planes of the folds as well as the beds strike in general about N. 20° -40° W. and dip eastward at high angles of 75°-90°. The most notable exceptions to this general rule are to be found in the region of the Harney Peak granite, where low dips in all directions have been noted. At points along the limbs near the apexes of the folds, strikes in other directions than northwest naturally occur. The only folds of this type known to the author on anything more than a very minor scale, occur in the Lead, the Nemo, and the Rochford areas. The folding in the Lead area is referred to by Jaggar, Irving, and Emmons,* and the Nemo fold in a paper read before the Geological Society of America in 1916 by Sidney Paige. The folding in the Rochford area was also referred to by Paige in the same paper but had subsequently been independently discovered and announced by the author in the summer of 1915. Small drag folds are common and have from the first been recognized, but the larger units have remained unknown or at least unannounced until recent years.

Sidney Paige has described two major faults, one lying just west of and parallel to the Homestake ore body at Lead and a second in the Nemo district. Numerous small faults, especially well marked in quartzites where closely folded, have been observed by the author in various places and very probably are quite common.

The pre-Cambrian sedimentary rocks and much of the basic intrusives, throughout the hills show a good cleavage parallel to the bedding except where small folds exist, or, in the neighborhood of the Harney Peak granite. From this fact it would seem that the pre-Cambrian of this area rep-

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*U. S. G. S. Professional Paper No. 26, (1903).

resents but a portion of a much larger structural unit. In the vicinity of Harney Peak the slates, limestones and quartzites that were invaded by the granite were subjected to great pressures, exerted in a direction normal to the granite surface, and in them has been developed a secondary cleavage parallel to the granite contact. If the directions of the micaceous cleavage of the scists thus developed were to be followed it would lead one to completely encircle the granite.

(Pre-Cambrian History.) The earliest period of which we have any record was a long one, during which many thousands of feet of muds, sands and limes were laid down and later compacted and cemented into solid rock. These rocks were then folded into a series of anticlines and synclines and raised to such an elevation that erosion cut deeply into them before they were depressed and a second system of rocks, largely conglomerates and sandstones, was deposited over them. Both systems were then intruded by masses of basic igneous material in the form of thick sills and dikes which was accompanied by, or closely followed by, a period of most extreme compression, deforming the rocks into a more complex series of folds and perhaps faulting them. Following this deformation, after an unknown interval, occurred the intrusion of the Harney Peak granite which caused further changes in structure, especially near to its surface. From the granite, thermal solutions penetrated the rocks at the sides and above, resulting in important changes in mineral composition in the rocks, both by reactions between rock and solutions, and by the preciptation of materials injected under pressure, forming veins. Veins of quartz, tungsten, and gold were formed in this way in the neighborhood of the granite and perhaps at considerable distances from it.

After the intrusion of the Harney Peak granite and before Middle Cambrian times the rocks of the region were deeply eroded and the granites and pegmatites were exposed at the surface.

In age, the pre-Cambrian sediments are probably the equivalents of one of the Huronians or the Animikean of the Lake Superior District.

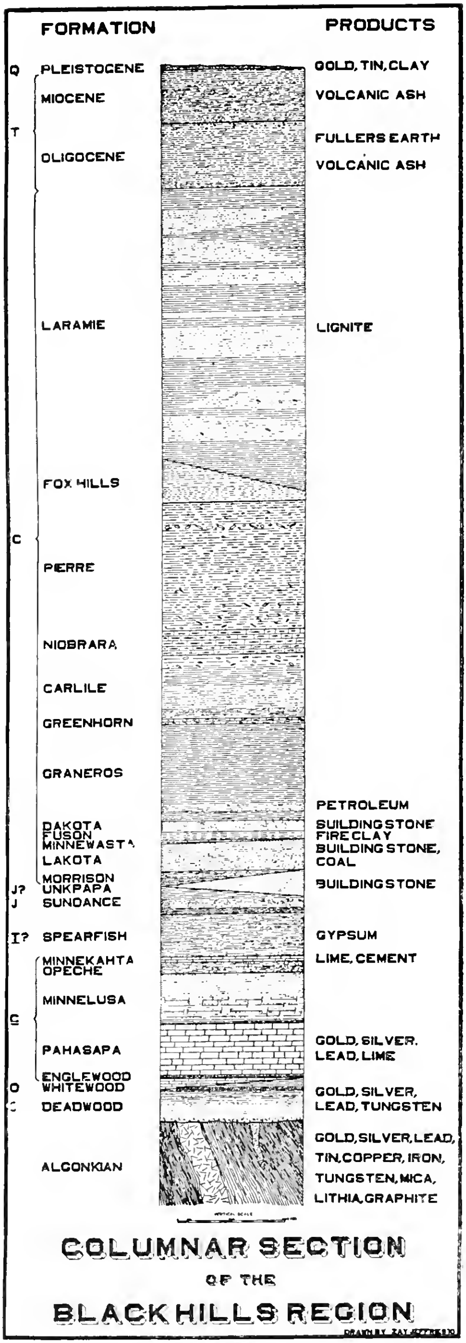
FORMATION
PRODUCTS
Q
PLEISTOCENE
GOLD, TIN, CLAY
MIOCENE
VOLCANIC ASH
T
FULLERS EARTH
OLIGOCENE
VOLCANIC ASH
LARAMIE
LIGNITE
FOX HILLS
C
PIERRE
NIOBRARA
CARLILE
GREENHORN
GRANEROS
PETROLEUM
DAKOTA
BUILDING STONE
FUSON
FIRE CLAY
MINNEWASTA
BUILDING STONE, COAL
LAKOTA
MORRISON
J?
UNKPAPA
BUILDING STONE
J
SUNDANCE
I?
SPEARFISH
GYPSUM
MINNEKAHTA
LIME, CEMENT
OPECHE
MINNELUSA
C
PAHASAPA
GOLD, SILVER, LEAD, LIME
ENGLEWOOD
O
WHITEWOOD
GOLD, SILVER, LEAD, TUNGSTEN
C
DEADWOOD
ALGONKIAN
GOLD, SILVER, LEAD, TIN, COPPER, IRON, TUNGSTEN, MICA, LITHIA, GRAPHITE
VERTICAL SCALE
COLUMNAR SECTION OF THE BLACK HILLS REGION
DRAWN BY ZAY JEFFRIES

Fig. 1.

**Post-Algonkian Sedimentary Formations.** The following table and columnar section give the principal characteristics of the sedimentary formations of the Black Hills area. Those of importance in connection with the tungsten deposits are described in more detail in Chapter III.

| System | Formation | Principal Characters | Thickness |
|---|---|---|---|
| Pleistocene | No Name... | Conglomerate, gravels | |
| Oligocene | White Riv.. | Conglomerate, sandstone, shale, volcanic ash | 600 Ft. |
| Cretaceous | Laramie.... | Sandstone, shale, lignite | 2,500 Ft. |
| | Fox Hills.. | Sandstone, shale | 250 Ft. |
| | Pierre...... | Dark-gray shale | 1,400 Ft. |
| | Niobrara.... | Impure chalk, calcareous shale | 175 Ft. |
| | Carlile...... | Gray shale with concretions | 700 Ft. |
| | Graneros... | Dark shale, some sandstone | 1,000 Ft. |
| | Dakota..... | Buff sandstone with iron concretions | 100 Ft. |
| Comanchean | Fuson...... | Massive shale | 50 Ft. |
| | Lakota..... | Coarse, cross bedded sandstone | 200 Ft. |
| Jurassic | Morrison.... | Massive greenish-gray shale | 120 Ft. |
| | Unkpapa.... | Massive gray sandstone | 75 Ft. |
| | Sundance... | Gray shale, buff sandstone | 275 Ft. |
| Triassic | Spearfish... | Red sandy shale with gypsum beds | 600 Ft. |
| Permian | Minnekahta. | Gray limestone | 40 Ft. |
| | Opeche..... | Red sandstone, sandy shale | 80 Ft. |
| Pennsylvanian | Minnelusa.. | Buff and red sandstone and limestone | 500 Ft. |
| Mississippian | Pahasapa... | Massive gray limestone | 500 Ft. |
| | Englewood. | Pink slabby limestone | 50 Ft. |
| Ordovician | Whitewood. | Massive buff limestone | 80 Ft. |
| Cambrian | Deadwood.. | Conglomerate, sandstone, greenish-gray shales and dolomitic limestone | 400 Ft. |
| Algonkian | No Name... | Slates, schists, gneisses, crystalline limestones | Very Great |

**Structure of the Post-Algonkian Sedimentary Rocks.** The major structure is that of a dome, somewhat elongated in a northwest—southeast direction. Were the sediments that have been eroded away from the central area to be replaced, their upper surface would lie more than 8,000 feet above the present surface of the crystalline rocks of the central hills. Near the axis of the uplift the dip of the Cambrian and other sediments that remain is low. On the western flank of the uplift, dips are gentle, while on the east they are much steeper. On the flanks of the dome are several minor flexures. Notable among these subordinate folds is one extending northward from Crow Peak, another lying near Whitewood, a third south of Belle Fourche, a fourth west of Edgemont and two near Hot Springs. These flexures are characterized by gentle dips to the east and steeper dips to the west. They run out under the plains with declining pitch. Faults in general are uncommon except where the sediments have been intruded by igneous rocks. Local doming of the sediments caused by laccolithic intrusions are numerous in the northern portions of the area.

**Tertiary Igneous Intrusives.** In the northern portion of the area on the flanks of the uplift as well as near the central axis occurs a remarkable series of intrusive igneous rocks varying in texture from even grained and porphyritic aphanites to medium coarse phanerites, and in composition from thoroughly acid thyolites to alkaline phonolites, and types as basic as diorite. Irving has distinguished the following families.*

Grorudite family.—Alkaline rocks containing orthoclase, quartz, aegerite-augite, and aegerite, with some albite, microcline and biotite.

Phonolite family.—Soda rich rocks composed of orthoclase, anorthoclase, microcline, aegerite-augite, nephelite, noselite, with accessory hauynite, biotite, magnetite, titanite, and garnet.

Rhyolite family.—Rocks of this type vary in texture and are characterized by a fine ground mass of quartz and feldspar with phenocrysts of orthoclase, plagioclase and quartz. Small amounts of hornblende and biotite occur. Silica varies from 65% to 78%.

Andesite family.—Rocks of moderately dense but markedly phorphyritic texture and basic character. They show a fine ground mass of plagioclase with accessory quartz and chlorite and phenocrysts of plagioclase, orthoclase, hornblende and biotite. Silica averages about 55%.

Dacite family.—Consists of a fine ground mass of quartz

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*Annals N. Y. Acad. Sci., Vol. 12, No. 9, page 224 et seq.

and orthoclase in which phenocrysts of plagioclase, orthoclase and quartz occur. Titanite, magnetite, and biotite are common accessories.

Diorite family. — Gray rocks composed of hornblende, plagioclase, quartz, biotite, and accessory orthoclase and having a granitoid texture.

Lamprophyres.—Contain fine automorphic crystals of augite and feldspar with accessory hornblende and magnetite.

**Structural Relations of the Tertiary Igneous Rocks.** The structural relations and dynamics of intrusion of the Tertiary igneous rocks have been admirably described by Jaggar,* Irving,** and Paige.*** For fuller information on this subject the reader is referred to these publications. In the central part of the Black Hills the Tertiary eruptives have invaded the older rocks in three horizons, viz., the pre-Cambrian schists and slates, the Deadwood formation, and the Pahasapa limestone. The form of the intrusion has been governed in no small degree by the character of the invaded rock.

In the pre-Cambrian rocks where the bedding and cleavage are nearly vertical, the intrusives take the form of dikes parallel to the bedding except where the mass is large or where apparently intruded under great pressure, and even in these cases the general trend of the intrusion conforms to the structural lines of weakness. At the lower surface of the nearly horizontal Cambrian beds, however, the intrusives exhibit a marked tendency toward lateral spreading. The jointed character of the Cambrian sandstone and the compressibility of the shale has allowed fractures to form and the magma was able to rise to higher horizons at various points where it might spread out in the form of a sheet. Where the magma was large in volume or the force of intrusion great, the overlying rocks were in many cases bowed up, producing

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*Laccoliths of the Black Hills, U. S. G. S., 21st. Ann. Rep. Pt. 3, Economic Resources of the Northern Black Hills, Professional Paper, U. S. G. S., No. 26, pp. 22-23.

**Economic Resources of the Northern Black Hills, Professional Paper 26, pp. 22-23.

***Journal of Geology, Vol. 29, pp. 541.

laccoliths. Within, and at the base of the Cambrian, sills are numerous, especially below shale horizons which are thought to have acted as cushions, and were compressed. The more competent Pahasapa limestone was not so easily compressed and furthermore was capable of supporting a greater load when arched so that beneath it we find the larger laccoliths. In places the limestone was fractured and the igneous rock was able to move to a higher horizon, but the increased viscosity of the magma did not permit a free movement and we find more irregular, steep sided masses within the formation, as subordinate laccoliths. The unsymmetrical laccoliths are a result of initial dip of strata or a sloping conduit. Breccias were formed of fragments of the host rock, probably by the force of intrusion. There is no evidence of the existence of any volcanoes in the region at the time of the intrusion of the sills and laccoliths. In places rhyolites cut phonolites, in others, the reverse is true, so that no clearly defined sequence of intrusion has been worked out for the various rock types. There is good evidence for believing that there had been some deformation of the strata before the intrusion and there was certainly a great deal in connection with it, so that the uplift probably began before the intrusions, but was largely coeval with them. In as much as beds of Laramie age are affected by the deformation and Oligocene and conglomerates contain pebbles of the intrusive porphyries, the intrusion and hence the Black Hills uplift, is believed to have taken place during the early Eocene.

**Post Algonkian History.** The interval of time between the formation of the latest pre-Cambrian and the earliest Paleozoic rocks, was an exceedingly long one, during which erosion had levelled high mountain ranges, leaving their cores or crystalline rock exposed on a surface of moderate relief, probably near sea level.

During much of the Paleozoic and Mesozoic Eras the present site of the Black Hills was covered by shallow marine waters, or by detached epicontinental seas in which deposits of clastic sediments washed down from the surrounding lands, or limestones from the accumulation of animal remains, were forming. The Cenozoic Era has been largely a time of erosion of the area uplifted at the end of the Mesozoic.

The Paleozoic Era in the Black Hills area was a time when conditions varied from those of rapid deposition in agitated waters, to deposition in rather quiet, clear waters where limestone might accumulate, and conditions of emergence, following withdrawals of the sea, when erosion of the deposits already formed, took place. Shallow marine waters lay over the area during the Middle Cambrian and Ordovician times, and to an unknown extent, during the Silurian and Devonian. The latter part of the Devonian surely, and very probably much of the interval between the Ordovician and Mississippian periods, was a time or erosion. During the Mississippian Period, again the area was the site of a warm, clear epicontinental sea. The closing periods of the Paleozoic were marked by more variable conditions when the formation of beds of sandstones, shales, and limestones, more rapidly alternated with times of erosion. The seas were shallow and the climatic conditions more severe.

The early Mesozoic was a time of arid climate, when the area was covered probably by a detached arm of the sea. Later the waters disappeared and erosion ensued, followed in turn by a readvance of marine waters in late Jurassic times. Still later in the Jurassic Period the waters again withdrew and deposits were formed in fresh waters. The Cretaceous Period was marked by the advance of a great sea from the south, in which thousands of feet of sands and muds were deposited. Upon the retreat of this sea, in late Cretaceous times marshes and lakes abounded in which were deposited sands and muds and the plant remains that formed the coal beds of the Laramie. Following the Laramie occurred the principal uplift of the Black Hills, accompanied by the intrusion of a considerable amount of igneous material into the rocks of the Northern Hills.

The early Cenozoic, following the uplift, was a time when erosion cut deeply into the formations, developing a surface of gentle relief, probably at a comparatively low elevation. During the Oligocene, deposits again formed in parts of the area, in swamps, along river plains, and possibly in lakes.

Since the Oligocene the area has been elevated at various times but no great amount of deformation has taken place. It has been during this recent period that the Black Hills have taken on their present topographic form, described in the first paragraph of this chapter.

# CHAPTER III.

## THE TUNGSTEN DEPOSITS OF THE BLACK HILLS

**Historical.** The presence of tungsten minerals in the pegmatites and quartz veins in the southern Black Hills and in the Nigger Hill district has been known practically since the development of those districts for tin which began in the early eighties. Up to the year 1916 little development or even prospecting for tungsten was done in these areas and the total production was very small. In 1906 the Reinbold Metallurgical Co. mined and shipped about 100 tons of tungsten ore to Germany from its mine on Sunday Gulch south of Hill City. In 1907 the American Tungsten Co. was organized and erected a small shaft house, hoist, power plant and concentrating mill on their claims four miles east of Hill City. A shaft was sunk to a depth of 100 feet and drifts and crosscuts run. Some excellent ore was obtained and stored. Subsequently the property has remained idle. In 1913 the Black Hills Tungsten Mining and Milling Co. was organized. On the property four miles east of Hill City, shaft houses, hoists, a power plant and a small mill were erected and several hundred tons of ore were mined, concentrated and marketed. For a time the property remained idle, but was operated again in 1916 for a short time. Since that time the ownership of the property has been changed to the Elkhorn Tungsten Co. At present the property is idle. During 1916 and 1917, while attempting to work tin ores in the vicinity of Hill City the Hill City Producer's Co. concentrated at the old Harney Peak Tin Co.'s mill, and sold several tons of tungsten ores obtained from leased claims. This property is also now idle.

There seems to be some doubt as to the exact date of discovery of tungsten in the Northern Hills. It is claimed by some that Prof. Jenney made the discovery of a tungsten mineral at the Comstock mine, now the property of Mr. S. R. Smith, 4 miles southeast of Deadwood, on one of his early expeditions to the Black Hills. The author, however, could find no mention of this occurrence in any of the early reports by Prof. Jenney. In the edition of 1893 of Dana's Descriptive Mineralogy, however, the mention of Black Hills hubnerite is made, the source of which is said to be the Comstock Mine, but the collector's name is not given. This is the first reference to tungsten occuring in the Black Hills that the author was able to locate. Headden gives an analysis of hubnerite from the same mine in volume III of the Proceedings of the Colorado Scientific Society published in 1906, and states that the presence of the mineral at this place was known in the early eighties. It is fairly clear then, that the hubnerite at the Comstock mine was the earliest known occurrence of tungsten in the Northern Hills but evidence is lacking that this discovery was made prior to the discovery of wolframite in the Southern Hills mentioned by Blake as early as 1883* and again by the same author in 1885**.

In 1899 was made the discovery of tungsten minerals in the vicinity of Lead in the Northern Hills. For some years what had been known as "black iron" had been mined with the refractory siliceous gold ores from the vicinity of Lead and on Yellow Creek. Most of this material contained such low values in gold that it was sorted from the gold ores and used as waste to fill old workings. Some of it had been shipped to the smelters for extraction of gold, with no knowledge of the true nature of the black material. Its great weight, however, attracted the attention of Mr. O. A. Ritz, a teacher in the Lead High School, who investigated its character and found it to be wolframite. The announcement of this discovery attracted the attention of manufacturers of tungsten steel and during the early part of 1899 some seventeen tons of ore containing about 53% tungstic acid were shipped to the East by Mr. S. W. Deininger of Phoenixville, Penn. This was the first shipment of tungsten ore from the hills. From 1899 to 1915 small amounts of the ore were mined along with the siliceous gold ores of the Cambrian dolomites and were shipped from time to time, but no serious attempts were

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*Am. Jour. Sci. 3rd Series Vol. 26, page 235.

**Trans. Am. Inst. Min. Eng. Vol. 13, page 694.

Plate V.

THE HARNEY RANGE FROM THE WEST

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Plate VI A.

HARNEY PEAK FROM THE WEST

Plate VI B.

HARNEY PEAK FROM THE SOUTH

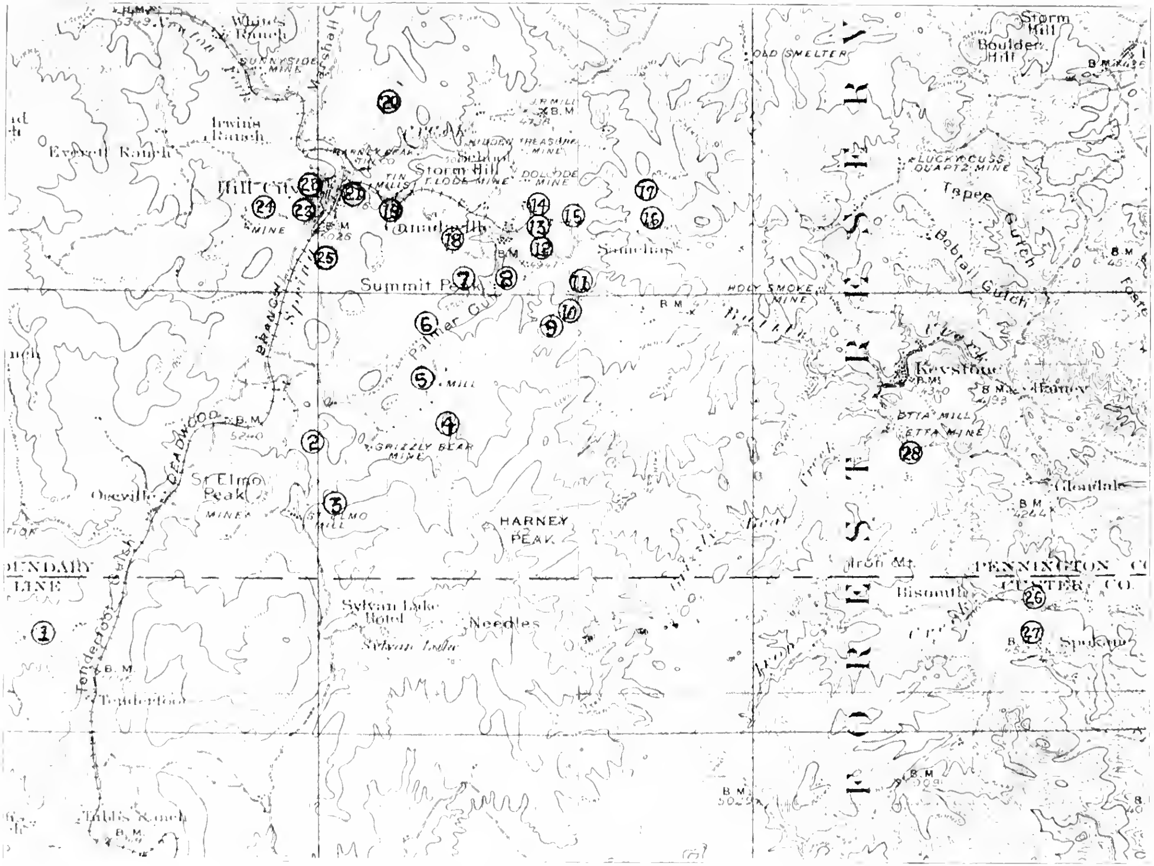

Plate VII

TOPOGRAPHICAL MAP OF HARNEY PEAK AREA
SHOWING LOCATION OF PRINCIPAL TUNGSTEN DEPOSITS

made to produce the metal until the great advance in prices due to the European War made the industry an exceedingly profitable one. Since 1915 the production in the Northern Hills has progressed steadily. More details of productions will be given in another place.

**Location of Deposits.** The tungsten deposits of the Black Hills, so far as known, are confined to three distinct districts. The largest area is in the vicinity of Harney Peak, largely in the western, northwestern, and northern parts of the granite area. One occurrence is known at Spokane 7 miles east of Harney Peak and at least one near Keystone, 6 miles northeast of the peak. A second area lies in the vicinity of Lead and Deadwood in the Northern Hills and a third area in the Nigger Hill district, 15 miles west of Lead.

**Types of Deposits.** The deposits may conveniently be classified into five rather distinct groups according to their geological mode of occurrence, viz., (1) pegamites; (2) quartz veins; (3) replacement deposits; (4) segregation deposits; and (5) placers. Types 1, 2 and 5 are confined to the Harney Peak and Nigger Hill districts and types 2 and 4 to the Lead-Deadwood district.

**Deposits of the Harney Peak Area.** The deposits of the Harney Peak district are closely associated in distribution as well as in genesis with the pegmatitic phases of the Harney Peak granite. They occur both within the pegmatites and genetically related quartz veins and within the schists developed by the metamorphic action of the granite. The granites and schists have been briefly described in the section on pre-Cambrian rocks. The pegmatites and quartz veins merit a more detailed description.

Ziegler* recognizes in the Harney Peak granite and associated permatites and quartz veins seven types of differentiation products. For the purposes of adequate discussion of the tungsten deposits it seems best to somewhat modify his classification and to recognize the following types: 1, the granite; 2, lithia bearing pegmatites; 3, pegmatites contain-

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*Economic Geology, Vol. IX, pp. 264-277.

ing little or no lithium minerals; 4, tin veins; and 5, quartz veins; some of which carry tungsten minerals.

From a mineralogical standpoint the lithia bearing pegmatites are perhaps the most remarkable, and therefore, most interesting, both on account of the great number of distinct mineral species found in them and because of the large dimensions attained by some of the crystals. In the Etta pegmatite near Keystone, the number of species and the dimensions of crystals reach a maximum. No less than 48 minerals have been reported from this one mass, while in it a crystal spodumene is known to have attained a length of at least 42 feet and others to have a diameter of fully five feet. The Etta has produced a few specimens of wolframite and some scheelite but neither in anything like commercial quantities. The lithia bearing pegmatites do not appear, on the whole, to be favorite hosts for tungsten minerals. The most important minerals of the lithia bearing pegmatites as a group are orthoclase, microcline, albite, oligoclase, muscovite, lepidolite, biotite, quartz, tourmaline, spodumene, amblygonite, beryl, apatite, triphyllite, lithiophylite, columbotantalite, with lesser amounts of garnet, struverite, andalusite, and various sulphides.

In the pegmatites that are not lithia bearing, the mineralogy is much simpler. The important species in these rocks are the feldspars mentioned above, quartz, muscovite, biotite, tourmaline, garnet, and in places a little pyrite. In this phase tungsten minerals are more common, especially in the parts rich in quartz.

In the tin veins we find cassiterite associated chiefly with feldspars, quartz, muscovite, and in places small amounts of columbite and wolframite.

In the quartz veins the chief minerals besides quartz are muscovite and graphite both of which show a tendency toward concentration along the walls of the vein. This type is the most important one of the granite differentiates as a source of tungsten.

The following brief description of the tungsten properties in the Harney Peak region gives the important geological characteristics of each. The number at the head of each paragraph will assist in locating the property on the accompanying topographic map. It is possible that some mistakes have been made in names and that some claims may have been omitted from the descriptions. The data here presented are all that the author was able to gain in the time that he was in the field.

1. Downing's Claim, 7 miles southwest of Hill City. On the principal claim coarse and fine crystals of black tungsten minerals occur with pyrite, muscovite and biotite in a quartz vein. The micas are especially well developed along the borders of the vein. The vein pinches and swells and has a maximum width of about 14 inches. The strike is N. 60°W. and the dip steep to the southwest. The development consists of prospect cuts for 50 feet along the strike and for a maximum depth of 15 feet below the surface. Nearby is a pegmatite containing some wolframite.

Two other claims belonging to Wright and Virtue and to Mr. H. H. Francis are reported to contain tungsten minerals in this vicinity. These were not visited.

2. Reinbold Claim, 5 miles south of Hill City. The tungsten ores are located mostly on the contact between small veins of pegmatite and schist, also in the pegmatites, and in seams in the schist. The schists are penetrated by small kidneys, lenses, and veinlets of pegmatite containing quartz, biotite, muscovite, feldspar and tourmaline, and by quartz veins carrying some muscovite. The quartz and pegmatite have in places cemented brecciated masses of schist. The width of the main lead probably does not exceed 5 feet on the surface. It seems to be a vertical zone more or less impregnated with fine veinlets, rather than a continuous, uniform mass. The mineralized zone runs N. 35° W. and from the direction of an inclined shaft apparently dips steeply to the southwest. To the west of the main vein lies a small quartz mica vein containing some tungsten and manganese minerals, of unknown extent. The tungsten mineral is hubnerite occurring in slender crystals of from ½ to 2 inches in length. An analysis by Headden* shows the mineral to be composed of 92.8% $MnWO_4$ and 7.2% $FeWO_4$. The surface material is much weathered and the hubnerite is covered

*Colo. Sci. Soc. Proc., Vol. 8, Page 176.

with brown iron oxide and black oxide of manganese. Development work on the property consists of 6 small prospect cuts and 1 inclined shaft 100 ft. in depth.

3. Tungsten Lode (Wehrlick, Faust and Gowan), 6 miles south of Hill City on the western flank of Harney Peak. The tungsten minerals occur in a coarse pegmatite containing feldspar, quartz and muscovite, about 30 feet in thickness with an apparent length of about 350 feet, dipping westward with the schists. The wolframite is most abundant in parts rich in quartz and muscovite. In places tourmaline occurs in streaks through the pegmatite and on the contact with the schist. Garnet also is abundant in places. The pegmatite has included fragments of schist.

4. McKinnon and Millers Claim, 4½ miles southeast of Hill City. Crystals of wolframite are found in quartz segregations and veinlets in a pegmatite sill from 1 ft. to 3 ft. in thickness that dips 75° to the west. The pegmatite contains rather fine quartz, muscovite, feldspar, pink garnet and green tourmaline. The wolframite is in places closely associated with garnet. In places there is considerable secondary manganese dioxide. The outcropping edge of the pegmatite has been opened up in numerous places for about 200 feet along the strike. The wolframite is especially abundant along the north end. An analysis of the mineral was calculated by Hess** to contain 71.4% $FeWO_4$ and 28.6% $MnWO_4$ and is therefore wolframite. A second sill 50 feet west of the one described, and paralleling it, outcrops for 100 feet along the surface. This vein is thin but richer in spots than the other.

5. Michigan Placer Ground (Nelson), 4½ miles southeast of Hill City on Palmer Gulch. Wolframite occurs in a sill of pegmatite containing quartz, feldspar, muscovite, garnet and tourmaline, and in a quartz vein from 3 inches to 2 feet in thickness. The veins are exposed for 20 feet along the surface and dip with the schist 15° to the northwest. The crystals of wolframite are small. Muscovite is concentrated along the vein walls.

6. Pettit and Pfander's Claim, 3 miles southeast of Hill

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**U. S. Geol. Surv. Bul. 583, page 30.

City. Tungsten minerals, wolframite and scheelite occur along the walls of a fissue filled with gouge consisting of clay, brown chalcedony, limonite and manganese oxide, cutting a coarse pegmatite dike 30 or more feet in thickness and dipping steeply westward. The tungsten minerals occur on the pegmatite surfaces and penetrate the gouge and are crystallized in druses. The crystals are considerably weathered and are stained with brown limonite and black manganese oxide. The scheelite coats the wolframite in honey like drops. The width of the fissure is from 3 inches to 1 foot and the strike is northwest. The pegmatite is coarse, containing feldspar, quartz, muscovite and tourmaline. On top of the dike 20 feet north of the main vein, a small cut exposes other fissures of the same sort. The development consists of a shaft 20 feet in depth, and a cut into the face of the dike 25 feet long and 10 feet vertically, parallel to the main vein.

7. The High Lode (Canfield) on the east side of Summit Peak, 3 miles southeast of Hill City. The wolframite occurs in good crystals in four quartz veins from 1 to 12 inches in width, cutting a pegmatite composed of quartz, feldspar and muscovite.

8. Vida May (Pettit and Nash) 4½ miles southeast of Hill City.

This property was not visited. The description here given is that of Hess.

"The vein * * * * * is visible for less than 100 feet along the surface and is irregular in thickness, strike and dip. The dip is 30° and more southward.

The dike occupies a fissure along an overthrust fault of unknown throw. At some points it reaches 10 inches in thickness and at others it pinches out. In the thicker part wolframite occurs in chunks, some of which are several inches thick. In places the dike pinches to half an inch and is almost wholly made up of wolframite. Some muscovite is present through the vein and shows a tendency to form in lines that give the vein a somewhat banded appearance.

One of the most remarkable features of the vein is a layer of impure graphite on each side from half an inch to 2½ inches thick. Muscovite occurs in this layer also and shows thin lines of minute flakes parallel to the vein. No structure of the graphite can be definitely made out. The graphite is undoubtedly segregated from the graphitic schists through the agency of the vein-forming materials. Smaller amounts of graphite have been noted at a number of places as included in the pegmatite dikes, but it seems significant that along quartz veins, the magmatic segregation which was probably most watery at the time of its intrusion, the most graphite should have been deposited. The same phenomenon was noted in Slaughterhouse Gulch. It is strongly suggested by these occurrences that the graphite is brought into solution by the hot waters accompanying the intrusion."

9. Blackbird Claim (Canfield, Hicks, and Roush), 4½ miles southeast of Hill City. A quartz vein of variable thickness is exposed in a prospect trench for a distance of 75 feet along the strike and in a vertical shaft perhaps 40 feet in depth. The strike of the vein is N. 45° W. and its dip nearly vertical. It cuts schists dipping northwest at a low angle. The vein was not well exposed and its extent and size are unknown, but it is small, at the surface. Some specimens of fairly good ore were found on the dump.

10. Martha Washington (C. H. Kammon), 4½ miles southeast of Hill City. A quartz vein containing muscovite and some high grade wolframite is exposed in a prospect trench for 100 feet along the strike. The vein strikes N. 65° E. and at the surface dips southward at a low angle. Near its eastern end small veins of quartz cut the main vein and extend for short distances into the schists. The main vein cuts the schists both along the dip and along the strike at high angles. Southwest from this vein occurs a second one exposed in a prospect cut for a distance of 25 feet along the strike. The latter vein is from 6 to 12 inches thick, has a variable strike from west to northwest, and dips southward at a low angle. Very little tungsten was exposed in the vein at the time of visit.

11. Property of the Elkhorn Tungsten Company, 4½ miles southeast of Hill City. On this property are exposed at least five, apparently distinct veins of tungsten bearing

quartz, cutting garnetiferous, mica schists, that are in places graphitic.

The westernmost vein was developed by an inclined shaft along the dip, and at the time of the visit had apparently been largely worked out, for no ore was found in place. The vein had a strike of N. 45° W. and a dip of 75° to the southwest. In form the vein was apparently lens shaped and was observed to have pinched out laterally, along the strike. The vein material had evidently been quartz with a little muscovite and possibly graphite. On the dump were found masses of schists penetrated by veinlets of garnetiferous pegmatite, showing, in places, segregations of quartz, especially along the margins. None of these were observed to bear any tungsten. Garnets were more abundant in the host rock near the vein contact and had evidently been developed as a result of reaction with the vein material. Specimens of good ore were obtained that had come from this vein.

400 feet east of this vein, one and perhaps two veins, occur near the power house. One vein of quartz, containing muscovite, graphite, and wolframite, averaging one foot in thickness, is exposed for 50 feet along the strike in an open cut, and in an inclined shaft along the dip for perhaps 40 feet. At the surface the vein swells and narrows very perceptibly. The vein exhibits a rude banding parallel to its length in consequence of segregations of mica, graphite, and wolframite in planes. Graphite and mica are especially abundant at the margins.

75 feet northwest of this second vein outcrops what is apparently a separate vein that strikes N. 35° W. and dips steeply to the southwest. This vein varies considerably in the direction of its trend and in its thickness at the surface. It is said to persist to a depth of at least 90 feet in the shaft and to continue for a considerable distance along the strike, in the underground workings. Its width where seen at the surface averaged perhaps 24 inches. The vein is developed by a shaft and underground drifts and raises. Some ore has been stoped out from the vein, milled and marketed. Specimens of the ore obtained were of good quality.

Another vein lying perhaps 150 feet northeast of the power house, was exposed in a prospect trench for 100 feet along the strike. The vein varies in thickness and direction of strike. It contains quartz with some muscovite and wolframite.

200 yards south of the power house is another vein of quartz, containing small amounts of muscovite and wolframite. The vein is exposed in prospect cuts, and in a small shaft of unknown depth. The trend of the vein is N. 75° W. and the dip steep toward the southwest. At the surface its width is from 8 to 24 inches.

On the property are a power plant, hoist, and a small well equipped concentrating mill. Some ore was mined and milled by the Black Hills Tungsten Mining and Milling Company in 1916. Since that time the property has mostly remained idle.

12. Success Claim (Amer. Tungsten Co.), 4 miles east of Hill City. Wolframite occurs in a quartz vein, cutting graphitic schists, with muscovite well developed along the border and in seams in the quartz. Wolframite occurs in bladed aggregates up to a length of 2½ inches and in places is especially rich along the borders of the vein. The vein varies from 8 to 18 inches in thickness. It strikes N. 45° W. and dips steeply northeast. It is exposed along the strike for 75 feet in prospect cuts and in a small shaft 25 feet in depth.

13. Good Luck Claim (American Tungsten Company), 4 miles east of Hill City. Wolframite, ferberite and a little scheelite occur in a quartz vein cutting graphite mica schist. The trend of the vein is parallel to the strike of the schists and is about N. 30° W. The dip is variable, but averages about 60° to the southwest. The width of the vein is from 18 to 30 inches, averaging throughout its known extent perhaps 24 inches. The vein is exposed in the main shaft to the 40 foot level; and at that depth in a drift for 97 feet along the strike; again in a small shaft 47 feet southeast of the main shaft to the 40 foot level; and also in a winze sunk from the 40 foot level, near the main shaft, to a depth of 30 feet. On the 40 foot level the vein is ore-bearing for at least 50 feet of its length, and in the winze, to the bottom.

The quartz shows minute cavities in lines parallel to the walls of the vein. It contains a little muscovite in cracks near the margin of the vein which in places is mixed with graphite. The wolframite occurs in tabular masses, roughly paralleling the vein walls. Some of these masses attain a weight of 8 or 10 pounds, and single cleavage blades have been found with a length of over 8 inches. A little green scheelite that is almost surely original has been found in the quartz. Where weathering has affected the tungsten mineral pitted surfaces filled with iron oxide occur. Some scheelite, also occurs as an alteration product of the wolframite. An analysis of the concentrate, reported by C. H. Fulton in a private mine report has been calculated as representing a mineral with 86.5% $FeWO_4$ and 13.5% $MnWO_4$ which would be classed as ferberite. An analysis by M. L. Hartmann, of the black mineral, shows it to contain 69.1% $FeWO_4$ and 30.9% $MnWO_4$, and hence the specimen was wolframite.

The development work consists of a 100 foot, two compartment shaft, fully timbered to within 2 sets of the bottom; 97 feet of drifts on the 40 foot level; a 30 foot winze from the 40 foot level; a 28 foot crosscut from the bottom of the main shaft; and a second small shaft 47 feet down the hill side and 12 feet below the collar of the main shaft, cutting the drift on the 40 foot level at a depth from the surface of 18 feet.

The equipment comprises a power plant, shaft house, hoist, mine tools and mill well equipped for concentration.

In an ore bin near the shaft house are stored about 40 tons of good ore that was stoped out from above the 40 foot level. At the house of Mr. A. H. Wabel, the owner, the author has seen several specimens of ore weighing from 50 to 100 pounds that he would estimate to contain 15% or more $WO_3$.

14. Cleveland Lode (American Tungsten Co.), 4 miles east of Hill City. Wolframite occurs in crystals up to 2½ inches in length with a little muscovite in a vein of glassy quartz. The vein strikes N. 30° W. and dips steeply to the northeast. Its width averages about 8 inches at the surface.

In places the vein is much fractured. The vein cuts garnetiferous schist that dips westward at a low angle. The ore is exposed in prospect holes for a distance of 40 feet along the strike of the vein.

15. Champion Lode (Pennington and Smith), 4½ miles east of Hill City. Wolframite occurs in the quartz and muscovite rich parts of a coarse pegmatite that contains also feldspar and tourmaline. The pegmatite is banded parallel to the walls. The dike is from 3 to 6 feet in thickness and is in places split by schist horses. The dike strikes northeast parallel to the schist and dips 45° to the northwest, more steeply than the schist except at the south end where it becomes a sill. The dike is opened up by several cuts to a depth of 20 feet for a distance of 600 feet along the strike. Across the road from the south end of the Champion Lode pegmatite, occurs a quartz vein from 1 to 2 feet in thickness containing good crystals of wolframite. The vein has been opened up by a 15 foot prospect hole.

16. Gireau's Claim, 4½ miles northeast of Hill City. The tungsten vein is exposed in a shaft 30 feet in depth. The shaft was not accessible at the time of the visit, but from specimens on the dump wolframite apparently occurs in a quartz vein.

17. Edna Hazel, 4½ miles northeast of Hill City. Wolframite crystals from ½ to 2 inches in length occur in a vein of clear glassy quartz from a few inches to 2 feet in width, cutting schist. In places the vein is very rich. Its direction is N. 20° W. and its dip is vertical. An analysis by M. L. Hartmann showed the mineral to be composed of 69.7% $FeWO_4$ and 30.7% $MnWO_4$, and hence to be wolframite.

18. Rundle, Mills, and Casler Claim, 2 miles southeast of Hill City. Black tungsten mineral occurs on the contact of the schists with a small quartz vein containing tourmaline, mica and some graphite. The vein is exposed for a hundred feet along the strike (N. 10° E.)

19. Dyke Claim, ½ mile east of Hill City. Black tungsten mineral occurs in a thick dike of pegmatite containing quartz, feldspar, muscovite, tourmaline and graphite. The dike strikes N. 50° W. and dips steeply westward. The dike

is exposed for a total length of 350 feet and is developed by prospect holes and a small shaft.

20. Black Metal Claims, 1 mile north of Hill City.

The excellent descriptions of the occurrences of tungsten bearing veins on this property, given by Hess* will be quoted here, for without a claim map the author was unable to check a number of locations on the claims described. On the more important geological relationships of the principal occurrences the author is in essential agreement with Hess.

"About 400 feet from the south end of the group, on the center line of Black Metal claim No. 3, which lies on the west side of China Gulch, is a quartz vein 6 to 8 inches wide striking N. 23° W., dipping steeply to the east, but almost vertical, and about 30 feet long. It cuts a gray fine-grained quartzose mica schist which strikes N. 75° W., with a dip of 35° N. 15° E. The walls are loose and show the effects of some slipping. The wolframite is of a bright, shining black color in irregular masses as much as an inch in thickness and several inches in length. So far as developed at the time, it was probably not rich enough to pay for mining. There is a small amount of muscovite mica, apparently following cracks in and thus later than the quartz. Thin seams of pyrites also follow cracks in the quartz. The wolframite decays, leaving in places a little scheelite, but generally only iron oxide. A similar vein, striking N. 88° W., with a steep dip to the north, though almost vertical, lies 42 feet farther south. This vein has been followed on the surface for 60 feet. It is faulted about 3 feet at the shaft. From the bottom of the shaft, which is 47 feet deep, the quartz showed pyrites along cracks and some that was possibly original.

Wolframite extends into the quartz from the sides of the vein in blades up to one-eight of an inch thick and 2 inches long, which must have been formed either before or contemporaneously with the quartz. Like the other vein, this one is only a prospect, but it is one which encourages further work.

Farther north, on the west side of China Gulch, on Black

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*U. S. Geol. Surv., Bul. 380, pp. 152-153.

Metal claim No. 5, is a quartz vein 9 to 12 inches thick, which is exposed in two prospect holes. The vein strikes N. 50°–55° E., dips 45° N. 35°–40° W., and has been followed for about 125 feet. It carries considerable black tourmaline in crystals an inch or more in length by one-sixteenth to one-eight of an inch in thickness. Some wolframite is found mixed with light-colored cassiterite in masses up to 2 pounds in weight. The color of the cassiterite is in places hidden by stains of iron oxide. During the tin excitement this ground was held as a tin claim.

On Black Metal claim No. 6, near the north end of the group, is a quartz vein 6 to 8 inches thick, striking N. 5° W. and standing nearly vertical. A vertical shaft about 4 feet wide has been sunk, with the vein in the middle at the top. At a depth of 65 feet the vein is in the east wall of the shaft. The vein is generally free, but is in places "frozen" to the walls. The country rock, as in the other claims of the group, is quartzose mica schist, in places graphitic and here and there, near the vein, impregnated with small needles of black tourmaline.

The vein carries wolframite intimately intergrown with light-gray cassiterite, some of which is almost colorless. These minerals form tabular masses reaching 1½ inches in thickness and probably 8 to 10 inches in breadth. They occur near the middle of the vein, and C. G. Todd, in charge for the Black Metal Mining Company, stated that none had been seen on the sides of the vein. A granitic dike a few inches in width is said to lie along the vein in places, and at such points the vein is richest.

A small shaft house has been erected and drifts have been carried on the vein for about 30 feet each way at a depth of 65 feet. The vein is said to be widening a little toward the north. What seems to be the same vein is seen several hundred feet farther north, but it shows neither wolframite nor cassiterite at that point.

Southwest of this vein, on the same claim, is a quartz vein 4 to 8 inches thick, with a strike of N. 55° E. and a variable dip. It carries some wolframite, slender needles of black tourmaline, and some muscovite. In places thin branch veins enter the schist, which is here graphitic, and at some points bunches of wolframite occupy the whole width of the vein, so that the wolframite is said to be in the "slate," the name by which the schists are generally known in the locality. The vein is traced for only a short distance.

On Black Metal claim No. 7 a thin quartz vein carries wolframite, small pieces of green and white scheelite, brown cassiterite, pyrites, and a little mica. On Black Metal claim No. 8 is an irregular quartz vein that carries some wolframite and small particles of scheelite, original in the vein. Part of the scheelite is of a delicate green color. There is some cassiterite, which, where free from iron-oxide stains, is light gray in color, and some pyrites."

21. Hayes Claim, 200 yards northeast of Burlington railroad station Hill City. Small, dull crystals of wolframite occur in a pegmatite, containing feldspar, muscovite and quartz. The dike strikes N. 25° W. and the dip is vertical at the south end, but westerly farther north. The dike is 3 feet thick near the south end and thickens to the north. The dike cuts slates dipping to the southwest and striking to the northwest. In its neighborhood are a number of small stringers of pegmatite and quartz lenses and "blowouts". The dike has been prospected by cuts for total length of 200 feet. An analysis by M. L. Hartmann shows the mineral to be composed of 36.3% $FeWO_4$ and 63.7% $MnWO_4$ and hence to be wolframite.

22. The Annie, ½ mile west of Hill City on Slaughter-House Gulch. Wolframite occurs in a quartz vein from 4 to 6 feet wide in places with graphite and muscovite especially along the vein walls. A little cassiterite and bismuth also occur in the vein. On the surface the vein shows numerous pittings containing iron oxide from which wolframite has probably weathered. The vein strikes N. 20° W., and dips steeply eastward. 50 feet east of this vein a second occurs wider than the first. It strikes N. 10° E. and dips 35° W. A small amount of wolframite occurs in this vein. Associated with the first vein is a pegmatite dike, from which the vein is probably a segregation. The dike contains quartz, feldspar, muscovite and cassiterite, and has been one of the more im-

portant tin prospects of the region. The quartz vein has produced some tungsten.

23. The Wolfram Lode (Mills) on the south side of Slaughter House Gulch 600 feet southeast of the Annie. Wolframite in small crystals occurs in a quartz vein containing graphite, biotite and muscovite along the border. The vein has a width of from 2 to 3 feet. It strikes N. 10° W. and dips 80° to the northeast. The vein cuts graphitic schist whose strike is parallel to the strike of the vein but which dips southwest.

24. Coates Claim, 1 mile southwest of Hill City. This claim the author was not able to locate in the field, but from descriptions by the owner, is a typical pegmatite containing small amounts of wolframite.

25. Mills Brothers' Prospect, 1 mile south of Hill City on the east side of Spring Creek valley 250 feet above the railroad. On a northeast extending ridge are exposed numerous quartz veins and bunches of milky quartz. The wolframite bearing vein contains some muscovite and graphite both along the walls and inclosed in the quartz. The inclosing rock is a graphitic slate which evidently has furnished the graphite contained in the quartz. The trend of the vein is 20° W. Its dip was not determined. The wolframite is exposed only at the north end for a few feet where a shaft had been sunk to a depth of 25 feet. At the north end where the wolframite occurs the vein apparently does not exceed 1 foot in thickness but widens to 3 feet farther south where it is barren on the surface.

26. Fern Cliff (F. G. Robertson) ½ mile north of Spokane, 7 miles east of Harney Peak. This occurrence is of especial interest for two reasons, first; it lies in a region near the lithia bearing pegmatites, where with but two minor exceptions tungsten is unknown, second; it is the only known occurrence in the Black Hills of primary scheelite in important quantities.

On the property two quartz veins occur that apparently apex to the north. The western vein strikes approximately N.-S., and the eastern one N. 30° W. The western vein is from 1½ feet to 4 feet in thickness and the eastern one is about 2 feet thick. Both were observed to pinch and swell along the strike and in the direction of dip. At the point where they seemed to apex the vein is easily 4 feet thick. Both veins are apparently vertical. The eastern vein is exposed for 100 feet along the surface and the western one for perhaps 50 feet. At the apex the veins are exposed in a shaft to a depth of 30 feet, and from the bottom of this shaft in a drift along the east vein for a distance of 30 feet. A short distance from the main shaft is a smaller one on the west vein that has been sunk to a depth of 24 feet.

The ore minerals scheelite and wolframite occur intimately intergrown, and separately, in irregular masses, some of which measure 3 or 4 inches in diameter, in a glassy quartz matrix. With the tungsten minerals and separately in the quartz, occurs a considerable amount of pyrite. Seams of pyrite in the quartz as much as ½ inch in thickness were observed. No graphite or muscovite were seen either at the margin or in the quartz vein, although the inclosing schists are graphitic. The greater part, at least, of the scheelite is unquestionably primary and was precipitated simultaneously with the wolframite and pyrite in the quartz. A photographic reproduction of a specimen of the ore may be seen in plate II B. In amount, the scheelite probably exceeds the wolframite. At the surface the tungsten minerals and pyrite have disintegrated and much of the quartz is stained red from iron oxide. Two pegmatite dikes occur to the east of the tungsten veins at distances of 200 feet and 400 feet respectively, and one to the west at a distance of perhaps 150 feet.

In places the ore is very high grade and should the veins prove persistent for considerable distances and maintain throughout the tungsten content they show at the surface, the property ought to be a valuable one.

28. Reinbold Claim, ½ mile northwest of Spokane. Tungsten minerals occur in seams of quartz from 1 to 18 inches in width cutting a pegmatite. The property is developed by a shaft 50 feet in depth and by several prospect cuts.

29. The Etta (The Standard Essence Co.), 2 miles

south of Keystone. The Etta has been described briefly above. As a producer of tungsten it is not important.

A small amount of wolframite and possibly scheelite have been found in placers in the Harney Peak district, but the commercial importance of this type of deposit is probably negligible.

**The Deposits of the Nigger Hill Area.** The Nigger Hill or Tinton district lies approximately 15 miles west of Lead near the Wyoming-South Dakota line. Nigger Hill is the center of a laccolithic intrusion of monzonite and syenite porphyries, of early Tertiary age. Within the laccolith are areas of schist, pegmatites and other intrusives of Algonkian age. The pre-Cambrian rocks are either detached masses of the underlying rocks that have been floated up on the intrusive porphyries or are islands in the surrounding younger rocks that still maintain connections with the other pre-Cambrian rocks below. The pegmatite dikes are of the same general composition as the tin bearing dikes of the Southern Black Hills. They contain quartz, feldspar, muscovite, tourmaline, and small amounts of pyrite, cassiterite, columbite, and wolframite. These dikes have been worked for their tin content but tungsten minerals have not been found in sufficient amounts to attract much attention.

An insignificant amount of wolframite has been found in placers.

**Summary of Characteristics of the Tungsten Deposits in Pre-Cambrian Rocks.** Wolframite is the most important of the tungsten bearing minerals. Primary scheelite, hubnerite, and ferberite are relatively rare but in some deposits scheelite, and in others hubnerite, are the dominant ore minerals. Secondary scheelite in small quantities is not uncommon.

The tungsten minerals occur in pegmatites with quartz, feldspar, muscovite, tourmaline, garnet, and smaller amounts of pyrite, cassiterite, and biotite. In the pegmatites the crystals of tungsten minerals are commonly small and many are dull in luster. The tungsten bearing pegmatites are commonly coarse in texture, but not so coarse as the lithia bearing pegmatites. In general the tungsten minerals are

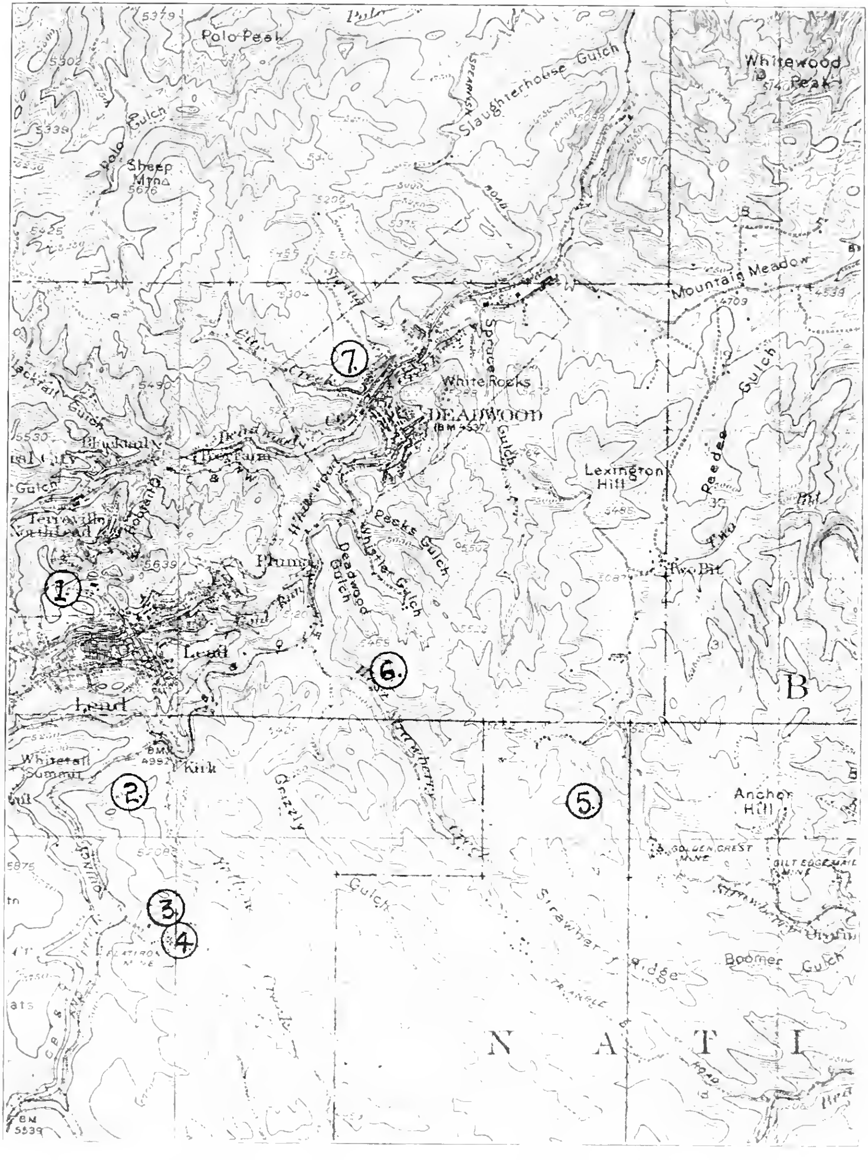

Plate VIII.

TOPOGRAPHICAL MAP OF LEAD-DEADWOOD REGION SHOWING LOCATION OF PRINCIPAL TUNGSTEN DEPOSITS

Plate IX A.

NORTHERN HILLS NEAR HOMESTAKE WOLFRAMITE DEPOSITS
WASP NO. 2 OPEN CUT

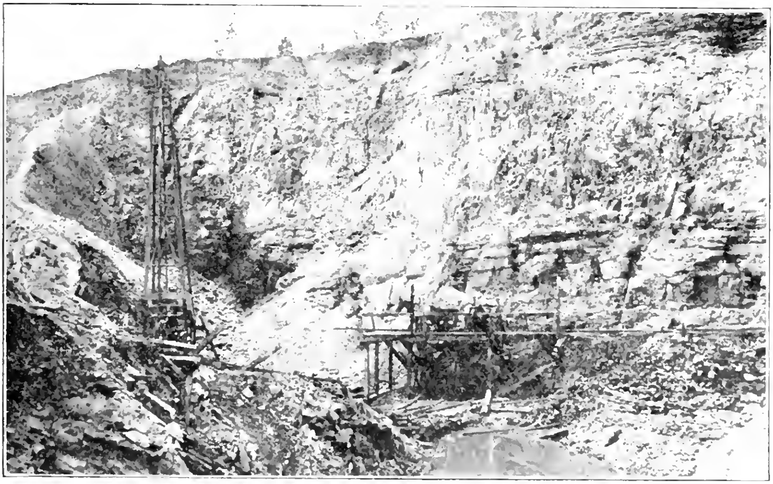

Plate IX B.

more abundant in the parts of the pegmatite rich in quartz, and in many cases are, in fact, in veinlets of quartz within the pegmatite. After quartz, muscovite is the closest associate of tungsten in the pegmatites. The pegmatites have in many places exerted a strong metamorphic action upon the inclosing schists, accompanied by the development of mica, tourmaline and garnet, at and near the contact. On the whole the tungsten minerals are less commonly found in the pegmatites and the crystals are of smaller size than in the quartz veins. Probably it is also true that the tungsten bearing pegmatites are not as rich as the tungsten bearing quartz veins.

The strike of the pegmatite dikes conforms closely to the strike of the schists, in dip, they are both parallel to, and cut across the bedding planes of the schist. The pegmatites are variable in thickness along the strike and dip and, in general, cannot be followed for great distances along the surface. Some are dike-like in form, while others more closely resemble the form of plugs.

The quartz veins are closely related to the pegmatites in distribution and genesis. Pegmatites may be found near most of the well developed quartz veins. Quartz veins may be traced into pegmatites both along the strike and along the dip. Many quartz veins are found in the pegmatites. Beside quartz, muscovite is easily the most common mineral of the veins. Much tourmaline and graphite also occur in places and frequently exhibit a tendency toward segregation along the vein walls and in planes parallel to the vein walls. The graphite is, so far as observations have extended, confined to those veins cutting graphitic rocks, and hence is believed to have been assimilated from the surrounding rocks. In places the host rock appears to have been somewhat altered near the veins, but the metamorphic effect of the quartz veins is less common and less intense than that of the pegmatites.

The quartz veins vary in width from the thinnest veinlets to thicknesses of four feet, and perhaps more. The veins exhibit a strong tendency to pinch, swell, and branch. Many veins lie parallel to the bedding of the schists, while others intersect the schists at high angles. Probably a majority of the veins lie nearly parallel to the direction of strike of the schists, especially where the schists dip steeply. Many veins change abruptly in direction of strike and in angle of dip. There are zones in which veins are very abundant that can be traced for more than a mile but within these zones no individual vein has been traced uninterruptedly, on the surface, for more than a few hundred feet. In places quartz veinlets of minute size have impregnated considerable masses of schist, but form no well defined vein. The veins in places occupy zones of weakness, clearly formed by movements in the host rock. In most cases the materials seem to have been injected under pressure and to have forced a passage.

The occurrence of the tungsten minerals within the veins is as erratic as the veins themselves. The crystals vary greatly in size, form and distribution. In places the minerals are concentrated along the vein walls and in other places, in shoots of irregular form and size. Rich spots occur both in the thin parts of the vein and in the thicker parts.

Tungsten-bearing quartz veins appear to be much more numerous near the outer margin of the pegmatite area than near the central mass of Harney Peak granite. A small area from 4 to 4½ miles east and southeast of Hill City contains more ore-bearing veins than any other equal area within the district. That there may be some connection between a considerable number of the veins in this area seems highly possible.

So little development work has been done that there are few data on the depth to which individual veins persist. Judging, however, from the lack of persistence of many of the veins in lateral extent, and their variability in size within the shallow zone of observation, it is doubtful that many of them extend downward for any great distance. However, there seems to be no good reason for thinking that a system of veins, or the zone in which veins may be found, does not extend to great depths.

**Origin of Tungsten Deposits in Pre-Cambrian Rocks.** The source of the ores is undoubtedly the Harney Peak granite. During its crystallization the minerals most soluble under the existing conditions, remained in solution after a part had solidified and were then injected along the planes of weakness into the granite and surrounding schists. The last minerals to crystallize in many cases, were the quartz, muscovite, wolframite and scheelite. These form the quartz-tungsten veins. In some cases no such separation took place, and the wolframite crystallized with the feldspars, quartz and mica in pegmatites.

**The Deposits of the Lead-Deadwood Area.**—(General Geology of the District.) The rocks of the Lead-Deadwood area of importance in connection with the tungsten deposits consist of a folded and metamorphosed series of sedimentary and intrusive, basic-igneous rocks, and a small amount of coarse grained granite, of pre-Cambrian age; a series of conglomerates, sandstones, and impure dolomites, limestones and shales of Cambrian age; thin Ordovician limestones; a series of thin bedded and massive pink and gray Mississippian limestones; and numerous intrusive dikes, sills, and laccoliths of Tertiary rhyolite porphyry.

The pre-Cambrian rocks are exposed within an elongated area eight or nine miles in length, from southeast to northwest, surrounded and partly covered by Paleozoic sediments. Within this area also are considerable masses of Tertiary intrusive rocks, which break the continuity of the pre-Cambrian rocks, and in many places cover them. The pre-Cambrian comprises a thick series of quartzites, garnetiferous and biotite schists, and calcareous and normal clay slates. These rocks form two distinct groups. The one lying to the west of Lead consists chiefly of clay slates and various quartzite layers striking N. 20°-30° W. and the second chiefly of calcareous slates, garnetiferous and biotite schists and quartzite, striking slightly east of north. The line of junction between these divergent groups of rocks is considered by Sidney Paige* to represent the line of a fault. The supposed fault lies very close to a line joining the tungsten area of the Homestake with the Etta, Bismarck and Wasp No. 2 mines. Paige regards the fault as forming the western boundary of the Homestake gold ore body.

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*Bul. of the Geological Society of America, Vol. 24, pp. 293-300.

As a whole the rocks are closely folded, in general with a steep isoclinal dip eastward. Near the supposed fault the western group is folded into a steeply northwest pitching anticline, and the eastern group into a complex anticline with a subordinate syncline on its western flank. This syncline plunges southward and is an important structural feature of the Homestake gold ore body.

The pre-Cambrian rocks of the Homestake mine show the effects of hydro-thermal metamorphism, that probably accompanied the introduction of the ores. This metamorphism resulted in the development of iron and magnesium silicates, such as cummingtonite and chlorite, in the calcareous series that had previously been intricately folded and compressed.

Pre-Cambrian igneous rocks comprise numerous dikes of amphibolites and an isolated occurrence on the western flank of Whitewood Peak of a coarse pegmatitic granite. The latter consists mainly of quartz and alkali feldspar in graphic intergrowth, muscovite, tourmaline and garnet, similar in every respect to the granites of Harney Peak. The total mass of exposed granite is very small, but it is of great significance in as much as it proves conclusively the presence of granite in the pre-Cambrian of the Northern Hills. This granite has evidently been floated up upon an intrusive mass of porphyry of Tertiary age. With it is a mass of dark basic schist probably of igneous origin, into which the granite is intrusive.

Rocks of the Cambrian System, locally known as the Deadwood Formation, overlie unconformably the upturned and truncated edges of the pre-Cambrian beds on a relatively mature erosion surface of slight relief. The basal member of the Deadwood Formation is commonly a massive, reddish-brown quartzitic sandstone. In most places the basal sandstone is more or less conglomeratic and in many it gives place entirely to a coarse conglomerate with pebbles several inches in diameter. The materials are largely derived from quartz veins in the pre-Cambrian and are of local origin. The basal conglomerate is, in places, as much as 25 feet thick but averages perhaps 5 or 6 feet. The conglomerates are in places auriferous and form the so called "fossil placers," which in former years were an important source of revenue.

The total thickness of quartzite and conglomerate rarely exceeds 30 feet. Resting upon the basal quartzite member, or, where this is absent, directly upon the pre-Cambrian formation is normally to be found about 200 feet of impure gray flaggy dolomites and limestone conglomerates interbedded with layers of green shale, grading downward into soft brown shales and calcareous red sandstone. The dolomitic beds where fresh contain a considerable amount of glauconite. Much of the original dolomite has been replaced by silica and contains well formed rhombohedrons of quartz as pseudomorphs after the carbonate. Where much weathered this rock passes into a soft "sand rock" heavily impregnated with oxides of iron and in places with oxides of manganese, yet exhibiting a marked stratification due to thin layers of shale. Above the dolomitic beds lie, upward of 100 feet of red sandstone with interbedded glauconitic sandstones and shales and finally a thin layer of soft green shales.

The Ordovician System is represented in the northern portion of the Black Hills by the Whitewood Formation. This formation comprises about 80 feet of massive, buff limestone, in places with a few feet of greenish shale at the top. Its hardness and massive character cause it to form benches in canyons, where exposed.

Overlying the Whitewood formation in the Northern Hills, in apparent structural conformity, occur beds of the Mississippian System and locally known as the Englewood formation. This formation consists chiefly of about 60 feet of thin-bedded, pinkish-buff limestone, with in places, some shale. The Englewood formation grades upward into the Pahasapa formation also of Mississippian age. The Pahasapa formation is a gray to buff massive limestone about 500 feet in thickness. It outcrops conspicuously in precipitious cliffs or forms the surface of board flat plateaus. Ores of gold and silver occur in the Pahasapa formation in the Ragged Top district and ores of lead and silver in the Carbonate district.

Dikes and sills of rhyolite porphyry of Tertiary age occur near or in immediate contact with all known occurrences of tungsten in the Northern Hills. The porphyry is a thoroughly acid rock, with a dense almost aphanitic texture and a grayish white color. Small phenochrysts occur sparingly. Fractured surfaces are in many places coated with black dendrites of manganese dioxide and brownish red stains of iron oxide. Under the microscope the ground mass is resolved into a fine aggregate of orthoclase and quartz and a little alkali plagioclase. Phenochrysts of quartz and orthoclose occur. Very little if any ferro-magnesian mineral is present.

(Location of Deposits.) Tungsten is known to occur (1) on the property of the Homestake Mining Co. on the divide between Gold Run and Deadwood Creek to the west of the Homestake open cuts, just north of Lead; (2) on the divide between Yellow and Whitewood Creeks, at the Etta Mine ½ mile southwest of Kirk; and again on the same divide near Flatiron on the properties of the (3) Bismarck and (4) Wasp No. 2 Mining Companies, 1½ miles farther south; (5) on west Strawberry Creek 1 mile south of Pluma; (6) on upper Two Bit Creek, 4 miles south-southeast of Deadwood; and (7) within the city limits of Deadwood, on the north side of Deadwood Gulch on the divide between City and Spring Creeks.

The numbers given above correspond with those on the accompanying topographic map (Plate VIII) and will assist in the location of the deposits.

**Deposits of the Homestake Mining Company.** Tungsten ores have been mined from the Harrison, Durango, Golden Summit, St. John, Reddy, Grant, Iowa, St. Patrick and Golden Crown claims of the Homestake Company. The deposits are all near the base of the flat lying Deadwood Formation and are found intermittently over a total area of perhaps 15 acres. The formation within this area consists of a thin basal conglomerate and quartzite, on the average less than 5 feet in thickness, lying upon the vertical schists. The quartzite is overlain by, from 30 to 36 inches of impure partially silicified dolomite, containing thin shale layers and this by calcareous shales. In places the quartzite and conglomerate are absent and the dolomites lie directly upon the schists. Upon the shales near by lies a thick sill of intrusive rhyolite porphyry and some of the middle Deadwood Formation but in the area of the tungsten deposits the igneous rock as well as the medial and upper beds of the Deadwood Formation have been eroded away.

The tungsten ores occur chiefly as replacement deposits in the lower dolomite but to a small extent also in thin shale layers within the dolomite also in the quartzite and as cement in the conglomerate. In the shale, quartzite and conglomerate the tungsten minerals have probably replaced only the calcareous portions. No tungsten has been found at this point in the pre-Cambrian rocks, nor in the Deadwood Formation above the lower dolomite.

In form the ores are largely irregular, tabular masses from a fraction of an inch to 2 feet in thickness and with a width parallel to the bedding, of from an inch to as much as 53 feet. The ore bodies branch, pinch and swell and in places appear on the breast of the stopes as isolated kidney and lens shaped masses of varying width and thickness. Within a single dolomite layer 30 inches in thickness as many as 4 or 5 horizontal ore bodies occur, separated in some cases by thin shale members. In the calcareous shale members of the dolomite beds, in places some replacement has taken place, but the form and general nature is not essentially different from the bodies occurring in the dolomite proper and are in most cases merely extensions of the latter. Within the quartzite the tungsten occurs much less commonly and in masses of much smaller extent than in the dolomite but in general take the same forms. Only a very few occurrences of tungsten have been found in the conglomerates where it fills the spaces between the pebbles that probably had been previously occupied by calcareous cement. The shapes of these bodies are very irregular and their total volume very small. The ores follow lines of fracture called verticals and extend laterally from them as a center. The verticals are perhaps more numerous parallel to the underlying schist layers than in other directions. One vertical in the Harrison Mine was followed for a distance of fully 500 feet, along which mineralization had taken place for an average width of about 30 feet throughout its entire length. In most cases the mineralization is as variable in extent along the strike of the verticals as the laterals are variable in width and thickness and it is very difficult to give anything like an average for the length, width, thickness or number of ore bodies within a single dolomite layer.

The tungsten ores in the Homestake property are every where intimately associated with silicious gold ores of the Deadwood Formation but there is by no means tungsten ore where ever gold ores occur. Irving* regards the tungsten as merely a basic phase of the gold ores and not as a separate and distinct deposit. The gold ores where unweathered consist of a hard, brittle, gray rock composed largely of silica, carrying pyrite, barite, fluorite and gypsum. It is largely within these siliceous ore bodies and to a lesser extent around their margins and as cappings over them that the tungsten ores occur. The general relations are shown in the accompanying cut, figure 2.

In the tungsten areas the siliceous gold ores are largely oxidized and are stained brown with oxide of iron and in places black manganese dioxide. In striking contrast to these soft brown oxidized gold ores, the portions bearing tungsten show very little effect of weathering and are practically everywhere hard, brittle, bright, sharply defined masses. Where the siliceous gold ores are unoxidized the line of separation betwen the tungsten bearing portions and the gold ores are in places sharp, while elsewhere they grade by imperceptible variations into each other.

The ore varies from a dense heavy black rock with a fine texture to nearly solid wolframite grains, to a gray quartzose rock containing small black, shiny specks of the mineral. The wolframite in these phases does not commonly exhibit crystal boundaries but shows small flat metallic cleavage surfaces. Individual grains are rarely more than one thirty-second of an inch in diameter but recently ores have been found that contain individual curved cleavage surfaces of more than an inch in diameter. The mineral in uniformly jet black aand exhibits a brilliant metallic luster on cleavage faces. A considerable amount of black manganese dioxide in places has impregnated the rock and has often been

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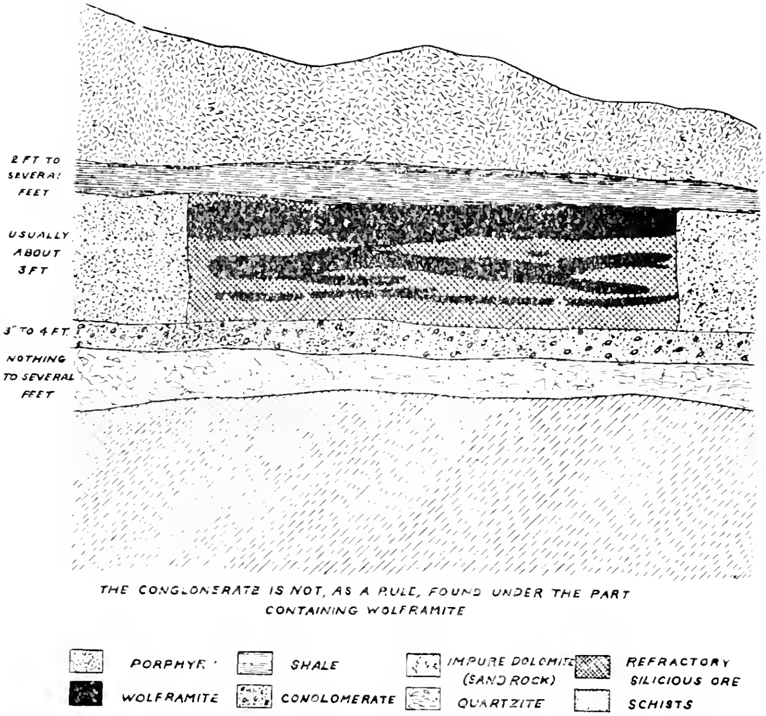
*Trans. Amer. Inst. Min. Eng., Vol. XXXI. page 689.



THE CONGLOMERATE IS NOT, AS A RULE, FOUND UNDER THE PART CONTAINING WOLFRAMITE

**Fig. 2.**

DIAGRAM ILLUSTRATING THE OCCURENCE OF TUNGSTEN ORES IN CAMBRIAN DOLOMITE, HOMESTAKE MINE, LEAD, S. D. (After A. J. M. ROSS)

mistaken for ore. It is easily distinguished from the wolframite by its dull luster, its lack of cleavage, and its lighter weight. Barite in well formed tabular crystals, grouped in interpenetrating and in radiating aggregates, is a prominent feature in places. Cavities of various sizes and forms lined with well formed wolframite crystals and others lined with druses of barite or quartz are not uncommon. The wolframite crystals show knife like edges and somewhat resemble the form of axinite. For the most part the crystals are very small, the largest attaining a diameter of scarcely more than ¼ inch. Small rounded aggregates of scheelite crystals resembling drops of honey in form and color frequently occur on the wolframite druses. This scheelite is regarded as most probably secondary. Thin seams occur entirely filled with well formed ingrowing crystals of wolframite. In the weathered ore drusy surfaces occur that are coated with yellowish material that has often been mistaken for tungstite but which in the specimens examined by the author proved to be jarosite. It is probable however, that some tungstite may occur in this form.

Under the microscope the leaner ores from the dolomites show well formed wolframite crystals occurring in a matrix of quartz much of which exhibits the form of the dolomite rhombohedron. In sections from the ore bearing quartzite the wolframite occurs in the irregular interstitial spaces between the rounded quartz grains. In both types scheelite may be seen intercrystallized with the wolframite and much of this is believed to be primary scheelite. The dense ore under the microscope, is opaque except where small masses of quartz occur.

According to W. J. Sharwood (personal communication) all analyses of the ore have shown the ore minerals to be wolframite low in manganese with small amounts of scheelite. Thus a typical carload of concentrate containing 60-61% $WO_3$ would probably carry between 3 and 4% manganese, with about 17% iron and 1% calcium, a minute amount of phosphorus, and not more than a trace of tin or copper. The follow-propositions of the principal minerals of a specimen of the ore have been calculated formerly from analyses by W. F.

Hillebrand.* These results show perhaps more scheelite than is contained in the average ore.

| | Per cent |
|---|---|
| Wolframite (FeMn) $WO_4$ | 75.60 |
| Quartz $SiO_2$ | 12.54 |
| Scheelite $CaWO_4$ | 4.77 |
| Barite $BaSO_4$ | .06 |
| Ferric Oxide $Fe_2O_3$ | 3.85 |
| Water $H_2O$ | .20 |
| Arsenic Oxide | 1.25 |
| Residual Clay (kaolin) | 1.34 |

In the Homestake ore tin, copper and antimony, occur only in traces; while in the Wasp No. 2 ore antimony frequently occurs, and occasionally appreciable amounts of copper. Tin is almost universally present in the southern Hills concentrate. In some parts of the Homestake Mine porous oxide of manganese (psilomelane) occurs at considerable depth, filling small fissures in porphyry (rhyolite). This has been found to contain a small amount—about 1%—of tungstic oxide.

The ore concentrated at the mill for the past years has averaged nearly 3 per cent $WO_3$ and $4.00 in gold per ton. The gold values recovered have been sufficient to pay most of the costs of mining and milling.

(Deposits of the Wasp No. 2 Mining Company.) The deposits of tungsten on the property of the Wasp No. 2 Mining Company are in all essential respects similar to the deposits at the Homestake, so that the above description may very well serve for both after a few minor differences have been noted. At the Wasp No. 2 a greater percentage of ore has been obtained from the basal quartzite member of the Deadwood Formation than at the Homestake. At the Wasp, basal quartzite is in places 20 feet thick and has proved ore bearing to an important extent. In this property rhyolite porphyry occurs in numerous dikes, sills, and irregular masses which have caused faulting in several places in the Deadwood Formation. The rhyolite occurs in intimate as-

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*U. S. G. S. Prof. Paper 26, page 167.

sociation with the gold ores and to some extent with the tungsten ores. An interesting mineral ocurrence in connection with the wolframite in the Wasp mine that has not been reported from the Homestake is that of stibnite in long radiating acicular crystals. Small amounts of malachite have also been found. An analysis of the ore by Hillebrand has been calculated to represent the following minerals:

| | Per cent |
|---|---|
| Wolframite (FeMn) $WO_4$ | 51.58 |
| Quartz $SiO_2$ | 9.60 |
| Scheelite $CaWO_4$ | 27.68 |

This analysis, as in the case of the Homestake ore given above, probably represents one containing more scheelite than the average.

The total area over which wolframite has been found to occur is perhaps 12 to 14 acres.

(Deposits of the Bismarck Mining Company.) On the property of the Bismarck Company lying adjacent to and north of the Wasp No. 2 Mine, wolframite deposits occur with gold ores as replacements in the lower dolomites and to some extent in the basal quartzite of the Deadwood Formation, as in the Wasp and Homestake. Numerous dikes and a 30 foot sill of rhyolite porphyry that has caused faulting in the ore beds, occur in association with the ores. The deposits have not produced more than a very small quantity of tungsten ore but ore is known to occur in places over an area of 6 or 8 acres.

(Deposits at the Etta Mine.) At the time the author learned of the occurrence of tungsten in this mine he was unable to make a visit to the property on account of the deep snow. From descriptions furnished by various parties that have visited the property it would apear that the geologic relations are very similar to those existing at the Wasp No. 2 and Bismarck. The property lies north-northwest of the latter at a distance of about ¾ of a mile. Rhyolite porphyry is said to occur in dikes and sills and to have caused considerable displacement of the lower beds of the Deadwood Formation probably along faults. Ores of gold as well as the tungsten ores occur in intimate association with the porphyry. Specimens obtained from the property contain wolframite in important quantities and appear similar in every respect to average samples from the Wasp, Bismarck and Homestake.

(Deposits at Deadwood) During the early days of 1916 when tungsten ore was selling at record prices, an interesting discovery of its occurrence was made within the city of Deadwood in rocks that had been widely prospected for gold in years past. The ore had lain unnoticed for years although within plain view of everyone. The rock had been quarried for the foundations of several houses in the vicinity, and in that of a house which had burned, the author found numerous blocks that in sufficient quantities would prove valuable ore. One block, perhaps one cubic foot in volume, was estimated to carry 15 per cent $WO_3$.

This occurrence lies directly above the town on the north upper slope of Deadwood gulch between City and Spring Creeks. The ore has been found in many places over a total area of perhaps 12 acres. The tungsten occurrences noted were in the basal quartzite of the Deadwood Formation which at this place is about 20 feet thick. The dolomite has been apparently eroded away from most of the area and the quartzite forms the surface capping of the upper valley slope, where it is exposed in numerous steep cliffs. To the north, pre-Cambrian garnetiferous schists and a quartzite, heavily impregnated with iron, locally known as the Great Iron Dike, appear at the surface. Farther north as well as in the south side of Deadwood Gulch at this place occurs a thick sill of rhyolite that probably once extended across the tungsten area above the ore horizon.

The ore occurs in thin seams and in lenses of from 2 to 6 inches in thickness and from a few inches to a few feet in length, as replacements in what probably were calcareous portions of the quartzite. In places elongated cavities occur, along the margins of which the tungsten mineral occurs in thin sheets, but no crystals were seen lining the cavities. The ore appears in all essential respects like the average ore from the Homestake. No ore masses noted were very large nor were there more than a few of them found at any one point, although large masses may well occur. Most of the ore observed was of low grade but a few boulders were found which contained important amounts, some perhaps upward of 15 per cent $WO_3$. Very little development has been done in connection with the tungsten and the value and extent of the ores is purely problematical.

(Deposits on The Denis Henault Claims.) The occurrence of tungsten on the property of Denis Henault on lower West Strawberry Creek are of especial interest because of their geological relationships and the light they may throw on the rhyolite as a source of the tungsten rather than for their known economic importance. Black tungsten mineral, probably wolframite, occurs at two separate points. One occurrence is on the west facing slope of West Strawberry Creek 100 feet north and 50 feet above the Henault cabin. The tungsten is exposed in a small prospect hole of about 6 feet in diameter and of about the same depth, in a dike of rhyolite porphyry. The dike trends in an east west direction and can be followed for several hundred feet along the valley slope. Its width is perhaps 50 feet. Cutting this dike near the tungsten occurrence, is what appeared to be a second dike of tinguaite porphyry. The extent of the latter and its exact relationships are unknown for at the time of the author's visit it was largely covered with snow. The rhyolite is a light gray rock with numerous phenocrysts of quartz from 1-16 to 1-4 inch in diameter with a dense ground mass of quartz and orthoclase.

The wolframite occurs apparently intergrown with the quartz and feldspar of the rhyolite; in small bladed crystals filling thin seams in the rock; and in druses with quartz crystals, lining small open cavities. In the latter the crystals of wolframite are very small and thin resembling minute axe blades probably in no case exceeding the length of 1/8 inch. In some cases the open spaces strongly resemble mairolitic cavities while in some cases the connection of the cavities with the small veinlets seems to favor their origin as a result of solution along cracks in the fractured rock. Had, however, the crystals of wolframite found intergrown with the quartz and feldspar, been introduced by replacement after the rhyolite had solidified it would seem that the solutions in which the tungsten was carried should have affected the rock in the vicinity of these crystals to some extent. The rhyolite in contact with the tungsten appears in no way different from that found at a distance from it. It seems more likely then, that the wolframite was a part of the rhyolite magma and that some of it was crystallized with the quartz and feldspar and some at a later period of crystallization, in spaces formed by shrinkage of the rock on solidification. More data are needed before this important problem can be conclusively settled. A photographic reproduction of a specimen illustrating this type of occurrence may be seen in plate. IV B.

About 20 feet below the wolframite occurrence the dike has been opened up by means of a tunnel for a distance of over 30 feet. While no tungsten occurs at this point the rhyolite contains a considerable amount of pyrite and sphalerite, in small grains intergrown with the other rock constituents, and in thin veinlets sphalerite and calcite occur. The rock in both exposures is said to be gold bearing, in fact the discovery of the tungsten was made while the rock was being prospected for gold. Zinc ore is being sought in the lower tunnel. The places of occurrence of the tungsten and of the sphalerite and pyrite are both below the basal Cambrian beds at this point.

The second occurrence of tungsten on this property lies about 100 feet above and 500 feet north of the one described. At this place a dike of rhyolite has penetrated the pre-Cambrian schists. Along the contact a breccia has been developed composed of schist fragments bound together apparently by infiltered rhyolite. The breccia grades on one side into rhyolite inclosing schist fragments and on the other into schist penetrated by minute veinlets of porphyry. At the contact of the rhyolite is very dense and contains minute crystals of pyrite. The wolframite occurs in small bladed crystals in thin seams in the rhyolite and with quartz crystals lining small irregular cavities in the breccia. Here again gold is said to occur in association with the tungsten.

A tunnel has been run in parallel to the contact for a distance of about 30 feet, along which the tungsten occurs for the entire distance. The total amount of development on the property is so small that no estimates are possible as to the extent or grade of the ore. In neither occurrence is there any indication of a tungsten ore body of any considerable magnitude and all the samples obtained were of low grade.

(Deposits on Upper Two Bit Creek.) On a branch of upper Two Bit Creek lying parallel to and about one half mile west of the Galena-Deadwood road, tungsten has been found at two distinct but closely contiguous points. The northernmost of the two occurrences is of historic interest inasmuch as it is said to be the first known tungsten occurrence in the Northern Hills. In the early eighties, specimens of hubnerite are reported to have been collected and recognized as a tungsten mineral. The property at that time was known as the Comstock mine. It is now the property of Mr. S. R. Smith. The tungsten ore has been obtained from a tunnel on the east side of the valley a few feet above the creek level.

So much of the bed rock in the vicinity is covered with soil and so small an amount of ore was exposed in the tunnel that it is difficult to give an adequate description of the geological relations. The ore occurs in what is apparently the lower part of the dolomite, near the base of the Deadwood Formation. Above the tungsten bearing formation, the dolomite is highly siliceous and in places highly impregnated with pyrite. Much of the dolomite rock is porous and vugs frequently occur lined with well developed quartz crystals. Shales overlie the dolomite rock, and above them, higher up the valley side, with a covered area intervening, occurs a thick sill of rhyolite porphyry. It appears more likely that the tungsten occurs in solution cavities in the dolomite than that it has intimately replaced the dolomite or that it occurs in a true vein. However, some of the ore has the appearance of a vein deposit. The hubnerite occurs chiefly in irregular masses of various sizes of closely aggregated, divergent groups of bladed crystals, here and there interspersed with masses and crystals of glassy quartz. The mineral evidently was precipitated in open spaces, for crystal aggregates frequently occur that have grown unhindered to lengths of 3 or

4 inches (see plate IV A). Many drusy surfaces are to be found covered with quartz crystals. A considerable amount of the ore has been oxidized and earthy manganese dioxide occurs in considerable quantities. Manganite was observed in mats of beautiful steel gray, wire like aggregates, also a number of exceedingly perfect pseudomorphs of manganese dioxide after dolomite rhombohedrons, as large as one inch across the face. An analysis of the tungsten mineral by M. L. Hartmann shows it to be composed of 96.8% $MnWO_4$ and 3.2% $FeWO_4$ and an analysis by Headden* of a sample from the same mine was calculated by Hess and Schaller to contain 94 per cent $MnWO_4$ and 6 per cent $FeWO_4$. The mineral is therefore to be classed as hubernite.

So far as was noted the tungsten occurred only in the floor of the tunnel and no good exposures of it were seen in place so that little idea was gained of its total extent. Specimens obtained, and most of the ore sacked in the mine, were of very high grade. One specimen weighing perhaps 40 pounds was estimated to contain perhaps 40% $WO^3$. About 1600 pounds of high grade hand picked ore were mined and marketed in 1916.

The southernmost of the occurrences on upper Two Bit Creek lies on the west side of the valley about 200 yards south of the Smith property. This claim is the property of Mr. Martin Bresnahan.

At this point the vertical pre-Cambrian schists are exposed in a small cut overalin by about 10 feet of the based quartzite of the Deadwood Formation. Upon the quartzite lies silicified dolomite perhaps three feet in thickness and upon it a sill of intrusive rhyolite the thickness of which was undetermined because of cover. About 30 feet above the lower dolomite are numerous angular boulders of mineralized dolomite in the soil, that are very probably derived from rock in place at this immediate point. If so dolomite lies above the porphyry sill. Farther up the valley side another sill of porphyry of unknown extent is exposed.

The rhyolite porphyry is a dense grayish white rock with

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*Proceedings of Colorado Scientific Society, Vol. VIII, page 175.

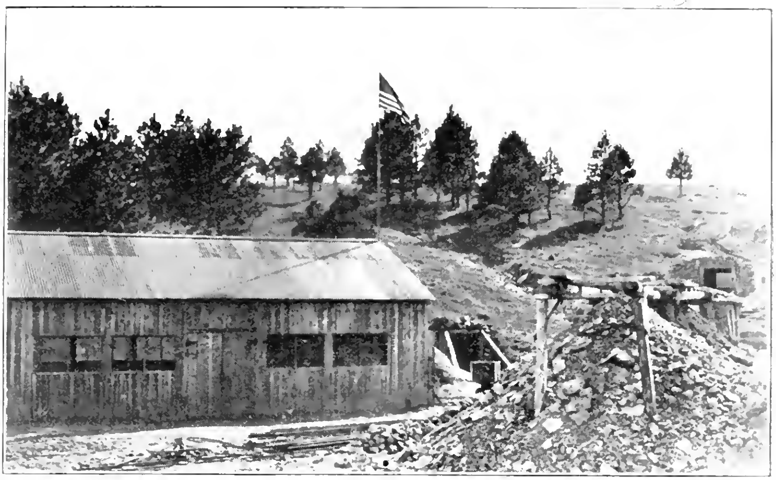

Plate X A.

HOMESTAKE TUNGSTEN MINE, LEAD, S. D.

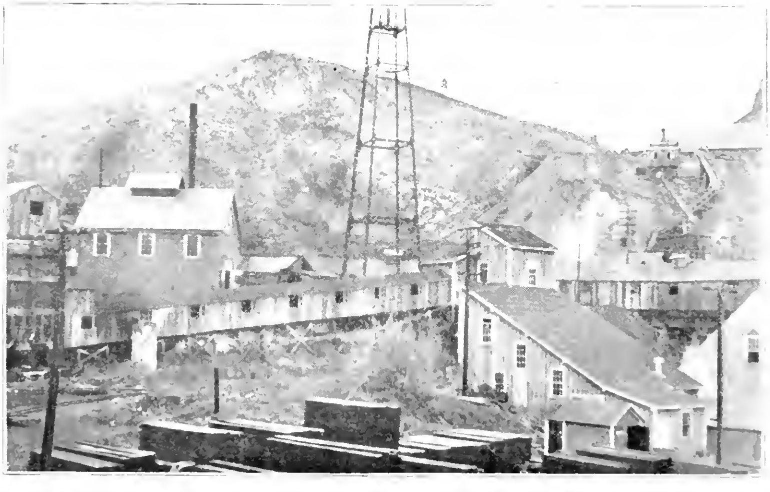

Plate X B.

HOMESTAKE TUNGSTEN MILL, LEAD, S. D.

Plate XI A.

WASP NO. 2 MILL

Plate XI B.

ELKHORN TUNGSTEN CO.'S PLANT

a fine grained ground mass of quartz, orthoclase and a little alkali plagioclase containing phenocrysts of orthoclase and quartz. Under the microscope titanite was seen to occur but no ferro-magnesian minerals were noted. In various sections minute black specks, possibly wolframite, occur. Specimens of the silicified dolomite taken from near the porphyry contact and viewed under the microscope show a high percentage of quartz, a considerable amount of which occurs in clearly defined rhombohedrons as pseudomorphs after dolomite. A few minute bladed crystals of dark green, slightly pleochroic amphibole were detected in one section.

The tungsten occurs chiefly in the dolomite both above and below the porphyry sill in well formed bladed crystals intergrown with quartz, also in crystals with quartz lining open cavities and to some extent apparently as replacements of the dolomite. A lesser amount occurs in minute bladed crystals in thin seams in the quartzite. From the porous nature of the ore, the well formed crystals of hubnerite and quartz, and from the high percentage of clear vein quartz in the ores it appears that the minerals have grown freely in open spaces of considerable size. Whether or not the ores follow a vein system could not be determined as only a small amount of the ore was exposed in place. It is highly more probable however that it has been formed largely in solution cavities in the dolomite. The richest specimens and the most persistent mineralization were found at or very near the contact of rhyolite and dolomite. No tungsten was positively identified in the rhyolite although well formed crystals of hubernite were found coating surfaces of the igneous rock at the lower surface. The occurrence above the rhyolite were not found in place but the large number of angular fragments of considerable size, their uniformity, the lack of rock fragments of other kinds in more than very small quantities and the depth (3 feet or more) at which they were found in the soil points strongly to the occurrence of the ores in place above the porphyry.

No analyses of the tungsten mineral were made but from its similarity to the hubnerite found 200 yards down the gulch it is believed to be the same mineral. Slender bladed crystals of hubnerite from 2 to 3 inches in length, intergrown with quartz crystals, occur in places in radiating and interpenetrating groups. Crystals ½ inch in length extending inward from what were the sides of elongated cavities, but which now are filled with quartz, are common. Within solid masses of quartz many crystals occur lying in various positions. One surface was found from which tabular wedge shaped crystals in parallel growth ¼ inch thick, one half inch wide and fully one inch in length, had grown. The hubnerite is a dark brownish black and shows brilliant metallic cleavage faces. Where weathered, it is frequently dull black or brown with oxides of manganese or iron. A considerable amount of manganese dioxide is found coating rock surfaces. No scheelite or tungstite were observed. The dolomites are said to be gold bearing at this place.

The development work on the property is small, consisting of three small prospect cuts, one of which has not even pentrated rock in place. From the meagre data it is impossible to say anything definite regarding the likelihood of a profitable ore body. The ore samples obtained were of a good grade and if found in sufficient quautities could doubtless be mined at a profit.

(Origin of the Tungsten Deposits of the Lead-Deadwood Area.) In a paper presented before The American Institute of Mining Engineers in 1901 J. D. Irving* describes the tungsten deposits at Lead now belonging to the Homestake Company, and the deposits of the Wasp No. 2 Company on Yellow Creek, and said regarding their origin:

"That they are formed through the gradual replacement of the country rock by wolframite seems to the writer to be clearly indicated by the character of the ore, the nature of the beds in which it is found, and the metasomatic origin of the ores with which it is inseparably connected. First, the wolframite itself is filled with cavities of irregular form and distribution such as are almost always to be observed in ores formed by replacements where the aggregate volume of the

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*Trans. Am. Inst. Min. Eng., Vol. 31, 1901, pp. 694-695.

mineral introduced is smaller than that of the original rock; secondly, the beds in which the ore occurs are composed chiefly of magnesian limestone, often quite impure, it is true, but of a prevailingly soluble character; thirdly, wolframite is an integral part of shoots of siliceous gold-ore, the metasomatic origin of which has been conclusively proved by careful microscopic study.

As regards the source from which the tungsten minerals have been derived, no positive conclusions can be formed; but the relation of the deposits to the geology and to the other ore bodies of the neighborhood seems to furnish some evidence as to their derivation. They are found at two rather widely separated localities on the west side of the outcrop of the Homestake ore-body. Along this line there has taken place, first, the heavy mineralization of the Algonkian rocks, which has produced that well known ore-body; secondly, the mineralization of the Cambrian above resulting in the formation of siliceous gold ores, which are richer and contain a more varied assortment of secondary character than ores of a similar character away from the Homestake lode; and, thirdly, the formation of the wolframite-ores themselves. It seems, then, that the line of strike of the Homestake lode is also a line along which mineralization has been both varied and unusually intense. During this extensive mineralization, the circulation of waters capable of dissolving the metallic contents of the surrounding rocks must have been active. That these waters were, in the case of the siliceous ores, and hence in the case of the wolframite, ascending waters is proved by the concentration of these deposits beneath impervious beds. It is therefore not unreasonable to suppose that if wolframite occurred in the Algonkian rocks at some point below the deposits now worked, just as it occurs in its normal relations at other points within the Hills, the action of ascending thermal waters upon this material should have given rise to the mineral bearing solutions which carried the wolframite up to its present position, and, there encountering rock sufficiently soluble to admit of metasomatic interchange, should have redeposited their metallic contents."

Regarding the source of wolframite in the siliceous gold ores of the northern Black Hills Irving* in 1903 said in part:

"Wolframite occurs in considerable quantities in rocks of the Algonkian associated with tin deposits, both in Nigger Hill and in the Southern Hills. Its occurrence suggests that similar deposits and bodies of eruptive granite may exist below the schist in the vicinity of the tungsten deposits near Lead and if so they may readily be supposed to have supplied this mineral to ascending thermal waters. It is, of course, possible that tungsten is present in the eruptive rocks, but if so, it is yet undetected. In the light of the evidence of the direction of flow of mineral solutions no such assumption is essential."

In 1909 Hess** described the then known occurrences of tungsten in the Black Hills and after presenting Irving's theory of the origin of the Northern Hills ores, says regarding the relation of the deposits of the Harney Peak and Lead areas:

"To the present writer it seems more likely that the ores of the two areas are more closely related genetically, than this hypothesis allows. It has been shown that in the Southern Hills wolframite occurs with ordinary pegmatites and with the later phases of such dikes that are seen in quartz veins. In the Lead region there are many rhyolite dikes, closely related in composition to the pegmatite dikes farther south. It is probable that either from them or from other intrusions closely related to a granitic magma watery solutions separated, holding a more tenuous solution than that which made the quartz veins of the Hill City and Keystone region, so that veins were not formed, but instead soluble carbonates were removed and replaced by quartz, wolframite, scheelite, pyrite, gold, and other minerals held in solution."

That Irving's theory of the source of the tungsten has much in its favor is evidenced by the data he presents and further by the fact that pre-Cambrian granite is now known to occur in the Northern Hills on the west flank of Whitewood Peak. The author has presented other evidences of its

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*U. S. Geol. Survey, Professional Paper, No. 26, page 158.

**U. S. Geol. Survey, Bull. 380, page

presence below the Lead area in a portion of the previous chapter dealing with the pre-Cambrian. The presence of tungsten in the Etta Mine southwest of Kirk, was unknown to Irving. This discovery adds one more occurrence to those he mentions along the line of mineralization parallel and adjacent to the Homestake ore body. And if, as Sidney Paige believes, this is the line of a fault along which solutions traveled, the idea would seem to have gained further strength. This theory then, must receive serious consideration until other evidence of a positive nature is presented for the origin of the ores from some other source.

The theory presented by Hess that the rhyolites are probably the source of the tungsten is apparently based on the fact that "in the Lead region there are many rhyolite dikes closely related in composition to the pegmatite dikes farther south." This is good enough for the rhyolites as a possible source of the tungsten, since acidic magmas are predominantly the parents of tungsten ores but it is not evidence that they furnish the ores in this region.

The occurrence of the tungsten at Deadwood, on Two Bit Creek and on west Strawberry Creek are, of course, not related to the line of mineralization of the Homestake ore body. A line drawn between no two of these occurrences is parallel to either the strike of the pre-Cambrian schists nor does it coincide with any known line of mineralization. The direction of strike of the pre-Cambrian rocks in all three of these localities is north-northeast. The "Great Iron Dike" in the pre-Cambrian that outcrops just north of the Deadwood tungsten area can be easily traced to a point just south of Lead where it meets a northwest striking series of quartzites that lie just west of the Homestake ore body.

Sills and dikes of rhyolite are in intimate association with the tungsten ores in the Etta, Bismarck, Wasp No. 2, Henault, and Breshnahan and Smith properties. The evidence is good that rhyolite sills once extended over the Homestake and Deadwood areas of tungsten and is certainly now to be found near by. Mineralization of the dolomites has occurred in contact with the rhyolite sills in the Bresnahan claim and tungsten mineral there occurs at the immediate lower surface of the rhyolite and probably very near to its upper surface. Tungsten minerals occur in cavities in the rhyolite and almost certainly also were crystallized with the feldspar and quartz of this rock on the Henault property. A considerable number of cases of gold ore associated with pyrite are known in the rhyolites. From these evidences it seems highly probable to the author that it was from the rhyolites or as Hess suggests "from other intrusions closely related to the granitic magma" that the solutions bearing the tungsten emanated. It appears significant that outside the areas of acid intrusives no tungsten is known to occur in the Northern Hills.

In regard to the age of mineralization Irving* says:

"Mineralization along fractures that are cut by eruptives has always exercised an influence on the porphyry either by producing a slight silicification at the point of contact or by the extension of the more powerful of the mineralizers, like fluorite, beyond the ore into the minute crevices of the eruptive rock. Eruptives have never been observed to contain angular fragments of ore, which would probably have been the case had magmas broken through such an extremely brittle material. These conditions have been observed to hold good for all of the varieties of eruptive rock. The mineralization is, therefore, later than the igneous activity."

Admitting this, it would seem then, that except in the one case where tungsten minerals evidently crystallized with the magma and possibly where the tungsten formed at the contact of the rhyolite and dolomite, the portions of the rhyolite that were intruded into the ore bearing rocks were not necessarily the sources of the ore. The igneous rocks that reached into the Deadwood and overlying formations may have been the first to crystallize, or, to state it in other terms, they may have been the first differentiation products of the parent magma. As is the rule in a great majority of cases in the Harney Peak and other areas, among the most soluble materials of the magma are the silica and tungsten. The differentiation may have taken place at a considerable

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*U. S. Geol. Surv. Prof. Paper No. 26, page 154.

depth below the present surface and in larger bodies of the magma than appear in the dikes and sills intruded into the Deadwood and overlying formations. As the less soluble material separated out, the silica, wolframite, gold, pyrite, a little fluorite, and some other materials remained in a liquid form. These it is thought, followed upward in aqueous solutions through crevices opened up by the earlier invasions of magma and were precipitated in the easily replaceable dolomites. The evidence that the ores are replacements, as Irving points out, is indisputable. The supposed fault at the western border of the Homestake ore body may have been a convenient avenue along which solutions might travel and have caused the localization of a number of deposits.

Scheelite occurs in cavities crystallized upon the wolframite, and interstitially with the wolframite in some of the ores of the Homestake and Wasp No. 2. If some of this scheelite is secondary, as is believed to be the case, it probably has been dissolved, at least in part, from ores lying above and precipitated in its present position. In so far as this is true the ores containing secondary scheelite may be regarded as having been secondarily inriched. The extent to which this action has taken place is unknown, but probably small.

If the porphyries are the source of the tungsten they are probably also the source of the gold, for gold occurs in considerable quantities in several of the tungsten deposits and is said to occur at least in small quantities in all of the others.

# CHAPTER IV.

# CONCENTRATION AND PRODUCTION OF ORE

## Concentration of the Ores

Up to the year 1915 practically all of the Black Hills tungsten ore sold, was marketed in the form of hand picked ore. Since that time by far the greater part of the product has been concentrated. Inasmuch as the degree of success of the milling operation has contributed in no small way to the profitableness of the industry it seems advisable to describe briefly the methods employed by the two principal producers.

At the Homestake tungsten mill, during 1917, 254 tons of concentrates of various grades were produced from approximately 7200 tons of ore, that averaged from 2% to 3½ per cent $WO_3$. The percentage of tungsten recovered approximated 73%. In addition to its tungsten content the ore carried on the average between $4.00 and $5.00 per ton in gold, which when extracted was sufficient to pay for the treatment of the ore.

The ore is delivered to the mill in ore wagons, teamed from the mine some distance away. At the mill it is dumped into bins, from which it passes to a 5K gyratory crusher. The discharge from the crusher is carried by means of a belt conveyor to the battery bin.

5 900-pound stamps and 2 small ball-mills complete the crushing and fine grinding equipment. The stamps, similar to those in the company's gold mill, have a crushing capacity of approximately 20 tons per 24 hours. These crush the ore to pass a screen—2 mesh by 12, giving opening 0.023 by 0.052 inches. The pulp from the battery on passing through the screen flows over a 4-foot amalgamation plate, to recover any free gold present in the ore.

The concentrating equipment consists of one Wilfley sand table and three Deister sliming tables. The discharge from the plates passes to a classifying cone, from which the coarse product is sent direct to the Wilfley table. The following products are made by the Wilfley; (1) a 70% $WO_3$ concentrate, (2) a 50% $WO_3$ concentrate, (3) middlings and (4) tailings. The middlings are sent to two small ball-mills for regrinding.

The overflow from the classifying cone is treated in two dewatering cones, and the thickened product is treated on the first Deister Slimer, where a 60% $WO_3$ concentrate, middlings and tailings are produced. The middlings together with the reground product from the ball-mills are treated on the two remaining Deister tables. These last tables make a 35% $WO_3$ concentrate, a middling and a tailing product. The middling product is then returned to the ball-mills.

The tailings from all the tables are sent to the company's gold mill where it joins the gold ore tailings and passes with them over amalgamation plates, through the regrind plant, cyanide plant, etc., effecting thereby the recovery of a large per cent of the remaining gold.

The four grades of concentrates, produced in the tungsten mill are separately dried on steam driers and sacked for shipment.

For the milling practice at the Wasp No. 2 mine the author quotes from an article by Supt. Ed. Manion:*

"The ore after being mined is taken to the ore house and there sorted and cobbed. It is then crushed to about one half inch and sampled and then sold to the highest bidder. .."

"We have recently constructed a concentrating plant to treat our low grade ores. This ore is crushed to one-eighth inch mesh by rolls and from there through a trommel screen, sixteen mesh. The oversize goes to the jig and from there to a small set of rolls, returning to the trommel screen. The through product from the screens goes to a cone classifier from which the agitated slimes go to canvas tables and the sands to Wilfley tables. The sand from the Wilfleys goes to a 4x5 ball-mill, discharging into an 8 inch elevator which elevates and returns the reground sand to the classifier. The slimes go from the classifier to nine 4x60 feet canvas tables

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*Pahasapa Quarterly. February, 1916.

which catch the concentrates, the slimes passing through a launder at the end of the tables and from there to an eight-inch elevator which deposits the treated slimes into a 420-ton tank as tails. Here the tails which carry high in gold are treated by cyanide.

"We are making three grades of concentrates, the first grade about 65% $WO_3$, the second grade about 45% $WO_3$, and the third, which are slimes from the canvas tables, run about 35% $WO_3$."

The old mill of the Harney Peak Tin Company at Hill City was used in 1916 and 1917 by the Hill City Producer's Company to concentrate both tin and tungsten ores. Other mills in the Southern Hills that have concentrated small amounts of ore are those of the American Tungsten Company and the Elkhorn Tungsten Company near Hill City. All of these mills contain standard types of crushing, fine grading and concentrating machinery. None of them are operating at the present time.

### Statistics of Production

During the past three and one half years, January 1915 to June 1918 inclusive, the total value of tungsten ore produced in the Northern Black Hills has exceeded one million dollars. During the same period the Southern Hills have produced ores, the value of which probably did not exceed $25,000.

In these days of high prices and increased production one is inclined to concentrate attention upon the fields with outputs of first rank and forget the conditions existing in the same fields before the war, and to overlook the fields of lesser importance. In this regard some interesting facts may be learned by a comparison of the average value of the annual production of the Boulder County, Colorado district, for the ten pre-war years, 1904-1914 incl., and the value of the Black Hills ores produced in the past three years. During the ten year period mentioned, the average value of the annual production of the Boulder field was $345,000, and the industry was regarded as a very profitable one except for the year 1908. Now when we consider that the 1915 production in the Black Hills was practically all obtained during the latter half of that year, the production can be figured as amounting to approximately $335,000 per year, for the three year period ending July 1st, 1918. This $335,000 per year undoubtedly furnished a much higher percentage of profit to the producer, than did the $345,000 of the Boulder deposits, for, enough gold was recovered from the Black Hills ores nearly, if not fully, to pay costs of mining and milling, not to mention the probability that the tonnage of ore treated in the Black Hills was considerably less.

Estimating the Homestake production for the first half of 1918 at the same rate that was maintained throughout 1917 and the first four months of 1918, this company will have produced by July 1st 1918 tungsten ore to a value of nearly $750,000.00. The total production of the Wasp No. 2 company has exceeded a value of $265,000.00. The amount of production of the Hidden Fortune Company, former owners of the Homestake tungsten property, probably did not exceed 150 tons of high grade ore and concentrate. The Smith and Bresnahan properties have produced a few hundred pounds.

In the Southern Hills the Black Hills Tungsten Company and the Hill City Tungsten Producer's Company have probably furnished the majority of the output, which is very small. From practically all of the claims in the Hill City district, described in this bulletin a few hundred pounds of ore have been obtained. The great majority of these properties are in the prospect rather than in the producing stage of their history.

The following table is believed accurate for the larger productions but may be somewhat in error for the smaller ones.

### Prior to 1915

| Producer— | Conc. or High Grd. | Value |
|---|---|---|
| Homestake | *§150 tons | $ |
| Wasp No. 2 | 25 tons | |
| Black Hills Tungsten Co. | | |
| Miscellaneous | §125 tons | |
| Total | §300 tons | §$ 25,000 |

### 1915

| Producer— | Conc. or High Grd. | Value |
|---|---|---|
| Homestake | 25 tons | $ 31,331 |
| Wasp No. 2 | 187 tons | 147,730 |
| Black Hills Tungsten Co. | | |
| Miscellaneous | 1 ton | 1,425 |
| Total | 213 tons | $180,486 |

### 1916

| Producer— | Conc. or High Grd. | Value |
|---|---|---|
| Homestake | 250 tons | $281,982 |
| Wasp No. 2 | 36 tons | 97,869 |
| Black Hills Tungsten Co. | 5 tons | 10,000 |
| Miscellaneous | 2 tons | 2,000 |
| Total | 293 tons | $391,851 |

### 1917

| Producer— | Conc. or High Grd. | Value |
|---|---|---|
| Homestake | 254 tons | $299,447 |
| Wasp No. 2 | 12 tons | 19,561 |
| Black Hills Tungsten Co. | | |
| Miscellaneous | 1 tons | 1,000 |
| Total | 267 tons | $319,008 |

### 1918 to July 1st.

| Producer— | Conc. or High Grd. | Value |
|---|---|---|
| Homestake | §125 tons | §$135,000 |
| Wasp No. 2 | | |
| Black Hills Tungsten Co. | | |
| Miscellaneous | | |
| Total | 125 tons | $135,000 |

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*Includes production of Hidden Fortune Co. prior to 1915.

§Estimated.

At the present time the production from the Homestake deposits is being maintained at the rate of about 25 tons of concentrates of all grades per month, and bids fair to maintain this rate for some time to come. The Bismarck mine has recently been leased by Mr. Ed Manion, the former operator of the Wasp No. 2 mine. It is the intention to concentrate the tungsten ores and to cyanide the tailings for gold, as is being done at Homestake and as was done at the Wasp No. 2. It is possible that the operation of the Bismarck may cause the production of tungsten in the Black Hills to increase in the year 1918.

As to future production, it appeals to the author that there is good reason for believing that the present output may be maintained for a considerable number of years and even, that it might be increased. Resumption of normal conditions may see the Wasp No. 2 again producing, the Homestake and Bismarck continuing, and a number of prospects opened up.

If, as is believed to be the case, the rhyolites are the source of the tungsten, it would seem more than likely that new discoveries may be made within the areas in which they occur. It seems entirely possible that tungsten ores might be found in the Pahasapa limestone as is the case with gold, silver, and lead ores. Perhaps scheelite is more likely to form in the Pahasapa limestone and might remain undetected for a long time, on account of its light color.

In the Southern Hills good ores occur in quite a number of the prospects. The important question regarding their value is the extent of the deposits. As was stated in the chapter in which these deposits were described ore bodies of this type are characteristically "bunchy," and likely to terminate suddenly, but certainly valuable deposits of precisely this type occur in many parts of the world, and it seems entirely possible that out of the many well known occurrences one or more may prove profitable. It would be a rash assertion to say that the present amount of development has either proved or disproved the existence of a deposit of considerable magnitude in this region.

# PART II.

# THE CHEMISTRY, METALLURGY, AND USES OF TUNGSTEN

BY MINER LOUIS HARTMANN

# PART II.

# CHEMISTRY, METALLURGY AND USES

## CHAPTER V.

### HISTORICAL

The element tungsten has probably had more names than any other element. In literature it has been designated by the words "wolfram", "woolfram", "wolframium", "wolferan", "wolfart", "wolfort", "wolfrig", "scheelium", "tungsteen", and "tungsten". Even today the metal is called by the names wolfram and tungsten, altho the latter is preferred.

The minerals of tungsten, especially those associated with tin ores, were known many years before the element had been discovered. The Cornish tin miners knew wolframite as an "obnoxious" ore because "it eats up the tin as the wolf eats up the sheep." (A. Gurlt, Trans. Am. Inst. Min. Eng. 22, 236, 1893.) The minerals were also known in the tin mines of Saxony and Bohemia. The Germans named it "wolfert", "wolfart" or "wolfrig", from which the present name of the mineral is derived.

The name "tungsten" is of Swedish origin, meaning "heavy stone". It was originally applied to calcium tungstate (our scheelite), on account of its high specific gravity.

The discovery of the metal has been claimed for both Scheele, the famous Swedish chemist, and for the Spanish d'Elhuyar brothers. Scheele undoubtedly first discovered (in 1781) that the mineral then known as "tungstein" (scheelite) contained a new element. According to the published accounts, the d'Elhuyar brothers were the first to isolate the metal. However there is good evidence to show that the work of these Spanish chemists was along lines laid down by Scheele, for they undoubtedly worked under the direction of Scheele and Bergan for several years. In fact they made no claim in the published account of being the discoverers of the metal, which indicates further that Scheele had probably already prepared the metal. They made the metal by reducing the oxide with carbon. They also described some alloys of tungsten with gold, silver and lead.

Tungsten was considered a rare element with no practical use until about 1850, when some investigations were made to determine its commercial utilization, especially in steel alloys. Some tungsten steel was made and used, but it was not until Hadfield, in 1903, reported the results of extensive tests of tungsten steel, that the industry developed to any great extent.

The use of tungsten in metal filament lamps brought the element before the public, although the amount of tungsten used for this purpose is very small compared to the quantity used in alloy steel. The history of the development of the tungsten steel and the tungsten lamp industries will be discussed more fully under those titles.

## CHAPTER VI.

# PREPARATION OF METALLIC TUNGSTEN AND FERRO-TUNGSTEN

Most of the tungsten used in the industries is made either in the form of tungsten powder or as an iron alloy containing a high percentage of tungsten (ferro-tungsten). In recent years about 90 per cent of the tungsten has been used as ferro-tungsten and 10 per cent as tungsten powder.

Working details of the processes at present used for making tungsten powder and ferro-tungsten are not available in the literature, and much of the information is carefully guarded at the plants. It is therefore impossible to give a detailed account of the methods. However certain general facts are well known concerning the various operations.

### Decomposition of Wolframite

**Sodium Carbonate Fusion Method.** The process of decomposing the ores most generally used in making tungsten metal and tungsten compounds is the sodium carbonate fusion method. This was patented in 1847 by Oxland and is still used with only slight changes. The ore or concentrate—usually wolframite (The term wolframite will be used here for iron-manganese tungstates) is finely pulverized and mixed with soda ash (sodium carbonate) and a small amount of sodium nitrate. The mixture is charged into reverberatory furnaces on a hearth of dolomite. After the mass is sintered (not fused) it is drawn out and crushed. In some plants it is sintered again, in order to make the extraction of tungsten more nearly complete. The sintered mass in either case is leached with hot water in filter tanks. The tungsten dissolves as sodium tungstate ($Na_2WO_4$) while the iron, calcium and most of the manganese remain insoluble. Some silicic acid and phosphoric acid also dissolve in the form of the complex silico-tungstates and phospho-tungstates. Some sodium manganate is formed in the presence of the nitrate during the fusion, and this also dissolves, but its presence is not objectionable in most cases. The manganese may be easily removed at a later stage in the process.

The silica and phosphorus are removed by converting the normal sodium tungstate into sodium para-tungstate. This is accomplished by adding to the boiling solution of the normal tungstate ($Na_2WO_4$) (which contains an excess of alkali carbonate) enough hydrochloric acid to give a neutral solution. On cooling, large tri-clinic crystals of sodium para-tungstate ($Na_{10}W_{12}O_{41}28H_2O$) precipitate out. These crystals are known in commerce as "tungstate of soda." The silico-tungstates and phosphotungstates of sodium are more soluble and remain in the mother liquor. To recover the tungstic acid remaining in the solution calcium carbonate is added, which gives a precipitate of calcium tunstate. This precipitate can then be treated as scheelite by one of the methods described below.

The para-tungstate can be transformed back into the normal tungstate by the addition of sodium hydroxide solution. Tungstic acid can be obtained from the boiling solution by adding to it hydrochloric acid. It is important to pour the tungstate solution into the acid rather than the acid into the tungstate. In the latter case, there will be formed para-tungstate which is only decomposed into the free tungstic acid by long boiling with hydrocloric acid. The tungstic acid is separated by filtration, washed, and ignited to tungsten trioxide ($WO_3$) and is then ready for reduction to the metal.

**Soda Solution Method.** The tungsten factory at Lutin, England (in 1915) decomposed the wolframite by boiling the finely ground ore with a solution of soda, whereby sodium tungstate is formed. The tungstic acid is precipitated by hydrochloric acid, and the oxide formed by ignition of the dried tungstic acid. (The only description of this process found in the the literature is in Mineral Industry 1915, page 702).

**The Aqua Regia Method.** The ore, if very finely ground, may be decomposed by boiling with nitric and hydrochloric acids (aqua regia) and evaporating to dryness. This gives insoluble tungstic acid (or the trioxide depending upon the temperature of drying), and most of the impurities are in the form of insoluble salts, except silica, columbic, tantalic and metastannic acids. The soluble salts are washed out and the residue treated with ammonia, which dissolves all of the tungsten as ammonium tungstate and part of the columbium, tantalum and tin as ammonium columbate, tantalate and stannate. On concentrating the solution, ammonium tungstate crystals separate out and on igniting, are decomposed into ammonia and tungstic oxide. The small quantities of columbium and tantalum are usually not harmful, at least in metallurgical operations, but they may be removed if desired by treating the oxides with ammonium sulfide, which dissolves the tungsten but not the columbium and tantalum. The tungstic oxide is then recovered by making the sulfide solution acid with hydrochloric acid and igniting the precipitated tungstic acid.

**Carbon-Tetrachloride Method.** A process for the decomposition of tungsten ores by means of carbon tetrachloride was patented in 1914 by Jannasch and Leiste (German Pat. 266,973). The ore is heated in a current of carbon tetrachloride vapor and the tungsten chlorides distilling over ore decomposed by means of mineral acids.

**Bi-sulfate Method (especially for tin-bearing ores.)** When tin is present in appreciable quantities, it must be removed because of the brittleness which it imparts to steel. If present in large quantities, it is of course valuable for itself, and in this case it must be free from tungsten. Magnetic separation of the wolframite from the cassiterite has been used quite successfully, but rarely gives a separation with less than one per cent tin oxide with the wolframite.

The tin bisulfate method (1233) described below has been successfully used for the decomposition of tin-bearing tungsten ores.

The ore is decomposed in a muffle furnace, the hearth of which is made with silica agglomerated with pitch. Potassium acid sulfate is fused in the furnace with the doors closed. After complete fusion, the finely ground ore is thrown in, the mass stirred continually and the temperature gradually increased until the mass is fluid enough to run out of the furnace. After solidification, the fusion is ground up and treated with water which dissolves the soluble sulfates and phosphoric acid and leaves insoluble potassium acid tungstate as a white amorphous precipitate. The compound is insoluble only in the presence of an excess of acid, so that about 50 per cent excess of bisulfate over that theoretically required, is used to decompose the ore. The insoluble portion contains besides the tungsten compound also silica, cassiterite and the insoluble sulfates. It is dried and treated with a warm solution containing ammonium carbonate, or with cold water into which is passed ammonia and carbon dioxide. Under these conditions, the potassium acid tungstate dissolves, leaving the silica, and cassiterite and the insoluble sulfates. The solution is evaporated to crystallization, which gives ammonium tungstate $5(NH_4)_2O.12WO_3.nH_2O$ where "n" is from 11 to 5 according to the temperature of evaporation. When heated in contact with air, the salt gives off ammonia and water leaving tungstic oxide.

If a purer tungstic acid is required as for chemical uses, the ammoniacal solution is treated with hydrogen sulfide, to form ammonium sulfo-tungstate. This salt is only slightly soluble in cold water and deposits as orange red crystals. On heating, the trisulfide ($WS_3$) is formed, which changes to the trioxide on roasting.

If sodium bisulfate with an excess of sulfuric acid is used in place of the potassium salt, a solution of sodium acid tungstate is obtained. This solution contains the soluble sulfates of the other metals present. These may be precipitated by electrolysis. The resulting solution is evaporated, the sodium sulfate separates and is removed. The tungstic acid is then precipitated by hydrochloric acid, and this on ignition gives the trioxide. This process was patented in Germany in 1902. (149,556).

## Decomposition of Scheelite

**Acid Method.** Scheelite is easily decomposed by heating with concentrated hydrochloric acid or nitric acid giving calcium chloride or nitrate and tungstic acid. This, after washing and heating, gives crude tungstic oxide. If a purer oxide is desired, the washed but not ignited precipitate, is dissolved in ammonia and ammonium carbonate solution. The ammonium tungstate may be crystallized out. Ignition of these crystals gives tungstic oxide.

**Alkali-Fluoride Method. (1233)** Scheelite may be fused in a reverberatory furnace with potassium fluoride, producing soluble potassium tungstate and insoluble calcium fluoride, which are easily separated. The solution of tungstate is then decomposed with hydrochloric acid, and the tungstic oxide obtained by ignition.

### Reduction of Tungstic Oxide to the Metal

**By Carbon in Crucibles.** The yellow oxide of tungsten ($WO_3$) can be reduced by heating with carbon or carbonaceous materials in crucibles. Slightly less than the proportion of carbon (coke, anthracite coal or charcoal) theoretically required for the reduction of the metal with the formation of carbon monoxide, is intimately mixed with the powdered tungstic oxide. The crucibles are then covered and heated to high temperature, which causes the reduction to metallic tungsten. On account of the very high melting point of tungsten, the metal does not fuse but remains as a fine gray powder mixed with coarser crystals and some unreduced or partly reduced oxide. The coarse crystals are separated by washing out the fine particles which are added to the next charge.

By careful control of operations this process can be used quite successfully. A number of plants in the U. S. are using it, with possibly some modifications. High Speed Steel Alloys, Limited, at Widnes, the English company which was organized to supply the English steel works with tungsten after the outbreak of the war, uses this method. The tungstic oxide powder, produced by the sodium carbonate fusion method, is ground with anthracite coal and charged into crucibles, which are then heated in coke and producer gas furnaces for 24 hours. The crucibles are allowed to cool for 12 hours before opening in order to prevent oxidation. The product is a heavy chocolate colored powder, running about 98½ per cent tungsten metal. This is claimed to be at least one per cent better than the tungsten powder supplied by German producers before the war (77).

**By Carbon in the Electric Furnace.** The oxide can be reduced directly in the electric furnace by means of carbon. This was the method used by Moissan (40) (46) (49). The metal is readily obtained in the melted form but Moissan found that it could be produced free from carbon if the heat was not allowed to actually melt it. According to Gin, fused tungsten containing not over two per cent carbon can be made in the electric furnace by using a little less carbon than is required for the production of carbon monoxide with the oxygen of the tungstic oxide. An intermediate electrode consisting of a trough filled with tungsten is used between the two main electrodes. There is formed at the contact of the fused slag of tungstic oxide with the metal an upper reduction zone and a lower oxidation zone, which gives better purification. Considerable loss is caused by volatilization of the oxide of tungsten at the high temperature. This may be recovered in the flue dust along with any fine particles carried over mechanically by the gases.

If the metal is produced in melted condition in the ordinary electric furnace, it can be decarburized by the methods given later, producing high grade ferro-tungsten.

**Reduction by Aluminum.** Powdered aluminum easily reduces tungstic oxide. The method of Goldschmidt (53) is quite simple. An intimate mixture of the oxide and powdered aluminum is charged into a crucible, and ignited by a fuse of sodium or barium peroxide mixed with some aluminum powder. On account of the excess heat of formation of aluminum oxide over that of tungsten oxide, the aluminum takes the oxygen from the tungsten and liberates the free metal. A slight excess of tungsten oxide is used because otherwise some aluminum tungsten alloy forms and dissolves in the metallic tungsten and impairs its value for metallurgical work. The slight excess of tungstic oxide forms an aluminum tungstate of unknown composition, which goes into the slag.

A modification of the Goldschmidt aluminum reduction process has been made by Voigtlaender (French Patent, 455,313 [1914] ). The mixture of tungstic oxide and aluminum is brought to high temperature by external heat, so that after the reduction reaction, the temperature will be high enough to melt the tungsten produced.

While the aluminum process is easy to carry out, its use is limited by the high cost of the aluminum. Theoretically 184 parts by weight of tungsten require 54 parts of aluminum, and at the present price of aluminum, the carbon and electric furnace methods are very much cheaper. In addition, the losses of tungsten in the slag are said to be excessive.

**Reduction by Silicon Carbide.** This process was patented by F. M. Becket in 1907. The process involves the reduction in two stages, the first by carbon and the second by silicon carbide. The first charge is heated in an electric furnace with carbon and reduced to a lower oxide. Silicon carbide is then added and complete reduction is effected. Metallic tungsten with low carbon content is thus obtained. (U. S. Pat. 858,329).

**Reduction by Boron and Silicon.** Becket has also patented a process for reducing tungstic oxide by means of metallic silicon and metallic boron in an electric furnace. The product is said to be very low in carbon. (U. S. Pat. 854,018; 930,027; 930,028).

**Reduction by Zinc.** Tungstic oxide can be reduced by heating with metallic zinc in an inert atmosphere. The excess zinc is removed by volatilization and the zinc oxide dissolved out with a solution of sodium hydroxide. The method is not used commercially.

**Reduction by Gases.** Very pure tungsten powder can be produced by reducing the purified oxide by hydrogen, carbon monoxide, or other reducing gases. Hydrogen is considered the best and this method is used for production of tungsten metal for electric lamp filaments. This process will be described in detail in the following section on the manufacture of ductile tungsten.

## Preparation of Ductile Tungsten.

Until about 1909, tungsten was known and described as a hard, brittle metal which could not be mechanically worked into shape. In connection with the manufacture of the tungsten electric lamp filaments, search was made for a method of producing tungsten in a ductile form so that it could be drawn into wires. It was found that by properly heating and working, tungsten loses its crystalline character and can be drawn into the finest wires.

For this purpose, a very pure tungsten powder must be produced. The tungstic oxide as made by any of the above described processes contains too many impurities from the ore, such as iron, manganese, silica, molybdenum, phosphorus, arsenic and sodium salts. Two methods of purification are used, either (1) the solution of the oxide in ammonia and the precipitation of tungstic oxide with hydrochloric acid, or (2) the solution of the oxide in ammonium and recrystallization and decomposition of ammonium paratungstate. Still greater purity can be obtained by using a combination of the two methods.

The pure tungsten oxide then obtained is reduced usually by hydrogen. Carbon may be used, but the process is difficult to control. The physical state of the powdered tungsten produced is quite important as a factor in the ductilization of the metal. The powder must also be free from carbon or oxygen.

The reduction by hydrogen is most generally used because the process is easily controlled. Electric resistance tube furnaces are used for the reduction. The powdered oxide is placed in boats and the current of pure, dry hydrogen passed thru the tube at a regulated rate. The temperature is gradually brought up to about 1100° C. The rate of heating and the rate of hydrogen flow effect the properties of the reduced metal. If properly regulated, the product is a gray, amorphous powder.

The dry tungsten powder, without a binder of any kind, is placed evenly in a heavy mould and pressed under very great pressure into a bar about 0.5x0.5x15 centimeters. This fragile bar is placed in an electric resistance furnace and heated to about 1300° C, which causes a slight sintering of the tungsten particles.

The bar, which can now be handled without danger of breakage, is clamped between two water-cooled clamps, and a water-cooled cover is placed over it, in order to maintain an atmosphere of hydrogen around the bar. A heavy electric current is passed through the bar for a few minutes, which heats it almost to the melting point (3200° C.). The bar is now thoroly sintered, but it is not ductile. The bar is next heated to 1500° in a resistance furnace thru which hydrogen is flowing. It is then rapidly transferred to the swaging machine, hammered a few times, reheated and swaged until a bar long enough to be fed thru the machine by rolls is obtained. After this it is drawn thru a gas furnace to heat it before going into the machine. The temperature is gradually decreased and when the diameter of the wire is about one millimeter (30 mils) the tungsten has become ductile at ordinary temperatures.

From this size down to the fine wires used in tungsten lamp filaments, the wire is drawn thru diamond dies. At first the temperature is kept at about 600° C, gradually decreasing as the wire becomes smaller. The steps between the dies are gradually decreased from one mil between thirty and fifteen mils, to one-twentieth mil decrease per step below fifteen mils. Wire as small as .0004 inches in diameter has been drawn. This is about one seventh of the diameter of a human hair (.003 inch) and only about twice the diameter of a strand of spider's silk (.0002 inch).

It has been found that a small amount of thorium oxide (less than 1 %) added to the tungsten oxide before reduction, causes the product to be much more ductile. This is probably related in some way to the use of metallic thorium in tungsten filaments to prevent recrystallization.

The effect of the thorium oxide in increasing the ductility of tungsten is not thoroly understood. According to the theory advanced by Jeffries and Fahrenwald, (327, 328, 329) from their studies of crystal growth in metals, the thorium oxide accumulates at the boundaries of the crystals of tungsten during their formation, and prevents their growth. In most cases the presence of a foreign substance would produce weakness in the mass, but in the case of tungsten, the thorium oxide seems to be in such form that it not only prevents crystal growth, but also maintains the strength of the mass.

The operation of hot forging also tends to reduce the size of the crystals, thus changing the brittle, coarsely crystalline material to ductile, very finely crystallized tungsten.

The ductile and malleable tungsten can be made into other forms by hot forging. Such articles cannot be shaped by machining when cold because of the hardness of the cold metal. Tungsten can be melted and cast into shape, but under these conditions it is very hard and brittle, and is limited in its applications.

## Manufacture of Ferro-Tungsten

Ninety percent of the tungsten extracted from the ores goes into high tungsten alloys with iron, which are known as ferro-tungsten. The proportion of tungsten in these alloys varies from 50 to 85 percent.

Ferro-tungsten before the War was produced almost entirely in Germany. Since then the number of ferro-tungsten plants in the U. S. and in England has increased greatly. "The Hudson Reduction Co. at Latrobe, Pa., operated in 1916 33 electric furnaces for making the alloy and the metal. The Primos Chemical Co., greatly increased its capacity; the Chemical Products Co., completed a large reduction plant near Washington, designed particularly for the treatment of lower-grade concentrates; The Tungsten Products Company of Maryland began operating a new plant early in January 1917 for making ferro-tungsten—using small electric furnaces; The Manhattan Reduction Co., also produced metal. In France there are important works, e. g. those of Girod; Schneiders, Chamoux, Keller, and Leeux, and the Froges and Giffre works. In England, the Thermo-Electric Co., at Luton, the High-speed Steel alloys, Ltd., at Widnes, the Continuous Reaction Co., at Hyde, the British Thermit Co., at Yarston, and a number of others." (C. G. Fink, Mineral Industry 1916, p. 742).

**Production of Ferro-tungsten by Reduction With Carbon in Crucibles.** One method which has been used to some extent for making ferro-tungsten is the reduction of tungsten ores by carbon in crucibles. The concentrated ore is placed in a clay-lined crucible, together with a suitable flux and coke or charcoal and the whole heated in a gas fired furnace, together with the correct proportion of iron or steel scrap. For a thirty percent tungsten alloy, the crucibles will last about three heats, but for a 65 to 75 percent product, they last but one heat. Most of the ferro-tungsten was made by reducing tungstic oxide and iron in crucibles up until the introduction of the electric furnace about 1900. This method is still used to a small extent. (275).

**Production of Ferro-tungsten by Alumino-thermic Method.** Ferro-tungsten can be made by reduction of wolframite, ferberite or scheelite with aluminum. Rossi (207) reduced ferberite with aluminum in a Sieman's type electric furnace, and obtained an alloy containing 75.9 percent tungsten, 21.4 percent iron, 1.6 percent silicon, .08 percent sulfur and .9 percent carbon.

The ores and tungsten trioxide may also be reduced by the use of aluminum as the reducing and heating agent, as in the regular "Thermite" reaction. The oxygen for the burning of the aluminum is furnished by the oxides of the metals in the ore. The requisite amounts of tungstic oxide or concentrates and aluminum powder are mixed in a magnesia crucible and ignited in the usual way by a fuse of sodium or barium peroxide and aluminum powder. The ferro-tungsten which is formed is almost free from carbon, but may contain aluminum, unless there is a slight excess of ore or tungsten oxide. The percentage of tungsten in the ferro-tungsten produced depends upon the amount of iron .present, either in the ore or as added hammer scales. The product will contain any other reducible metals such as copper, manganese etc. which may be present in the ore.

**Preparation of Ferro-tungsten by the Silico-thermic Method.** Gin has produced ferro-tungsten by the reduction of scheelite or artificial calcium tungstate by 20 percent ferro-silicon, in an electric furnace, with two contiguous hearths in series, having ferro-silicon electrodes and an intermediate electrode of fused ferro-silicon. Upon the melted bath of ferro-silicon is placed scheelite, which melts, the silicon oxidizes at the expense of the tungstic oxide and forms a slag of calcium silicate, while the iron unites with the tungsten to form ferro-tungsten. A small amount of silicon goes into the alloys. (1233)

**Direct Reduction of Tungsten Ores in the Electric Furnace.** The most common method for the production of ferro-tungsten is by the reduction of tungsten ore concentrates in the electric furnace with carbon as a reducing agent. This product usually contains more carbon than is desired for the manufacture of alloy steels, and must be decarburized (see below). Ferberite, wolframite and huebnerite are easily reduced by this method, but scheelite is more difficult, because of sticky, basic slags. Manganese is either volatilized or goes into the slag. (275)

The furnaces used are usually of the intermittent tilting type. The reduced charge is tapped from the furnace and cast in molds or allowed to solidify and then broken out of the furnace. (275)

In experiments conducted by Keeney, (269) (275) a flux of lime and fluorspar was used with Colorado ferberite and iron ore. After the reduction reaction was complete a decarburizing slag of iron ore lime and fluorspar was added to the furnace and allowed to act for ten to twenty minutes. The percentage of carbon in this product was kept below 2 percent, and the amounts of phosphorus, silicon, manganese, and sulfur which went into the ferro-tungsten were small. Four to eight percent tungsten was lost in the slags.

Ferro-tungsten as made in the electric furnace, contains from 50 to 80 percent tungsten. One dealer in ferro-tungsten guarantees his product to contain 72-78 percent tungsten, and not over .07 percent sulfur, 0.06 percent phosphorus, 1.0 percent carbon, .75 percent silicon.

In 1912, it was reported (264) that the Ampere Company of Berlin was employing a process of reducing scheelite directly from the ore in the electric furnace with sulfide of iron as flux and carbon as the reducing agent. Ferro-tungsten with low carbon content was produced. The silica contained in the scheelite was fluxed by the addition of lime. The slag was easily fusible. Further information concerning the process seems not to be available.

**Decarburization of Ferro-tungsten and Cast Tungsten.** As stated above, the carbon content of ferro-tungsten must be kept as low as possible for the manufacture of alloy steels. As made by reduction with carbon, either in crucibles or directly in the electric furnace, both ferro-tungsten and metallic tungsten usually contain more than the desired quantity of carbon. The common practice seems to be to reduce the carbon content in the electric furnace after reduction has taken place, by means of a decarburizing slag as explained above.

Tungsten metal produced by the carbon reduction in the electric furnaces may be high in carbon. The carbon content can be reduced by adding either tungstic trioxide, tungstic dioxide, hammer scale, or iron oxide. It is necessary in the case of tungsten metal to add metallic iron before decarburizing. Using iron oxide, the carbon content can be reduced as low as 0.15 percent. (275) (278[a])

The electric furnace with melted electrodes may also be used. The carburized tungsten is cast into electrodes which are used in the furnace with contiguous hearths, using a soft steel intermediate electrode. The bath above the metal is of tungsten dioxide and magnesium aluminate. The electrodes melt and their carbon is burned out by the tungsten dioxide. The resulting alloy will contain not more than 0.15 to 0.25 percent carbon. The oxidation of the carbon by oxide of iron results is the formation of tungstate of iron which entails losses; the amount thus formed may be reduced by adding silica, in order to form ferrous silicate. (1233)

(Dephosphorization of ferro-tungsten.) Ferro-tungsten can be dephosphorized by the method of Becket (U. S. Pat. 1,081,569). The solid ferro-tungsten in finely divided form is fed onto the surface of molten basic oxidizing bath, for example of scheelite and lime, maintained at a temperature equal to or higher than the melting point of the ferro-tungsten.

(Quality of ore demanded by users.) The following quotation from bulletin No. 652 of the United States Geological Survey "Tungsten Minerals and Deposits" by Frank L. Hess gives the results of his extensive inquiry into the quality of tungsten ores demanded by the consumers in the United States.

> Inquiries were addressed by the Geological Survey to firms known to be reducing tungsten ores, asking what, for their purposes, was the relative desirability of the tungsten ore minerals, the impurities most hurtful, and the limiting percentages of impurities that would be accepted.
>
> Eight firms courteously gave the desired information in considerable detail, and another with less detail.
>
> Of these firms, one reduces its ores by sodium carbonate ($Na_2CO_3$), leaching with water separating tungsten trioxide by hydrochloric acid, and reducing the trioxide to a metallic powder; two reduce the ores by other wet chemical processes; two use both the sodium carbonate fusion process and direct reduction in an electric furnace; two use an electric furnace only; one uses processes in which the ores are first treated with wet chemicals and reduction is then completed in an electric furnace. Another firm, the Crucible Steel Company, has in use a number of processes, part of which are covered by the Johnson patents.
>
> By the sodium carbonate fusion process, only powdered metallic tungsten is obtained. One of the other wet chemical processes produces powdered tungsten, and another makes powdered ferro tungsten. The electric furnaces produce only ferro-tungsten.
>
> Most of the processes used for reducing tungsten from its ores also partly or wholly reduce nearly all the metallic and some other impurities in the ores, and these impurities are carried with the tungsten into the steel to which it is added. For such use iron makes no difference, but a number of other elements are not wanted, either because like copper and phosphorus, they are detrimental to the steel, or because, like manganese, if they are wished in the steel, they can be added more advantageously in some other way. Objectionable impurities found in tungsten ores are antimony, arsenic, bismuth, copper, lead, manganese, nickel, tin, zinc, phosphorus and sulfur. Few of these occur in large quantity in ores found in this country. Copper is perhaps the commonest hurtful impurity, and therefore most is said about it, but ores from some foreign countries contain nearly all the impurities mentioned. During the early part of 1916 tungsten ores were so eagerly sought that nearly all offered were bought with little objection to impurities, but under more normal conditions consumers are much more particular.
>
> The wet chemical processes give more opportunity to get rid of

most impurities than the electrolytic process so that companies using wet chemical processes are, as a rule, though not uniformly, least particular about the ores they buy. Two of the firms that use wet chemical processes buy tungsten ores almost without regard to the impurities present, but one objects to more than two percent copper, and both buy ores containing as little as twenty percent tungstic oxide.

Only the one firm mentioned is known that does not object to copper in any grade of ore. Another will take cupriferous ore if "the content of $WO_3$ is sufficiently high". The others either will not take copper bearing ore, when other ores are to be obtained or set limits of 0.2 to 2.0 percent copper, and not less than 50 percent $WO_3$, except that one firm will take ores that carry five percent or more copper, for such a percentage will pay for separation.

Two companies take ores without regard to impurities other than copper, provided the content of $WO_3$ is sufficiently high. Most of the companies object to tin, sulfur, phosphorus, antimony, arsenic, bismuth, lead, and zinc, two of them object to manganese, and one to nickel. The last company referred to set extreme limits of 0.25 percent for phosphorus, 0.25 percent for nickel, 6.0 percent for manganese, and a trace of arsenic.

As to the different tungsten ore minerals—ferberite, wolframite, huebnerite, and scheelite—two companies using wet chemical processes reported that they made no discrimination; a company using both processes reported that it made no discrimination if the ores carried more than 60 percent $WO_3$; one company uses ferberite and scheelite and will not use wolframite or huebnerite; another prefers scheelite but will take any tungsten ore mineral; a user who does not make steel and whose product does not enter into steel also prefers scheelite. Three others gave their estimates of the comparative values as follows (the estimate being stated in the same order): if ferberite can be bought at $7 per unit then wolframite is worth $7, $6.30, $6.25; Huebnerite, $6.50, $5.60, $6.25; scheelite $6, $6.60, $6.50.

So far os can now be learned, the foreign buyers are quite as various in their demands as the domestic users, and are in general more strict in the limits set, and they also demand a purity of 65 to 70 percent $WO_3$, which means loss in concentration, for ores cannot ordinarily be concentrated to so high a percentage without great waste in slimes.

Brokers are naturally ruled by the consumers to whom they sell and make the same restrictions as to quality of the ores bought.

From the very different ways in which the ores are valued by different buyers, it will be seen that in general, a seller should know the market well, especially what the different buyers will pay before disposing of his product. (915a)

(Chemical Treatment of Impure Ores.) Several processes have been devised and patented for decreasing the quantity of the objectionable impurities in ores from certain localities.

Wolframite concentrates from parts of Arizona and Bolivia contain impurities which are severely penalized by ore buyers. Baughman (76) has used chemical treatment to remove these objectionable impurities. The concentrate is digested in strong hydrochloric acid containing nitric acid for four hours, or until manganese and iron are in solution, using steam for heating and agitation. The solution is filtered off and the gold and bismuth precipitated by passing in hydrogen sulfide gas. The solution is then evaporated to dryness in a retort into which is charged solid ferrous chloride collecting the hydrochloric and nitric acid distillate in a coke tower. The residue is leached with strong sodium chloride solution to dissolve silver, and the silver precipitated by passing the solution over scrap iron. The residue in the digester is washed with hot water, the tungstic acid dissolved in ammonia, and the solution evaporated to obtain ammonium tungstate which is 99 percent pure. The cost of the treatment is claimed to be considerably less than the difference in market value of the pure and impure products.

Becket has patented several processes particularly for removing phosphorus and manganese from tungsten ore. The ore or concentrate is first subjected to a reducing action by heating with carbon, hydrogen carbon monoxide, producer gas, or other reducing gas below the melting point of the product. This reduced product is treated for the removal of some manganese and phosphorus by adding an excess of sulfuric acid (1.2 sp. gr.) and allowing to stand for 24 hours, with frequent stirring. The solution is drained off and used for further treatment of ores. Seventy percent of the manganese is removed and also much iron and phosphorus, and a corresponding concentration of the tungsten. The product is now melted in an electric furnace with or without carbon or reducing agent, depending on the completeness of the first reduction, giving directly a commercially available metal or ferro-alloy.

Certain ores may be treated directly with concentrated sulfuric acid. The ore is first ground to 100 mesh and treated with excess of acid. Thirty to ninety percent of the phosphorus and less than one percent of tungsten goes into solution. High phosphorus ores do not respond to this simple treatment. These ores are first given an oxidizing roast and then reduced and treated as above. Good results are claimed.

Mixed acids and oxidizing solutions are also used. If the ore is deposited near an inert anode (for example, lead in sulfuric acid), the solvent action is improved. If the purified ores are smelted in the electric furnace with silicon as a reducing agent, the product is low in both carbon and phosphorus. (U. S. patents 1,081,568; 1,081,570; 1,081,571; 1914).

In a later patent, Becket recommends treating the ore (in this case scheelite) with concentrated sulfuric acid at red heat, whereby phosphorus goes into solution, and tungsten remains insoluble. (U. S. Patent 1,153,594; 1915).

## CHAPTER VII.

# PROPERTIES OF THE METAL

### Physical

Tungsten is ordinarily obtained as a powder or semi-fused crystalline, brittle metal harder than glass and having a specific gravity between 16 and 17. That obtained by Moissan in the electric furnace has a specific gravity of 18.7 and was softer than glass.

The properties of pure ductile tungsten are entirely different from those of the powdered or cast metal. The hardness varies from 4.5 to 8 (razor steel is about 6), depending on the manner of working. The hardest will readily scratch topaz. The density of the pure wrought tungsten ranges from 19.3 to 21.4, depending on the mechanical treatment of the metal. For comparison, aluminum has a density of 2.7; iron 7.8; lead 11.4; gold 19.3. Only three other metals have a higher specific gravity, platinum 21.5, iridium 22.4, and osmium 22.5.

The melting point is higher than that of any other metal Langmuir gives it as 3267° C. (5913° F.) while Worthing determined it as 3357° C. The boiling point has been estimated at 3700° C., but this has not been determined directly. The vapour pressure of tungsten at 2000° C. is 6.45x10—12 mm. (of mercury) and 1.14x10—3 mm. at 3100° C.

At 1227° C. the conductivity was found to be 0.98 watts per cm. per degree centigrade. The specific heat was 0.04 to 0.05 between 1600 and 2200° C. (114)

The following table compiled by C. G. Fink (Mineral Industry 1914) gives a number of the physical properties of the common metals and tungsten.

**Physical Properties of Aluminum, Copper, Nickel, Iron and Tungsten.**

| | Density at 18° C. | Coefficient of expansion at 18° C. | Tensile strength in pounds per square inch. | Modulus of elasticity in pounds per square inch. | Specific heat in calories, 1 gram -1°C. | Melting point in °C. | Electric resistance in microhms per cubic centimeter. |
|---|---|---|---|---|---|---|---|
| Aluminum ........ | 2.7 | 21.8 by $10^{-6}$ | 43,000 | 10 by $10^{-6}$ | 0.214 | 660 | 2.62 |
| Copper ........... | 8.87 | 15.9 by $10^{-6}$ | 66,000 | 19 by $10^{-6}$ | .091 | 1,083 | 1.589 |
| Nickel ............ | 8.75 | 12.7 by $10^{-6}$ | 96,000 | 29 by $10^{-6}$ | .106 | 1,453 | 6.93 |
| Iron .............. | 7.8 | 11.2 by $10^{-6}$ | 450,000 | 30 by $10^{-6}$ | .105 | 1,600 | 8.85 |
| Tungsten .......... | 19.6 | 3.5 by $10^{-6}$ | 610,000 | 60 by $10^{-6}$ | .034 | 3,267 | 4.42 |

Note.—The figures given for iron in the third and fourth columns are for high tensile strengtn steel. Of the figures for tungsten those showing specific heat are given by Honda, those showing the melting point by Langmuir; the others were determined by Fink.

Tungsten becomes more ductile and malleable after being heated and hammered. It increases in tensile strength during the process. When properly treated, it can be drawn into wires, having a diameter of only .0004 inch or about one-fifth of the average diameter of a human hair.

## Chemical Behavior

Tungsten is unaffected by air or oxygen at ordinary temperatures. At red heat, it burns with incandescence in air or oxygen. Likewise water does not attack it below red heat, but above red heat the water is decomposed and the metal oxidized. It does not combine directly with nitrogen. Molten phosphorus and sulfur attack it slowly, and their vapors much more readily at red heat. When heated with carbon, silicon or boron in the electric furnace, it forms carbides, silicides and borides, which are bright metallic substances with great hardness. Fluorine attacks it at ordinary temperatures, with incandescence. Chlorine attacks it very slowly at ordinary temperatures, and quite readily above 250° C. The fine black powder dissolves readily in a mixture of ammonia and hydrogen peroxide. (149)

W. E. Ruder gives the following experimental results on the solubility of ductile and malleable tungsten. Tests were made on disks about 18 mm. in diameter and 2.5 mm. in thickness. The surface area was 650 sq. mm. on the average. The weight, according to thickness, varied from nine to twelve grams.

**Solublilty in Hydrochloric Acid.** Wrought tungsten is insoluble in hydrochloric acid of any concentration at room temperature and only very slightly so at 110° C. After 45 hours the hot concentrated acid (sp. gr. 1.15) showed no effect upon the tungsten. After 175 hours, however, a black coating of oxide formed and the metal lost 0.5 percent in weight.

In dilute acid, at 110° C., it lost 0.05 percent after 22 hours but showed no further loss after 50 hours. After 175 hours the metal was coated with tungstic oxide and there was a gain in weight of one percent due to oxidation. This oxide formed an adherent coating and protected the metal against further loss.

**Solubility in Sulfuric Acid.** At room temperature this acid has no effect upon wrought tungsten nor has the dilute acid at 110° C. Concentrated acid attacks it very slowly at 110° C., the loss in weight being 0.1 percent after eighteen hours, 0.16 percent after 40 hours, and 0.63 percent after 175 hours. Increased temperature hastens the action for at 200° C. 0.62 percent was lost in four hours. In another experiment 1.18 percent dissolved in 8 hours.

**Solubility in Nitric Acid.** Concentrated nitric acid at 110° C. showed no action on tungsten after 48 hours other than a slight dulling of the bright, metallic surface. The dilute acid, however, produces the yellow oxide on the surface. There is a slight gain in weight after 15 hours and then no further change even after 175 hours' immersion.

**Solubility in Aqua Regia.** Aqua regia, at room temperatures, oxidizes the surface to tungstic oxide. After 215 hours the loss in weight was 0.31 percent. At 110° C. the chlorine was all driven off in about four hours and the tungsten disk had lost 0.1 percent and it was covered by a tough, greenish yellow deposit. If this coating of oxide was allowed to remain, continued boiling in fresh aqua regia had no further effect upon the metal.

**Solubility in Hydrofluoric Acid.** The acid, hot or cold, did not attack tungsten, not even to the extent of dulling the surface, during numerous evaporations of the acid.

**Solubility in Potassium Hydroxide.** Potassium hydroxide solution, of any concentration, does not attack wrought tungsten, but the fused alkali attacks the metal slowly. In this case there was 31 percent loss in weight after 15 hours, and in about 40 hours the disk had all dissolved.

**Solubility in Alkaline Carbonate.** In fused sodium carbonate, potassium carbonate, or mixtures of the two, tungsten dissolves slowly. About 2.5 percent loss was noted in four hours. The addition of potassium nitrate hastens the solutions considerably. In this experiment 32 percent dissolved in six hours.

**Other Experiments.** A saturated sodium hypochlorite solution was found to attack tungsten at the rate of 4.27 percent in twenty hours. A mixture of sulfuric acid and chromic anhydride did not act upon the metal. A mixture of hydrofluoric and nitric acids dissolves tungsten very rapidly with the evolution of nitric oxide and the production of tungstic oxide.

## Atomic Weight of Tungsten.*

The anatomic weight of tungsten has been determined by numerous investigators. Schneider (152a) by the reduction of tungsten trioxide to the metal and oxidation of the metal to the trioxide found the average value 184.11, while Marchand (153b) found an almost identical value. Roscoe (527) by the same method obtained the number 183.48, and by the analysis of the hexachloride the number 184.02, while Waddell (155) by the reduction of the trioxide found the higher number 184.33. More recently Pennington and Smith and Desi (157) have found the still higher number 184.8 by Schneider's method, but their results have been criticised by Schneider (157a) as untrustworthy. The investigations carried out by Smith and Exner (163) who converted the hexachloride into the trioxide by the action of water and synthesized the trioxide from the metal, gave an average value for the atomic weight of 184.06. (1245) The accepted value at the present time is 184.0.

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*From Roscoe and Schorlermeyer, "Treatise on Chemistry."

## CHAPTER VIII.

## USES FOR THE METAL

### In Iron Alloys

**Introduction.** By far the greatest use of tungsten is as a constituent in steel alloys, especially in those known as high-speed steels. High-speed steels have revolutionized modern manufacturing industries. By means of tungsten steels (and other alloy steels) machines and lathes can be run at much higher speed, thus saving in both machines and men. The saving amounts to many millions of dollars a year.

As an illustration of the efficiency of high-speed steel and its effect on the price of a familiar product, it was stated by Mr. Ellwood Haynes of the Haynes Automobile Company that his company would be compelled to increase the selling price of each automobile about $200.00 if they should have to use carbon steel in place of high speed steel tools. The efficiency is from three to five times that of carbon steel for cutting tools.

The value of high speed steel not only depends upon the greater hardness, but also upon the fact that the tools can be used for cutting other metals at such a rate that friction raises the cutting point to over 500° C. (red heat) without injury.

**Historical.** It is a curious fact that the old Damascus steel, always celebrated for its retention of temper, has been found to contain both tungsten and chromium, altho probably not intentionally added.

The first attempts to produce tungsten steel were probably made in 1855 by Jacobs and Koeller in Austria. They obtained patents in France for its production. They noted the fine silky grain produced by tungsten upon iron in the presence of carbon.

Mayr in Styria is also credited with producing tungsten steel about this time on a commercial scale and it was claimed that his steel was equal to Krupp's steel.

Oxland in England took out patents in 1857 for the production of tungsten steel. In the same year Mushet patented several methods for producing it. Mushet did more than any one else to perfect tungsten steel. He manufactured tool steel for many years under the name "Mushet's metal", keeping his manufacturing methods secret. He must have overcome great difficulties for the alloys needed were obtained with great difficulty and were of uncertain composition. His steel contained from 7 to 12 percent of tungsten, from 1.5 to 2 percent carbon and about 2 percent manganese.

Other investigators worked on tungsten steel. In France in 1865, tungsten steel springs were made for railway cars but they did not possess any remarkable advantages. In 1868, steel rails were manufactured containing a small percentage of tungsten, but an unfavorable report was made on their use.

In 1886, Heppe, in Germany recommended tungsten steels for cutting tools of all kinds, as well as for rails, locomotive tires, axles, etc.

In 1900, high speed tool steels containing tungsten and chromium manufactured by Taylor and White at the works of the Bethlehem Steel Company were exhibited at the Paris Exhibition, and created a great sensation among those familiar with metal working. These tools, by suitable heat treatment, could be used for cutting up to a temperature of 300 C. without losing their cutting edge. This temperature would ruin any carbon steel tool. It was stated that a young machinist had lighted a cigarette with a newly cut chip, which was almost unbelievable at that time.

In 1903, Hadfield published the results of very extensive investigations of the properties of tungsten steels. Since then the investigation of alloy steels has added many varieties for many different uses.

### Manufacture of Tungsten Steel.

The following extract from Bulletin No. 100, United States Bureau of Mines "Manufacture and Uses of Alloy Steels" by Henry D. Hibbard, gives an excellent account of the manufacture and uses of simple tungsten steels, and high speed tungsten steels.

**Simple Tungsten Steel.** Tungsten steel is generally, if not always, made by the crucible process. The pots are charged cold by packing in the materials, the tungsten being placed at the top to counteract in a measure its tendency to settle because of its high specific gravity. If this tendency operated unchecked there might be at the bottom of the pot a rather infusible mush of high-tungsten alloy, which would not pour out, and if it did the ingot would have an irregular composition because of the uneven distribution of the tungsten.

The steel is melted and then "killed" in the crucibles by holding them in the furnace for 30 to 40 minutes after the charge has melted, until the steel ceases to bubble or work and lies dead in the pot.

The pots are sometimes cast singly or doubly by hand pouring or collectively by means of a ladle into which all of the pots of a furnace charge are emptied. Good tungsten steel makes remarkably sound solid ingots, except for the pipe, tho tungsten itself is not considered to aid in removing or controlling either the oxides or the gases. It is added solely for its effect on the finished and treated steel.

This lack of power of tungsten to deal with oxides and gases arises no doubt from its low calorific power, its heat of combustion being given (with qualification) as about 1000 calories, whereas iron burned to $Fe_3O_4$ gives 1,612 calories.

**Method of Working.** Simple tungsten steels of commercial grade are heated, forged and rolled in much the same manner as other high carbon steels, presenting no special problems or difficulties.

**Properties and Uses.** Simple tungsten steel is at present chiefly used in permanent magnets for electric meters, in small dynamos and hand use, for which it has been used for thirty to forty years. The consumption in 1913 is thought to have been between 5000 and 6000 tons. This steel contains about 0.6 percent carbon and 6 percent of tungsten. Some has been made in recent years containing 0.2 to 0.3 percent of vanadium, chromium, or molybdenum, which were considered at the time to give greater retentivity to the steel, but those ingredients are now generally held to be of no practical value, adding nothing to the fitness of the steel for its purpose.

Some buyers of magnet steel do not specify composition but only performance, that is, what magnetic properties the steel must have.

To make permanent magnets retain their magnetism as much as possible they are made very hard by heating and quenching. They are then magnetized, and if they are to be used for electric meters they are seasoned by a treatment involving protracted heating to 100° C. (212° F.) to make their magnetism as nearly constant as possible.

A variety of tungsten steel containing about 1 per cent of carbon and 3 to 4 per cent of tungsten is made and used as a tool steel for taking finishing cuts on iron and steel in the machine shop. It acts more like a simple steel than a self-hardening steel, as it requires to be hardened by quenching in water and then drawn in the same general way that simple steels have been drawn, presumably for thousands of years. It will cut at a higher speed than a simple steel, say 40 feet per minute on steel having a tensile strength of 80,000 pounds per square inch, and is also more durable.

The presence of tungsten in steel is generally stated to lower the fusion point of the steel. Mars (272) gives a table of fusion points of tungsten steels with contents of tungsten ranging from 0.5 to 17 per cent, from which he concludes that tungsten lowers the fusion point. However, when his results are corrected for the lowering effects of the contained carbon, silicon, and manganese doubt arises as to the correctness of his conclusion. Thus, a steel containing 0.66 per cent C, 0.03 per cent Si, 0.04 per cent Mn, and 3.11 per cent W fused at 1,488° C. The carbon would lower the fusion point about 60° C., and the silicon and manganese slightly, so that the plain iron-tungsten alloy should have a fusion point a little above 1,548° C., which is about 20° C. above that of pure iron. Seemingly this is the effect of 3.11 percent tungsten.

The erosion of the bore of cannon by the powder gases is held to depend largely on the fusion point of the metal of the tube or liner, the higher the point, the greater being the resistance to erosion. So it has been found that the nearer the metal comes of being pure iron, the higher its fusion temperature and the better it resists erosion, but the strength required compels a certain amount of hardening and strengthening elements to be present in the steel. Tungsten raises the strength and possibly the temperature of fusion and so has been employed for the tubes of cannon, particularly by the Government of Austria. Arnold and Read (280) found that steel with 0.71 percent carbon and 5.4 percent tungsten had in the annealed state the tensility of 88,900 pounds per square inch, an elastic limit of 60,200 pounds, an elongation of 20 percent, and a concentration of area of 34.7 percent, values that compare favorably with those of the steels usually employed in the manufacture of cannon.

They give data regarded a series of annealed tungsten steels as follows:

**Data Regarding Annealed Tungsten Steels**

| Composition | | | | | | | Tensile Properties | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| % C | % W | % Si. | % Mn. | % P. | % S. | % Al | Tensility Pounds | Yield Point Pounds | Elongation in 2 inches Percent | Contraction of area Percent | Condition when turned |
| 0.73 | 2.4 | 0.11 | 0.15% or less | 0.02% or less | 0.04% or less | 0.01% or less | 84,200 | 48,100 | 20.5 | 31.5 | Moderately tough. |
| 0.71 | 5.4 | 0.11 | | | | | 88,900 | 60,200 | 20.0 | 34.7 | Tough. (see note) |
| 0.70 | 9.7 | 0.04 | | | | | 126,100 | 90,000 | 14.0 | 22.1 | Very tough. |
| 0.73 | 15.0 | 0.03 | | | | | 98,500 | | 25.0 | 43.3 | Very tough. |
| 0.72 | 21.1 | 0.06 | | | | | 104,300 | 57,300 | 20.5 | 39.2 | Very tough and slightly hard. |
| 0.67 | 26.3 | 0.06 | | | | | 110,600 | | 9.0 | 11.4 | Ditto. |

Note:—Tough means that the lathe chips curled off in spirals.

The strength and hardness of these steels may be greatly increased by heat treatment, involving quenching and with only relatively small decrease in ductility.

**Theory of Tungsten Steel.** Arnold aud Read concluded that the carbon in the steels they examined was combined with iron when the tungsten was low, but that the higher the tungsten the more of the carbon was combined with it until in steel containing 11.5 percent of tungsten, none of the carbon was combined with iron, but all of it with tungsten. With still higher tungsten content the excess of tungsten was combined with iron.

**High-Speed Tool Steels.** High-speed tool steels, also called rapid steels have in the past fifteen years worked a remarkable revolution in the machine shop business of the whole world, affording largely increased outputs and commensurate lower costs. As a consequence they are now being used very generally and in some shops almost exclusively for machining iron and steel as well as some others by cutting operations by machine tools.

The revolutionary feature wherein tools made of these steels differ from and exceed in service the tools formerly used in their ability to maintain a sharp strong cutting edge while heated to a temperature far above that which would at once destroy the cutting ability of simple steel tool. Because of this property a tool made of high-speed tool steel can be made to cut continuously at speeds three to five times as great as that practicable with other tools, and when, as the result of the friction of the chip on the tool, it may be red hot at the point on top where the chip rubs hardest, and the chip itself may, by its friction on the tool and the internal work done on it by upsetting it, be heated to a blue heat of 296° C. (565° F.) or even hotter to perhaps 340° C. (644° F.)

This property of red-hardness or ability to retain hardness at a red heat may be imparted to steels of suitable composition, comprising chromium and tungsten, by the unique heat treatment to which they may be subjected. This treatment, described later, was introduced by F. W. Taylor and Maunsel White, as has been described by Taylor, (236) at the works of the Bethlehem Steel Co., in 1899, and the tools so treated were shown at the Paris Exposition in 1900, where they naturally created a sensation among those familiar with the machining of metals.

In this country in 1913 about 7000 tons of highspeed or rapid tool steel was made by some fifteen makers, that output requiring about 8000 tons of ingots.

**Manufacture of High-Speed Tool Steels.** High-speed tool steels are all made by the crucible or electric furnace process. Except at one works, the crucibles or pots are made of graphite. The average life of the crucibles or pots varies in different works from six to nine melts. Some makers use clay lined graphite pots in melting this steel to prevent or hinder the absorption of carbon from the pot. The clay lining is only one-eighth to three-sixteenth of an inch thick, and is sometimes cut through on the second or third melt; in that event the molten steel may absorb too much carbon. Other makers use a graphite pot twice—first for melting other kinds of steel and then for rapid steel when the inner surface of the pot is somewhat slagged over, because of which the absorption of carbon is much less that when the pot was new.

The large producers use gas-fired melting furnaces for heating the pots, which are charged into the furnace at the top. Each melting hole contains six pots and each pot takes a charge of 90 to 100 pounds. The charge is melted and then "killed" in the usual way by being held 30 to 40 minutes. Such procedure, together with the presence of the large amount of alloy, regularly gives sound piping steel. If run continuously a furnace full of pots will be melted about every four hours.

In packing a pot with the charge for rapid steel the tungsten must be placed on top of the charge—as with simple tungsten steel—to guard as far as possible against the tendency of the tungsten to settle because of its high specific gravity. That tendency seems to be less with the rapid steels than with the simple tungsten steels. Whether the chromium of the former influences or hinders the settle of the tungsten is conjectural.

The smaller ingots, which are made from one pot of steel, vary from 3.5 to 5 inches square. The steel is sometimes teemed directly into the mold by hand pouring, but in some works clay funnels are placed on top of the mold to direct the stream down the center of the mold to avoid cutting its wall, as might happen if the stream impinged directly on it. Funnel pouring is also advantageous when two pots are to be combined to make a larger ingot, as the steel can be poured into the funnel from opposite sides at the same time, a procedure that will mix the liquid steel and give a more uniform ingot than when one pot follows another, as in hand pouring when no funnel is used.

Some of the larger producers of rapid steels use for casting a large bottom-pouring ladle into which the steel is poured from the pots of one or more furnaces, and from which the ingots are top-cast; that is the molds are filled from the top. This method presents the advantages that (1) the product is more uniform; (2) the individual pot charges which might not be of the prescribed composition or might be otherwise unsatisfactory, are merged with the others without detriment to the whole; (3) large ingots are easily made; (4) one analysis serves for the whole number of pots; (5) one test serves for the whole ladleful of steel. It is a matter of experience that complaints from customers become much less frequent after the introduction of the ladle for casting this steel.

The strong tendency of rapid steel to pipe is checked considerably in most plants by the use on each ingot of a hot "dozzler", which is a clay ring preheated red hot, that is placed on the ingot top and filled with molten steel. This arrangement keeps the top of the ingot molten long enough so that the pipe is of diminished size and nearly or quite all contained within the part of the ingot surrounded by the "dozzler". The proportion of the ingot to be rejected on account of the pipe is therefore much decreased. The molds are usually closed at the bottom end and are either made with parallel walls or tapered so that the ingot is larger at the top than at the bottom. The molds must be split when the walls are parallel and are sometimes split when the ingots are tapered.

High-speed tool steel as cast has a coarse structure and dark color, as compared with the structure and color of simple steels of the same carbon content. A corner is broken from the top of each ingot to show the grain and the ingots when hand poured directly from the pots are classified by the eye as in the production of simple crucible steels. If the ingots are cast from the large ladle a test is taken for analysis which determines the disposition of the whole ladleful of steel.

As a rule the ingots show a strong columnar structure or arrangement of crystals, whose axes are normal to the cooling surface. Some makers refer to the structure as a "lemon structure", the crystals of the metal being thought to resemble the cells forming the pulp of a lemon. If the casting temperature is lower than usual, this "lemon" structure may be absent, and in that case the interior of the ingot will have a much finer grain than the ingots cast at the usual higher temperature. The subsequent heating and working of the steel entirely destroys the crystalline structure of the ingot, and the worked steel, on a fresh fracture, shows a most beautiful porcelanic structure.

The ingots run from 3.5x3.5 inches to 16x16 inches but most of them are from 5x5 inches to 9x9 inches. For hot working they are heated in the furnace chamber having a temperature of about 1,180° C. (2,156° F.) At this high heat the steel may be worked satisfactorily under the hammer or press and may be quickly worked down to the dimensions desired.

**Composition of High-speed Tool Steels.** The tendency of the makers is toward a somewhat uniform composition as regards the contents of the alloying elements, whose benefits have become fairly well known, and whose use as a consequence may be considered as established. Specifically, these alloying elements are tungsten and chromium. The addition of vanadium and cobalt in important proportions is considered by some makers to give distinct improvement to high-speed steel, and some vanadium is almost always present.

The following analyses are of steels recently made, most of which are considered to be good commercial steels:

**Results of Analyses of High-Speed Steels Made in 1913 or 1914.**

| Samples | % C. | % Mn. | % Si. | % S. | % P. | % Cr. | % W. | % V. | % Co. | % Ni. | % Mo. | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A ..... | 0.65 | 0.15 | 0.20 | 0.02 | 0.03 | 4.75 | 17.50 | 0.90 | .... | .... | .... | |
| B-1 .... | .66 | .27 | .14 | .04 | .05 | 4.51 | 17.48 | .70 | 4.22 | 0.17 | .... | |
| B-2 .... | .74 | .31 | .13 | .04 | .02 | 4.20 | 15.63 | .67 | 2.70 | .... | .... | |
| B-3 .... | .63 | .13 | .07 | .04 | .05 | 4.26 | 17.16 | .45 | 3.80 | 0.20 | .... | |
| B-4 .... | .69 | .34 | .14 | .03 | .04 | 5.28 | 16.35 | .64 | 5.28 | .... | .... | |
| C-1 .... | .66 | .22 | .17 | .03 | .02 | 3.44 | 16.51 | .73 | .... | .... | .... | |
| C-2 .... | .64 | .21 | .16 | .03 | .03 | 3.30 | 16.06 | .66 | 4.02 | .... | .... | |
| C-3 .... | .67 | .23 | .25 | .02 | .02 | 3.85 | 16.06 | .70 | .... | .... | .... | |
| D-1 .... | .75 | .28 | .36 | .03 | .... | 4.10 | 19.00 | .75 | .... | .... | .... | Good |
| D-2 .... | .68 | .38 | .40 | .03 | .... | 4.65 | 17.85 | .53 | .... | .... | .... | Inferior |
| D-3 .... | .69 | .36 | .38 | .04 | .... | 4.67 | 17.90 | .50 | .... | .... | .... | Do |
| D-4 .... | .57 | .20 | .26 | .02 | .03 | 4.82 | 15.38 | .50 | .... | .... | .... | Do |
| E-1 .... | .61 | .23 | .35 | .04 | .... | 4.10 | 17.20 | 1.00 | .... | .... | .... | Good |
| E-2 .... | .68 | .45 | .40 | .04 | .... | 4.00 | 14.26 | 1.09 | .... | .... | .... | Inferior |
| E-3 .... | .70 | .50 | .39 | .05 | .... | 4.08 | 14.50 | 1.07 | .... | .... | .... | Do |
| E-4 .... | .60 | .23 | .12 | .03 | .02 | 3.90 | 17.27 | .90 | .... | .... | .... | Do |
| F- ..... | .64 | 2.29 | .12 | .02 | .01 | 4.39 | 16.09 | .59 | .... | .28 | .... | |
| G- ..... | .72 | .37 | .18 | .03 | .02 | 4.50 | 13.30 | 2.50 | .... | .... | .... | |
| H-1 .... | .77 | .16 | .21 | .02 | .02 | 4.05 | 18.64 | 1.35 | .... | .... | .... | |
| H-2 .... | .67 | .16 | .20 | .02 | .02 | 4.66 | 13.86 | 1.08 | .... | .... | .... | |
| I ...... | .64 | .23 | .29 | .02 | .02 | 4.57 | 19.10 | .54 | .... | .... | .... | |
| J-1 ..... | .64 | .30 | .26 | .02 | .01 | 2.93 | 18.71 | 1.22 | .... | .... | .... | |
| J-2 .... | .71 | .14 | .26 | .03 | .03 | 2.97 | 18.21 | .97 | .... | .... | .... | |
| K-1 .... | .55 | Tr. | .23 | .02 | .04 | 4.46 | 16.05 | .80 | 4.72 | .... | 0.72 | |
| K-2 .... | .70 | Tr. | .18 | .01 | .02 | 4.25 | 15.50 | .88 | 4.72 | .18 | .67 | |
| K-3 .... | .74 | .31 | .13 | .04 | .02 | 4.20 | 15.63 | .67 | 2.70 | .... | .... | |

Note:—Sample A to I represent American steels, the numerals indicating different samples from the same maker; Sample J represented an English steel; Sample K represented a German steel.

Samples D-1 and E-1 gave excellent results in a competitive test, whereas D-2, O-3, E-2, and E-3, manufactured by the same makers, gave distinctly inferior results in the same shop.

The occurrence of nickel in four of the samples may have been accidental, having been due to nickel in some of the scrap steel used in the charge. Most makers now put in vanadium and steel like that represented by sample G, which had the highest vanadium content of all the samples represented in the table, was the winner in a recent competitive test.

The average specific gravity of the steels represented in the table was about 8.8, the increase over the specific gravity of iron being due chiefly to the tungsten content.

There are so many factors beside the ultimate composition that affect the value of rapid tool steels, that no conclusion can be drawn from the analyses alone. The melting, hot-working, and heat treatment all must be done correctly or the final result will not conform to expectations.

**Carbon in High-speed Tool Steel.** The proportion of carbon aimed at in high-speed tool steels is about 0.65 percent, which in a simple steel would not be enough to give the maximum hardness even if the steel were heated above the critical point and quenched in water, and still less so when the steel is cooled as slowly as these steels are in their treatment. This shows that the carbon acts in a different way from what it does in simple steels, as is discussed later.

**Tungsten in High-speed Tool Steel.** Tungsten is well established as the most important if not indespensible ingredient of commercial tool steels, being almost or quite universally used in quantity therein. The best proportion of tungsten, all things considered, seems to lie between 16 and 20 percent, the tungsten content in 95 percent of all the American steel coming within these limits. Some published analyses of European high-speed tool steels shows a higher content of tungsten than this, but American makers generally agree that any tungsten in excess of twenty percent adds nothing to the usefulness of the steel, and they therefore make that proportion the upper limit of the amount added. One effect of the tungsten is that the best percentage of carbon in rapid steels is but about half that required in simple tool steels intended for the same kind of service.

**Chromium in High-speed Tool Steels.** The effect of chromium in high-speed tool steel, as in other steels, is undoubtedly as a hardener, entering into double carbide of tungsten and chromium which gives or causes the proper cutting edge. Although the proportion of this element present in these steels varies considerably, it is always large, perhaps never less than 2 percent or more than 6 percent in American steels, and in European steels the upper limit is at least 9 percent.

**The Heat Treatment of High-speed Tools.** The heat treatment given to high-speed steels for the commoner uses as lathe and planer tools has generally been simplified to heating to incipient fusion and quenching in oil. Cooling by an air blast and double treatment, which were formerly recommended, are now not common, except that a second (drawing) heating is given to milling cutters and similar tools, the temperature imparted to the tool depending on the material to be cut.

The treatment is usually done by the blacksmith, who heats the tool in his forge fire and then immerses it in a tank containing enough oil so that its temperature does not rise materially. Ten gallons of oil is a common quantity to use when the size and number of the tools is moderate, as in most shops. The fire is a deep compact coal fire, the coal in the center where the tool is heated being pretty thoroly coked, that is, most of its volatile matter distilled out. This manner of heating has the advantage that free oxygen does not get at the tool to oxidize it, but its environment is non-oxidizing, or even reducing, owing to the presence of an excess of burning carbon surrounding the tool. Any flame is more or less oxidizing, at least unless heavily charged with smoke or free carbon, and a piece of steel heated directly by a flame as in the ordinary heating chamber of a furnace is likely to be somewhat oxidized on its surface, the depth to which the oxygen penetrates varying according to the conditions, particularly the temperature, the access of air, and the length of time. Heating in a muffle will also result in oxidizing the steel unless extraordinary precautions are taken to keep out oxygen or to consume all that enters. The temperature of quenching usually about 1,260° C. (3,300° C.), is determined by the fusion of the scale and its visible collection into drops or beads on the surface of the tool.

Quenching is done by quickly plunging the heated tool into the oil as soon as it has reached the desired temperature and moving it about in the oil until cold. Cooling in oil is thought by some to give a better tool than cooling in the air blast, one reason seemingly being the protection of the steel from free oxygen while it is hot enough to be oxidized thereby. The oxygen of the air blast forms a scale of oxide on the hot steel and the oxygen probably penetrates the metal below the scale to some extent, injuring the quality as deep as it goes. A tool on its second grinding when the oxidized metal is removed may then give better service than on the first, unless the first grinding has for that reason been heavy enough to remove the oxidized metal.

In some shops, however, the original treatment recommended by Taylor (236) and White is given, the cutting edge of the tool being heated to incipient fusion and then immersed in a bath of melted lead at about 565° C. (1050° F.). The heating is done in a small furnace over a deep coke fire, blown by an air blast so that the environment of the tool while being heated is substantially non-oxidizing. Flames of carbonic oxide play out of the openings thru which the tools are inserted indicating little if any free oxygen within. In these shops however, milling cutters and other tools that are machined to a particular form are treated by heating them to a slightly lower temperature, in order not to damage the cutting edges and then plunging them into cold oil.

When cooled to the temperature of the lead, it is taken out and placed in an air blast to complete the cooling. Some tools desired to be especially tough so as not to break in service are given a second heating to 565° C. and then cooled in the open air or air blast if saving time is important.

Rapid steel when well annealed will bend considerably without breaking even in as large a section as 2.5 by 1.25 inches, the bending being edgewise, as in a tool at work.

Gledhill (226) found that one of these steels after having been annealed twelve to eighteen hours at 760° C. (1400° F.) had a tensility of 129,200 pounds per square inch, an elastic limit of 89,600 pounds per square inch, an elongation of 18 percent in two inches and a contraction of area of 35 percent. The ductility is rather high and would enable a tool to be bent considerably without breaking. Such annealed steel may be easily machined for making milling cutters and other shapes that require machining.

Carpenter (225) found that the higher the temperature from which rapid steel is cooled the more it resisted etching for metallographic work. He also found that no tempering change occurred when it was reheated at a temperature of less than 550° C. (1022° F.) to a visible red in the dark, indicating a stability that is doubtless the cause of its property of red hardness.

Whether a rapid steel is made harder by the heat treatment given it depends somewhat on the conditions of the bar before treatment. If it has previously been annealed, the treatment hardens it, whereas heat treatment may not harden a piece in the natural state. Taylor (236) found that some tools having useful red hardness could be filed rather readily. Edwards (243) on the other hand found treated high-speed steels to be exceedingly hard—as hard as any steel could be made by quenching. Gledhill (226) found that high-speed steel was good for turning chilled rolls which are extremely hard and require to cut them the hardest kind of tool.

Trials on window glass of a number of different rapid steels showed that the cutting edge of some but not of all would scratch it. The same was true of the untreated ends of the same tools, as some would and some would not scratch the window pane.

The hardness of the steel when cold is not the determining factor of usefulness in any case. It is the hardness when heated under conditions of work.

The cutting edge of a rapid steel tool at work is probably never as hot as the metal just back of it, where the heating caused by the friction of the chip as it is deflected and rubs hard on the tool, is most intense. The edge itself is kept relatively cool by the cold metal flowing upon it.

**Theory of High Speed Steels.** Carpenter found the heating and cooling curves of a rapid steel to be radically different from each other, and also that the cooling curve when the steel was cooled from 930° C. (1706° F.) was greatly different from that when the steel was cooled from 1250° C. (2282° F.). When the steel was cooled from 930° C. the curve had an abrupt jog, which showed a great retardation in rate of cooling, occurring between 700° C. and 750° C. (1292° F. to 1382° F.). The jog did not occur when the steel was cooled from 1250° C., 320° higher, the line representing variations in rate of cooling being nearly straight. The rate of cooling to get these curves was slow or at least not accelerated, and one cannot say what the curve would be like if the rate of cooling were hastened, as in quenching, but the curves obtained seem to show much light on the question. The property of red hardness seems to be connected with the elimination of the great retardation mentioned.

The following explanation, based on the work of Carpenter (225) and Edwards, (243) of the properties of high-speed steels, seems to be helpful or even satisfactory:

Their researches on the heating and cooling of these steels have shown that such steels have an extraordinary stability of composition after they have been heated to 1,200° C. (2,193° F.) or more, and that a second heating of 550° C. (1,022° F.) has no softening or drawing effect. It seems fairly evident that red hardness depends on or is the natural result of these facts.

At a temperature higher than 1,200° C. (2,192° F.) a double carbide of chromium and tungsten is formed, which persists largely even when the steel is cooled slowly as in the open air, and more so when cooling is accelerated. This double carbide imparts to the steel the high degree of hardness and is stable at all temperatures up to 550° C. (1,022° F.) or somewhat higher. At 550° C. the steel has a low red color visible in the dark.

If the above theory be true, then at a temperature of 1,200°C. (2,192° F.) the chromium and tungsten must have a stronger affinity for carbon than iron has w,hereas at lower temperatures say from around 930° C. down to the critical point the affinity of carbon for iron is slightly stronger than that of either chromium or tungsten or both, and the carbon then exists wholly or in part as carbide of iron, or a complex carbide of iron with one or both of the other elements.

Carbide of iron or hardening carbon which causes the hard condition of iron in simple steel that has been quenched from a temperature higher than the critical point, is unstable at even slight elevations of temperature above atmospheric temperature, its unstableness increasing with the degree of heat though not being proportional thereto. Boynton (236a) has shown that between 400° C. (752° F.) and 500° C. (952° F.) the amount of change and consequent softening is much greater than at other temperatures, either lower or higher.

The proportion of carbon in rapid steel should perhaps be only as much as will combine with the chromium and tungsten at 1,200° C. (2,192° F.) and leave none to exist as unstable hardening carbon of hardened simple steel.

## Uses of Tungsten in Non-Ferrous Alloys.

Tungsten alloys readily with nickel, cobalt, molybdenum, uranium, chromium, iron, manganese, vanadium and titanium, and less easily with most of the other metals. Alloys of tungsten of many kinds and for many purposes have been invented but in numerous cases the cost of the alloy is altogether out of proportion to its usefulness. Only the more recent important alloys will be discussed here.

"Stellite", invented by Haynes, (321) is one of the chief competitors of high-speed steel. It is an alloy of about 75 percent cobalt, 20 percent chromium and 5 percent tungsten. Other elements are sometimes added. The alloy has some very valuable properties for cutting tools.

"Partinium" is an alloy of aluminum and tungsten which is very light and strong. It has been used in automobile construction. Tin, copper, magnesium and other metals are sometimes added.

"Duralium" is another alloy of aluminum containing 2 to 3 percent tungsten. It is much harder than aluminum metal. An aluminum alloy containing 10 percent copper and ten percent tungsten has been patented by de Buigne for type metal. An alloy with copper and aluminum is used in the manufacture of propeller blades.

Numerous patents have been taken out for alloys of tungsten and small amounts of thorium. (323) The thorium has the property of making the tungsten ductile, and this alloy is used in making drawn tungsten wire. An alloy of one percent thorium and 0.2 percent platinum with tungsten makes a tough ductile alloy (U. S. Pat. 1,167,827).

"Tungsten-nickel" containing varying amounts of the two elements was used at one time in making metal filaments for electric lamps because it is a ductile alloy. (See following sesction. Irmann (325) found that the 18 percent tungsten alloy with nickel is ductile and very resistant to dilute sulfuric acid.

"Chrome-tungsten" is made by reduction of chromic tungstate with tungsten silicide (Gin) (1233). The chromium tungstate is made by mixing solutions of chromium sulfate and sodium tungstate. This alloy is used in the manufacture of high-speed steel.

Tungsten-molybdenum alloys varying in composition from pure tungsten to pure molybdenum have been studied by Fahrenwald and Jeffries. (327, 328, 329). The alloys are made in the same way as ductile tungsten. The tungsten molybdenum alloys are all ductile and malleable. They are being used as substitutes for platinum in dentistry.

E. Weintraub has patented an alloy of 20 to 60 percent tungsten and 80 to 40 percent platinum for use in electrical contacts, jewelry, etc. (U. S. Pat. 1,096,655.)

### Uses of Tungsten in Metal Filament Lamps.*

Tungsten has become a household word thru the introduction of the drawn tungsten filament lamps. Briefly summarized, the transition from the carbon filament lamp to the present day gas filled tungsten lamp was as follows. The carbon filament lamp had an efficiency of three watts per candle power. It was succeeded by the "metallized" carbon filament, (that is, a carbon filament on which had been deposited a hard, lustrous coating of carbon by heating electrically in an atmosphere of ligroin or benzine) which used 2.5 watts per candle power. Then came the drawn tantalum filament lamps which were used extensively from 1905 to 1911. Their efficiency was 1.7 watts per candle power. The "squirted" tungsten filaments were next used, with an efficiency of 1.25 watts per candle power. The chief disadvantages of these filaments were their fragility. This defect was corrected in the drawn tungsten filaments and the efficiency

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*Material for this section was taken largely from S. T. Johnstone, "The Rare Earth Industry", London, 1915.

was also increased, i. e. 1 watt per candle power. More recently the gas filled drawn tungsten filament lamp has been developed with the remarkable efficiency of 0.5 watts per candle power.

The savings which have resulted from the introduction of the tungsten filament lamps amount to millions of dollars per year. Not only has the cost per candle power been reduced, but the number of consumers has increased greatly, and offsets any loss to the producer of electric current by the increased efficiency of the lamps. Furthermore, the low cost allows otherwise impossible extension of artificial lighting, with the resulting benefit and pleasure of man.

The high melting point of tungsten (3200° C) suggested it as a possible metal for filaments. It has been shown by Waidner and Burgess (89) that the light emitted by an incandescent metal varies as the twelfth power of the temperature, while the energy required varies as the fifth power of the temperature. It can be seen that a high melting point is an important advantage. Tungsten, as it was known at the time of its introduction in electric lamps (1904-5), was a hard, brittle metal, which it was impossible to draw into wires. The filaments were therefore produced by a "squirting" process, or by producing a coating of tungsten on a core of carbon or other refractory substance. The many processes which have been employed up to the present time may be classified as follows:

(1) Substitution; (2) amalgamation; (3) squirting a paste containing tungsten powder; (4) squirting colloidal tungsten; (5)) drawn wire; (6) alloy processes.

In the first process, a filament of carbon is made by "squirting" as was the usual method of carbon filaments. This carbon filament was then heated in an atmosphere containing a volatile compound of tungsten, such as the oxychloride, and a small amount of hydrogen. When the filament was heated to redness by passing an electric current thru it, the tungsten displaced the carbon.

In the amalgamation process, a mixture of metallic tungsten powder and an amalgam of cadmium and mercury was "squirted" thru small die in the usual way. The cadmium and mercury in the filament thus produced were volatilized by heat. The tungsten filament thus formed was very brittle, but after moderate heating it became pliable and could be bent into shape.

Many modifications of the paste squirting process were invented. The binder may be such that it volatilizes on heating, leaving a carbonaceous residue and reduces or partly reduces the tungsten. Substances used were gum, sugar, gelatine, or nitrocellulose dissolved in amyl acetate. It is difficult to remove the last traces of carbon from the filament. A binder might also be used which would hold the material together, but would not leave a carbonaceous residue after heating, such as paraffin, wax, camphor, and pinene hydrochloride. In this latter case, the heating of the pressed filament is done in hydrogen in order to reduce the tungsten compound used with the binder.

In some processes, metallic tungsten powder was made into a paste with a non-carbonizing binder, squirted into threads and heated to dry the binder, and ignited by passing an electric current thru them in an atmosphere of hydrogen.

Plastic tungstic acid can be made for production of squirted filaments without binders. Hydrated tungstic oxide is boiled with ammonia until crystallization occurs. The crystals are heated to 250° and then boiled with water until the mass changes to a viscous plastic mass, which is then ready for squirting into filaments (French Patent 379,069 [1907]).

Plastic tungsten acid for this purpose can also be made by treating the hydrated oxide with ammonia at —20° C.

Some claim that the lower oxides, either the brown dioxide or the violet pentoxide are better than the yellow trioxide for squirted filaments.

The colloid tungsten process for making filaments was one of the most successful and interesting processes. The advantages are that no binder is required and there is no carbon to remove. The process is covered by several patents granted to Dr. Kuzel about 1904. Other metals beside tungsten have been made into colloidal form and can be made into filaments.

The colloidal tungsten is prepared by allowing an electric arc to form between electrodes of tungsten under water. The finely divided tungsten can be separated from the water by slow evaporation and the plastic product squirted into filaments. The filaments as first prepared are not good conductors of electric current, but after heating to 60° C. they conduct well enough to allow final drying and sintering of the particles by the electric current. Sometimes a voltage of 400-1000° is used for the drying and sintering. (English Pat. 12,968) 1908.

In order to avoid irregularities in the filament the heating is conducted in an inert or reducing atmosphere and the pressure kept down to 150 mm. or less. During this process a continuous current of gas, consisting of 80% nitrogen and 20% hydrogen is passed thru the apparatus.

Drawn wire tungsten filaments were developed in the highly organized research laboratory of the General Electric Company. The general principles of the method used for preparing the ductile tungsten for drawing into filaments has been described (see page ——).

The bars of ductile tungsten are drawn usually thru draw plates. The dies are of diamond or ruby. The successive dies used vary only slightly in diameter, thus starting with a wire of 0.65 mm. diameter, they decrease about 0.0125 mm. as far as 0.35 mm. diameter. From this size down to 0.1 mm. the interval is .0065 mm. and from 0.1 to .075 mm. the interval is .03 mm. From 0.075 to 0.0375 mm. it is .0025 mm. and finally from .0375 down to the smallest wires drawn .01 mm. the size of the dies change by only .00125. Over a hundred dies are required for drawn lamp filaments. The filaments in the regular lamps are probably the finest wire ever produced by straight drawing.

The draw plate is lubricated by deflocculated graphite and water. To point the wires, in order to start them thru the next smaller die, they are immersed in melted potassium nitrate until they are reduced to the proper size. If the wires are already small in diameter they may be reduced by making them anodes in a solution of potassium cyanide.

During the drawing the wire is protected from oxidation by an inert or reducing atmosphere. They may also be protected from oxidation by plating with gold, silver or copper (Eng. Pat. 21,513 [1916]).

The drawn tungsten filaments are very much stronger than squirted filaments and have practically entirely replaced them.

When pure tungsten is used, no matter by what process, the filaments become brittle, after being used a short time. This defect is due to crystallization of the tungsten. This is obviated to a large extent by the addition of thorium oxide to the tungsten oxide before reduction.

Numerous alloys of tungsten with other elements have been invented for use in filaments. In some of these, the foreign element is removed in the finished filament, while in others, it remains.

An example of the first type is the process of Siemens Brothers of London. An alloy of tungsten with nickel is quite ductile and can be drawn into fine wires. Thus an alloy was made by mixing nickel tungstate with tungstic acid and heating to 1650° in hydrogen. The 12% nickel alloy was usually made. After the filaments are made, the nickel was volatilized by heating in a vacuum. On account of blackening of the bulb, this process has been discontinued.

The other type process is illustrated by the tungstic thorium filament. This process consists in producing a filament composed of tungsten alloyed with thorium and other rare earth metals. The filament thus produced is said to be very ductile, even in the cold and remains in this condition even after being used for some time. Different processes for making the tungsten thorium alloy have been devised. The mixture of colloidal metals may be used, or the mixture of oxides may be reduced in hydrogen.

Gas filled tungsten lamps have been developed in the last few years. The account of the invention was first published by I. Langmuir and T. A. Orange (376). While investigating the cause of blackening of metallic filament lamps, they found that this was due to volatilization of the metal filament and that it was lessened by putting an inert gas into the bulb. Nitrogen was first used because the loss of heat by convection was much less than with hydrogen. It was found that the loss in efficiency of a tungsten filament in an atmosphere of inert gas was greater for wires of small diameter (.002 inch) than for large wires (over .005 inch). This lead to the practice of coiling the fine wires into tightly wound helices. The helex is supported on a "spider". Such lamps have the advantage of giving a maximum of light in the horizontal plane. Gas filled lamps are also much more efficient than evacuated lamps, consuming only about 0.5 watts per candle power. The light is of a penetrating character and is better adapted for replacing arc lamps than for lighting small interiors. They are furnished in capacities up to 2000 candle power.

## Miscellaneous Uses.

The unique properties of tungsten make it very valuable for other purposes than for alloy steel and electric lamp filaments. Its melting point is higher than that of any other known metal; its tensile strength exceeds that of iron and nickel; it is para magnetic; it can be drawn to smaller sized wires than any other metal; and its specific gravity is 70 per cent higher than that of lead.

One of the most important uses for tungsten is in replacing platinum and platinum iridium alloys for contact points in spark coils, voltage regulators, telegraph instruments and other electrical devices. It is better than platinum, due to its greater hardness, higher heat conductivity and lower vapor pressure.

Great savings in platinum have been made by the substitution of gold coated tungsten dental pins in the last few years.

Electric furnaces (laboratory) with resisters of tungsten are also used. In some of these tungsten wire is wound around a suitable refractory shell and protected from oxidation by an atmosphere of hydrogen. Other furnaces use a tungsten metal tube to take the place of the helical carbon resister in vacuum furnaces.

Tungsten gauze is acid and alkali resisting and is useful for separating solids from liquids. The gauze has been used in some of the apparatus designed by Cottrell for the electrastatic precipitation of fumes.

Wrought tungsten targets for X-Ray tubes are now generally used. The great advantage is the high density of the metal. The targets are sometimes made with a surface of tungsten on a backing of some other metal, as silver and copper which conduct the heat away more rapidly.

Finely divided tungsten is said to be an excellent catalytic agent in the production of ammonium from nitrogen and hydrogen.

Besides these, many other applications have been suggested. Owing to its chemical stability, and the fact that it can be drawn down to .0004 inches in diameter, it would be useful for galvanometer suspension and cross hairs for telescopes. It also has been suggested to use thin wires in surgical operations in place of the coarser gold and silver wires. Laboratory apparatus has been made from wrought tungsten and is useful for certain purposes. Since it is paramagnetic and elastic, it has been tried out in electrical meters and watch springs, which can never be magnetized. Many of the possible uses of tungsten will probably never be made commercially, because of its cost. On the other hand, many new uses are being found for the metal, and its field of usefulness is not yet fully explored.

# CHAPTER IX.

## COMPOUNDS OF TUNGSTEN AND THEIR USES.*

**Oxides.** Tungsten is said to form a number of oxides the separate existence of which is not definitely settled. Thus, when sulphuric acid acts on metallic tungsten under varying conditions, the blue oxides, WO, $W_2O_3$, $W_4O_3$, $W_5O_9$, are formed; sulphurous acid acts on tungsten forming the oxide $W_5O_{14}$, and a beautiful purple oxide with a yellow metallic lustre, $W_3O_8$, is obtained by heating ammonium metatungstate to a bright red heat or by fusing tungstic acid with potassium iodide. 449

The hydroxide $W_5O_{14}$, $H_2O$, a dark blue powder with a purple lustre, is formed when tungstic acid is reduced with stannous chloride and hydrochloric acid, or by heating the acid with hydrogen iodide in a sealed tube at 200°. With ammonia it yields ammonium tungstate and the hydroxide, $W_3O_8$, $H_2O$. (454)

The only oxides which are definitely known are $WO_2$, $W_2O_3$, $WO_3$.

Tungsten dioxide, $WO_2$, may be prepared by the reduction of the trioxide or an alkaline metatungstate with zinc and hydrochloric acid, (594) or by heating the trioxide to dull redness in hydrogen. (459a) (35) It may be obtained crystalline by reducing lithium paratungstate with hydrogen. (471c)

Tungsten dioxide may be formed by heating an intimate mixture of tungsten trioxide and 1/5-1/10 its weight of glycerol, ethylene glycol or similar hydroxyl compound, to a bright red heat for some hours. (Eng. Pat. 18,922; 1907; J. Soc. Chem. Ind. **1908,** 22)

Tungsten dioxide, prepared in the wet way is of a copper red color, prepared in the dry way it is a brown powder. It is readily oxidized to the trioxide; heated in chlorine it yields a yellow oxychloride $WO_2Cl_2$. When amorphous it is soluble in hydrochloric and in sulphuric acid, but it is quite unacted on when crystalline.

Blue tungstic, oxide $W_2O_3$, formed when tungsten trioxide is reduced with hydrogen at 250°-300°, (26) or by electrolysing fused sodium tungstate (439) is readily oxidised to the trioxide.

Tungsten trioxide, $WO_3$, occurs naturally as wolframite and as tungstite or meymacite, (899) also in the form of tungstates in wolfram and scheelite. It may be prepared by calcining in contact with air, the lower oxides, the metal, a sulphide or its hydrate (tungstic acid).

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*Quoted from Thorpe's Dictionary of Applied Chemistry, 1913 Edition.

Tungsten trioxide forms a yellow powder which may be obtained crystalline by heating the amorphous metal to a very high temperature in air or by fusion of tungstic acid with borax in a porcelain vessel; (864) or by passing hydrogen chloride over tungstic acid or a mixture of sodium tungstate and sodium carbonate at a white heat. (437a) Its sp. gr., when amorphous, varies between 5.27-7.13, when crystalline between 6.30-6.38. It is fusible with difficulty and is insoluble in water. When heated in hydrogen it gives the blue oxide at 250°, the dioxide at a red heat, and the metal if the latter action is prolonged. It is also reduced when heated with zinc and certain other metals. (59) When heated with chlorine or sulphur monochloride, it is converted into a volatile oxychloride and in the former case also into the hexachloride. (451) (603) (779)

The oxide is soluble in hydrofluoric acid, but not in hydrochloric or nitric acids or in aqua regia. (142)

Plastic masses of tungsten oxide for incandescent lamp filaments may be prepared by treating the oxide or hydrated tungstic acid with ammonia at -20° or below, or when in alcoholic suspension with gaseous ammonia. (Eng. Pat. 14850; J. Soc. Chem. Ind. **1908** 1198, 1104)

**Tungstic Acids.** Tungsten trioxide forms two well characterized acids, $WO_3$. $H_2O$ or $H_2WO_4$ and $(WO_3)_4H_2O$ or $H_2W_4O_{13}$. In addition the salts of a number of polytungstic acids are known. (509)

Tungstic acid $H_2WO_4$ may be obtained by precipitating a solution of a tungstate with excess of hot acid. If cold acid is used, the white hydrate $H_2WO_4,H_2O$ is formed, from which the acid may be obtained by boiling. It is prepared by digesting a tungsten mineral with hydrochloric acid, then with aqua regia until the brown powder has become yellow, when the iron and manganese have been dissolved out. The residue is well washed and then shaken with ammonia which dissolves the free tungstic acid. On filtration and evaporation the tungstic acid crystallises out. The finely powdered mineral may be fused with calcium chloride or with alkali carbonates or sodium chloride. The melt is lixiviated and the calcium or other metallic tungstate residue is then decomposed with nitric or hydrochloric acid.

Tungstic acid may be prepared from wolfram or other minerals containing tungsten, by heating the mineral under pressure with a concentrated solution of potassium hydroxide, lime or baryta being added to form insoluble compounds with some of the impurities.

The tungstic acid is then separated from the solution either by fractional precipitation with acid, the impurities separating first, or the whole of the precipitate formed by adding sufficient acid, is fractionally redissolved by alkali. The process is said to be economical, convenient, and to give very pure acid. (Fr. Pat. 389040; 1908; J. Soc. Chem. Ind. **1908,** 939)

Tungstic acid may be purified by treating tungsten trioxide with carbon tetrachloride vapour at a red heat. The resulting volatile chlorine compound is sublimed, condensed and treated with aqua regia; the tungstic acid formed is then further purified by solution in ammonia and reprecipitation with dilute nitric acid. (U. S. Pat. 926,-984; J. Soc. Chem. Ind. **1909,** 794)

Tungstic acid is a yellow powder insoluble in water and almost so in all acids except hydrofluoric acid, in which it dissolves to the extent of 44.7 p. c. at 25°, 55.3 at 50°, using 50 p. c. hydrofluoric acid. (476) It is readily soluble in alkalies.

Freshly prepared tungstic acid dissolves in aqueous solutions of most aliphatic amines forming substituted ammonium tungstates such as $(NMeH_3)_6W_7O_{24},6H_2O$, which crystallise on evaporation. When heated they are decomposed forming the amine, tungstic acid and the blue oxide of tungsten. (567) It also gives crystalline precipitates with pyridine and quinoline. (476)

Colloidal tungstic acid may be prepared by adding hydrochloric acid to concentrated sodium tungstate solution until it has an acid reaction. The white gelatinous precipitate formed, protected from currents of air, is washed by decantation several times at 0° to 5°; 15 parts of the acid are then dissolved in 1 part of concentrated oxalic acid by gently warming, and the liquid is subjected to dialysis. If the outer water is changed frequently, the oxalic acid may be completely removed. (4716) (474a)

Colloidal tungstic acid may be obtained by dissolving 5 grms. of tungsten tetrachloride in about 50 c. c. of a mixture containing equal volumes of ethyl alcohol and ether; the filtered solution is diluted to 250 c. c. with alcohol and then mixed with an equal volume of water. The colloidal solution thus obtained behaves as a positive colloid; it may be kept for some days without appreciable opalescence being observed, but coagulation occurs more quickly by adding a larger quantity of water, and immediately when small quantities of neutral salts, hydroxides, or strong acids are added. Weak organic acids or rise in temperature exert no effect. If an electric current is passed through, a deep blue precipitate separates at the cathode. (480) (478) (69)

The colloidal acid is also prepared by dialysing a 5 p. c. solution of sodium tungstate to which sufficient hydrochloric acid has been added to combine with the sodium. Colloidal tungstic acid forms a gum-like mass which may be heated at 200° without becoming insoluble and which at a red heat is converted into the trioxide. The colloidal acid has, probably, the constitution of the meta acid.

Tungstic acid and sodium tungstate are used in the production of color resists for aniline black. 200 grms. sodium tungstate dissolved in 1 litre of gum tragacanth paste constitutes a white resist which may be rendered more lustrous and opaque by passing the printed tissue, after steaming, through a solution of barium chloride. The compound thus formed may be colored by pigments, such as vermilion, ultramarine blue and chrome green, a series of pale resist colors being formed, along with which the usual albumin and tannic acid color mixtures may be printed. (472)

Tungstic acid may also be employed in the production of resist effects upon p-nitraniline red and of discharge effects upon indigo-dyed tissues. In the latter case, the tissue dyed with the indigo is padded in a solution of sodium tungstate, dried and printed with a steam discharge mixture containing barium chlorate, potassium ferro-cyanide and a basic dyestuff able to withstand the oxidizing action, such as rhodamine 6 G, ultramarine, or chrome yellow. The colors are rendered faster by the addition of albumin together with an alkali citrate or tartrate.

Metatungstic acid $H_2W_4O_{13},7H_2O$, first isolated by Scheibled,(488) may be prepared by decomposing the lead salt with hydrogen sulphide or the barium salt with dilute sulphuric acid. It crystallizes in small yellow octahedra, very soluble in water, giving a bitter solution and loses its water of crystallization at 100°. For its behavior on electrolysis see Leiser. (475)

Paratungstic acid, the acid corresponding to the salts of the formula $12WO_3,5M_2O$, Aq. has been prepared in dilute solution by mixing barium paratungstate with a quantity of dilute sulphuric acid not quite sufficient for complete decomposition. The solution cannot be concentrated even in vacuo without decomposition, and when boiled it yields tungstic acid. (472a)

**Tungstates.** The alkaline tungstates, $M_2WO_4Aq$, are prepared by fusing a naturally occurring tungstate with sodium or potassium hydroxide or carbonate, preferably with the addition of a silicious or other flux. The alkali tungstate falls to the bottom and may be tapped off, or, after cooling, the slag may be removed. (Eng. Pat. 30053, 1897; 6045, 1900)

The sodium salt crystallizes in thin prisms, soluble in 4 parts of cold, in 2 parts of hot water, the solution having a bitter taste and and alkaline reaction. It has m. p. 698°. (513)

The potassium salt forms large prismatic crystals. The ammonium salt is very unstable.

Calcium tungstate, $CaWO_4$, occurs native as scheelite and may be prepared artificially by the interaction of calcium chloride and a normal tungstate. If the amorphous white precipitate so obtained is mixed with lime and heated in a current of hydrogen chloride, it is obtained crystalline. The corresponding barium tungstate was prepared by Rousseau for use instead of white lead. (505[a])

Lead tungstate occurs native as stolzite and crystallizes in red tetragonal pyramids.

Ferrous tungstate occurs as wolfram (FEMn)$WO_4$ forming dark grey or brownish-black prisms.

Manganese tungstate is found as hubnerite. Granger has proposed the employment of the tungstates in the ceramic industry. (450) (457)

Ammonia copper tungstate $CuWO_4,4NH_3$, deep blue crystals, are readily decomposed. A similar zinc salt is also known. (508a)

The copper compound $CuO,4WO_3,6NH_3,8H_2O$, has been obtained by the interaction of an ammoniacal solution of copper sulphate and ammonium tungstate. It forms small blue needles. (508a)

Sodium paratungstate $Na_{10}W_{12}O_{41}$,Aq is known commercially as tungstate of soda and may be prepared on a large scale by roasting wolfram with soda ash and lixiviating the fused mass. The boiling solution is then nearly neutralized with hydrochloric acid and allowed to crystallize when large tricline crystals of the salt separate. It is sometimes used as a mordant instead of sodium stannate in dyeing and calico printing. It also renders cotton, linen, etc., non-inflammable. The corresponding potassium salt is formed in glistening scales when normal potassium tungstate is boiled with a little water.

For various paratungstates see Hallopeau. (505) (507)

Metatungstates $M^1{}_2W_4O_{13}$,Aq were discovered by Margueritte. (522) The alkali salts are readily formed when the normal tungstates are boiled with tungstic acid until the filtrate no longer gives a precipitate on addition of hydrochloric acid. The other metatungstates are best prepared by double decomposition of the barium salt with the required sulphate or carbonate. The metatungstates have a bitter taste, are generally readily soluble in water and deposit tungstic acid on prolonged boiling. A large number of them are known but there is considerable difference of opinion as to their constitution. (511) (513a) (514a) (514b) (508)

Pertungstates $M^1WO_4$,Aq are formed by boiling a paratungstate with hydrogen peroxide; (493a) or by electrolysing a slightly acid solution of sodium tungstate. (504) More highly oxidized compounds are formed by treating the pertungstates with hydrogen peroxide. (500a) (506a)

**Tungsten Bronzes** are compounds of the alkali metals with tungsten and oxygen, which, owing to their color and insolubility in acids and alkalis have been employed as substitutes for bronze powders. Their exact constitution is not known, although they are generally regarded as compounds of the tungstates with tungsten dioxide. They may be obtained by the reduction of the tungstates heated to redness with hydrogen, coal gas, zinc, iron or tin.

Tungsten bronzes may be prepared electrolytically by fusing tungstic acid with the calculated amount of metallic carbonate and electrolysing the mass. A series of brightly colored mixed alkali and alkaline earth tungsten bronzes of various compositions are described by Engels. (524a) (509)

Four tungsten sodium bronzes are known, $Na_5W_6O_{18}$ of a golden yellow color, $Na_2W_5O_{15}$ of a blue color, $Na_2W_3O_9$ of a purple red color, and $Na_4W_5O_{15}$ which forms red-yellow cubes and yields a brown-yellow powder. (523)

Potassium forms one bronze, $K_2W_4O_{12}$. (524)

Blue lithium bronzes are described by Hallopeau. (471c)

Tungstates of the rare earths are described by Hitchcock. (496)

**Tungsten and the Halogens.** Tungsten hexachloride $WCl_6$ is prepared by heating metallic tungsten in excess of pure dry chlorine, particular care being taken to exclude all traces of air and moisture in order to avoid the formation of the oxychloride. (527) A small quantity of the latter is formed at the beginning of the reaction, however, in spite of all precautions. It should be driven off beyond the portion of the tube where the chloride is to be collected. Tungsten hexachloride forms dark violet opaque crystals, which are very stable when pure but are readily decomposed by moist air or water, if the slightest trace of the oxychloride is present. It has m. p. 275°, b. p. 346.7°/759.5 mm.

Tungsten pentachloride $WCl_5$ is formed by the incomplete reduction of the hexachloride in a current of hydrogen. It is volatile and when redistilled forms long, pure black shining crystals, m. p. 248°, b. p. 275.6°. It is hygroscopic and dissolves in water forming an olive-green solution, but most of it decomposes into the blue oxide and hydrochloric acid. (527)

Tungsten tetrachloride $WCl_4$ forms the non-volatile residue in the production of the pentachloride. It may also be prepared by the distillation of the latter or of the hexachloride or better, a mixture of the two chlorides in a current of hydrogen. It forms a greyish-brown crystalline powder. (527) It is hygroscopic, infusible, is partially decomposed by water and is reduced by hydrogen to the metal.

Tungsten dichloride $WCl_2$ is best prepared by heating the tetrachloride in a current of carbon dioxide at the temperature of a moderately hot zinc bath. It is a grey non-volatile powder partly decomposed and partly dissolved by water forming a brown solution. (527)

Tungsten dioxydichloride $WO_2Cl_2$, obtained by passing chlorine over the dioxide, forms light lemon-yellow scales. Heated with ammonia it forms the compound $W_4O_4N_4H_2$. (529a)

Tungsten oxytetrachloride, beautiful red needle-shaped crystals, m. p. 210.4°, b. p. 227.5° is formed by the interaction of the trioxide and phosphorus pentachloride; (528) or by passing the vapor of the hexachloride over the heated trioxide.

Tungsten hexabromide, $WBr_6$, obtained by heating tungsten with dry bromine vapor in an atmosphere of nitrogen, forms blue-black needles which decompose when heated to a high temperature, give a colorless solutioon in aqueous ammonia, fume in air and give a royal blue oxide when treated with water. (529f)

Tungsten pentabromide, prepared by passing dry hydrogen bromide over tungsten hexachloride at 300°, or betted by the action of excess of bromine on tungsten, forms fern-like aggregates of dark needles with green reflex, m. p. 276°, b. p. 333°. It is very hygroscopic, yields the blue oxide when treated with water and dilute acids and is decomposed by alkalies, alkali nitrates, carbonates and bisulphates. (529h)

Tungsten oxybromides $WO_2Br_2$,$WOBr_4$ and the compounds $WCl_3$-$Br_3$, $WCl_6$, $3WBr_6$ are also known. (529g)

Tungsten tetriodide $WI_4$, obtained by the action of an excess of liquid hydrogen iodide on tungsten hexachloride at 110°, is a black crystalline substance of sp. gr. 5.2 at 18°, decomposed by water, alkali-hydroxides and carbonates. Soluble in absolute alcohol. (529f)

Tungsten diiodide, $WI_2$, obtained by the action of hydrogen iodide on tungsten hexachloride at 400°, is an amorphous, insoluble, infusible, non-volatile brown powder of sp. gr. 6.9 at 18°. (529e)

Tungsten hexafluoride WF may be obtained by the interaction of tungsten hexachloride with anhydrous hydrofluoric acid or with arsenic trifluoride, or, best of all, antimony pentafluoride. It has m. p. 2.5° and b. p. 19.5°. Is readily soluble in alkalies, attacks glass and most metals and forms double salts with alkali fluorides. When acted on by water it yields tungstic acid. (530)

Tungsten oxytetrafluoride $WOF_4$, obtained by the interaction of the oxytetrachloride and anhydrous hydrogen fluoride, forms small colorless hygroscopic plates, m. p. 110°, b. p. 185°-190°, is decomposed by water forming tungstic acid and absorbs large quantities of ammonia in the cold. (530)

Tungsten dioxydifluoride is known in an impure state. For various double fluorides see Marignac. (489) (529b) (529c) (529i)

**Tungsten and sulphur.** Tungsten disulphide $WS_2$ may be prepared by passing hydrogen sulphide over tungsten hexachloride at 375°-550°, or by fusing an intimate mixture of pure dry potassium carbonate, flowers of sulphur and tungsten trioxide. It is a grey-black crystalline powder, insoluble in water, fairly stable, and has sp. gr. 7.5 at 10°. (532d)

Tungsten trisulphide $WS_3$, best obtained by treating a sulphotungstate with excess of acid, is a brown powder which becomes black when dried, is slightly soluble in cold water, more so in hot water, and readily in alkali hydroxides and carbonates. (532b) It has been obtained in the colloidal state by Mimsinger. (532c)

The compounds, $WCl_6$, $3WS_3$ and $WO_2S$ (532c) and a number of metallic sulpho- or trio-tungstates, $M_2WS_4$ (532b) have been described. A di—and tri-selenide (532a) and a tri-telluride are also known.

**Tungsten nitrides** $W_3N_2$,$W_2N_3$, a number of oxynitrides, nitretamido and oxynitretamido compounds, and also a hydroxylamine tungstate have been obtained. (534) (564) (449) (454) (533a) (534a)

**Tungsten and Phosphorus.** Tungsten combines directly with phosphorus when heated to redness, forming a dark green phosphide $W_3P_4$.

Tungsten diphosphide $WP_2$ produced by heating tungsten hexachloride at 450° in a current of hydrogen phosphide forms a black crystalline mass insoluble in water, sp. gr. 5.8. The phosphorus is readily displaced by the halogens and by sulphur and nitrogen at high temperatures. It may be reduced by heating with hydrogen, zinc or copper. (543a)

If tungsten diphosphide is heated with a large excess of copper phosphide in a graphite crucible in a wind furnace and the product treated with dilute nitric acid, it yields the monophosphide WP, grey lustrous prismatic crystals, sp. gr. 8.5. (543b)

Another phosphide $W_2P$ is formed by reducing a mixture of phosphorus pentoxide (2 mols) and tungsten trioxide (1 mol.) in a charcoal crucible at a high temperature. (542a)

Phosphotungstic acid. Tungstic acid combines with phosphoric and also with arsenic, antimonic and vanadic acids to form complex compounds of varying composition, $M_2O_5:WO_3=1:7$ to $1:24$ analagous to the molybdates. Phosphotungstic acid is used as a reagent for the precipitation of alkaloids, proteins and some of their products of hydrolysis, also for the detection of potassium and ammonium salts with which it gives insoluble precipitates. It may be prepared by acidifying a solution of 4 parts of sodium tungstate and 1 part of sodium phosphate with sulphuric acid and extracting the phosphotungstic acid with ether. (543)

Literature on phosphotungstic acids and the phosphotungstates. (542c) (542b) (543c)

**Tungsten and Arsenic.** Tungsten arsenide $WAs_2$, prepared by heating tungsten hexachloride in a current of hydrogen arsenide at 150°-360°, is a black crystalline insoluble powder of sp. gr. 6.9 at 18°.

Tungsten chloroarsenide $W_2AsCl_9$, obtained by heating the above substances in a sealed tube at 60°-70°, forms hygroscopic bluish-black crystals, decomposed by water and acids. (543b)

For arsenictungstic acids and tungstates see Kehrmann and Ruttimann. (545d)

Vanadotungstates (545a) (545e) (543c); antimoniotungstates (545c); zirconetungstates (545b); alumino- and alumino-phospho and arsenotungstates (545f)

**Tungsten boride** $WB_2$, prepared by fusing the two elements together in an electric furnace, crystallizes in hard octahedra, sp. gr. 9.6. (550a)

**Tungsten and Carbon.** When tungsten trioxide is fused with calcium carbide in an electric furnace, it forms an iron-grey carbide, $CW_2$, which is harder than corundum and has sp. gr. 16.06 at 18°. In the presence of a large excess of iron, the carbide CW, an iron-grey crystalline powder of sp. gr. 15.7 at 18°, is formed. (553) (554a)

Chromium tungsten carbide $CW_2,3C_2Cr_3$ is formed by heating a mixture of chromic oxide, tungstic acid and carbon in a carbon crucible in an electric furnace for five minutes with a current of 400 amperes at 75 volts and treating the product with warm hydrochloric acid, then with concentrated ammonia solution. It forms small hard stable crystalline grains of sp. gr. 8.41 at 22°. By the addition of tungsten to chromium steels, the formation of this stable hard carbide might give rise to the production of new steels with special qualities. (555)

Iron tungsten carbide $3W_2C,2Fe_3C$, a magnetic substance, sp. gr. 13.4 at 18°, has also been prepared. (554) (554b)

**Tungsten and Silicon.** Tungsten silicide $WSi_2$ has been prepared by heating copper silicide with amorphous tungsten in an electric furnace, using a current of 800-900 amperes and 50 volts, the resulting product is then washed successively with nitric acid, caustic potash, warm hydrofluoric acid and water. It may also be prepared by reducing a mixture of silica and tungstic anhydride with sulphur and alumina. It forms brilliant, grey crystals, of sp. gr. 9.4, which are not magnetic and are very stable. (560) (559a)

The silicide $W_2Si_3$ is obtained by heating the trioxide with silicon in the electric furnace, after which the mass is suspended in dilute hydrochloric acid (1 in 10) and electrolysed. The excess of metal dissolves and the silicide is removed, washed with aqua regia, then with ammonia, and is finally separated from carbon silicide gravimetrically by suspension in methyl iodide. (559) It forms beautiful steel grey crystals with a metallic lustre, sp. gr. 10.9. (563a)

Tungsten aluminum silicide forms black hexagonal crystals. (762)

Silicotungstic acids of the formulae, $H_8W_{10}SiO_{36},3H_2O$; $H_8W_{12}SiO_{42},2OH_2O$, $H_8W_{12}SiO_{42},29H_2O$ etc. were discovered by Marignac. (558) The acid corresponding to the last formula is formed by precipitating its salts with mercurous nitrate and decomposing the mercury salt with hot hydrochloric acid. It crystallizes in large tetragonal prisms, is readily soluble in water, alcohol, and ether, and forms a valuable reagent for alkaloids. The salts, most of which are soluble in water, are prepared by boiling gelatinous silicic acid with metallic polytungstates. (545e) (558a)

**Organic Salts of Tungsten.** Esters of tungstic acid are described by Smith and Dugan; (565) alkali tungsten tartrates by Henderson and Barr, (564b) citrates by Henderson, (565a) Orr and Whitehead; tungsten oxalates by Rosenheim (564a).

Tungsten forms ozosalts which are readily soluble and difficult to obtain free from the normal salts used in their preparation. The following have been described:

Sodium ozotungsten oxalate $NaC_2O_4WO_4.5H_2O$ and also the corresponding ammonium and calcium salts which have only 1 mol. of water of crystallization. (566)

Complex compounds of the tungstic acids with organic acids have been obtained by Grossmann and Kramer; (565c) and by Mazzuschelli and Borghi; (568) and additive compounds of the tetra, penta, and hexachloride with organic esters by Rosenheim and Loewenstamm. (565b)

# CHAPTER X.

## ANALYTICAL CHEMISTRY.

**Qualitative Detection of Tungsten.** In minerals. (593) Tungsten may ordinarily be detected in minerals by boiling the finely powdered material with concentrated hydrochloric acid until insoluble yellow tungstic acid is formed. Zinc or tin is then added and if tungsten is present in appreciable amounts a blue color forms in the solution or the yellow residue turns blue, due to reduction by the nascent hydrogen.

If only small amounts of tungsten are present, a larger portion (about half a gram) of the finely powdered material may be thoroughly mixed with four grams of sodium carbonate and fused. The fused or well sintered mass is dissolved by boiling water in the crucible. The aqueous solution is next ecidified with an equal volume of concentrated hydrochloric acid, a small piece of tin added, and the solution warmed gently if necessary. The volume of the solution should not be over 10-20 cc. A fine blue color in the solution or a blue residue indicates the presence of tungsten. In either case, if reduction is continued long enough, a brown color is obtained.

These tests, if properly used, will show the presence of tungsten in materials as low as two per cent, and by using special precautions, will detect tungsten in even lower grade materials. Tin is preferred to zinc for the reducing action, because if only a small quantity of tungsten is present, the zinc reduces it very quickly to the brown oxide, and the blue color may be unnoticed. The action of tin is slower but much more certain. If much tungsten is present, either tin or zinc gives good results.

Columbium is the only element at all likely to give a blue color followed by a brown color under the conditions of this test. The columbium blue is not so brilliant, and can be distinguished from the blue of tungsten oxides by the fact that it disappears when the blue solution is diluted with water. Vanadium also gives a blue color when solutions of its salts are reduced, but tartaric acid also will cause this reduction, whereas it will not reduce tungstic oxide. Molybdenum on reduction goes thru a series of color changes from violet to blue to black. Titanium gives a violet color. No other elements will originally interfere with the reduction test for tungsten.

The following procedure (617) will remove the above elements which if present may obscure the tungsten blue color. The solution obtained by extracting the sample after fusion with sodium carbonate (or caustic alkali) is acidified with hydrochloric acid and boiled. The precipitate, which may contain antimony, molybdenum, columbium, silica, tantalum, tin and tungsten, is filtered off and the moist residue treated with a solution of yellow ammonium sulfide. Antimony, molybdenum, tin and tungsten pass into the filtrate, columbium and tantalum remain on the filter. The ammonical sulfide extract is acidified with hydrochloric acid and boiled. The precipitate is filtered and washed with a little hydrochloric and nitric acid. Antimony, molybdenum and tin pass into the filtrate, while sulfur and tungsten, as tungstic acid, remain on the filter. Tungsten is now confirmed as follows, portions of the precipitate being taken:

1. The residue is suspended in dilute hydrochloric acid and a piece of zinc, aluminum or tin placed on the solution. A blue colored precipitate or solution indicates tungsten.

2. A portion of the precipitate is warmed with ammonium hydroxide and the extract absorbed with strips of filter paper. A strip of this paper is moistened with dilute hydrochloric acid and warmed. A yellow coloration is produced in the presence of tungsten. Another strip is moistened with a solution of stannous chloride, which produces a blue color in presence of tungsten. A third strip dipped into cold ammonium sulfide remains unchanged until warmed, when the paper turns green or blue if tungsten is present.

The following test for tungsten in steel is given by Johnson (692):

> Dissolve 0.2 gram of the sample with 5 cc. sulfuric acid (1 to3) in a test tube * * * * * If the steel has .100 to 0.3 per cent of tungsten, a black insoluble residue will be found in the bottom of the tube. This black sediment forms also with small amounts of molybdenum and phosphorus. But on addition of 1 c. c. of nitric

acid (1.20 sp. gr.) to such a solution the black entirely disappears if due to the presence of the two last named elements. The black precipitate, if caused by a small quantity of tungsten, on addition of the nitric acid, changes to a yellow. If the amount of the latter is small, it is better to put the test tube back on the water bath and permit the tungstic acid to settle for two hours, when it can be seen plainly as a yellow spiral thread rising up thru the solution by giving the test tube a rotary motion.

Other qualitative tests are known, but the above will suffice for nearly all cases, if properly carried out.

**Quantitative Determination.** The methods for the quantitative determination of tungsten in ores and other materials are quite varied and in recent years, on account of the high price of tungsten, there has been much dispute concerning the proper methods of obtaining the true tungsten content. The U. S. Bureau of Standards, under the direction of Dr. W. F. Hillebrand is now making a careful study of the methods of analysis of tungsten materials, with the idea of developing a standard method. In view of this fact, a comprehensive discussion of methods will not be made at this time. There are given herewith several well known methods which are now in common use for the determination of tungsten.

### Ammonia Method for Tungstic Oxide in Ores and Concentrates. (Ledoux and Company, New York)*

The sample for analysis should be ground impalpably fine; half an hour's work with an agate mortar will save time in the end.

Weigh 1 gram into a 250 c. c. beaker and treat it with 40 c. c. HCl, (1.20 S. G.) digest for half an hour on a steam bath and add 5 to 10 cc. $HNO_3$ (1.42 S. G.). Stir well to break up crusts of tungstic oxide and evaporate to dryness, stirring from time to time. (In this and subsequent evaporations it is important that the temperature of a steam bath, that is 85° to 95° C., shall not be exceeded, especially when the mass is nearing dryness; otherwise the tungstic oxide may become rather insoluble in ammonia.) Add 20 c. c. more HCl, stir thoroughly to break up all incrustations on the bottom of the beaker, add 3 c. c. of $HNO_3$ and again evaporate to dryness. Add 5 c. c. more HCl and again evaporate to dryness. The object of the final evaporation with HCl is to expel all $HNO_3$.

To the dry residue add 1 c. c. of HCl, warm for a moment to dissolve Fe, Mn and Ca chlorides, then add 150 c. c. of water and

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*Private communication, 1916.

boil. There is a slight tendency toward bumping, but it is not serious. To the hot solution add 2 c. c. of a 10% solution of cinchonin (in 1-1 HCl) and let stand over night. Filter using a little paper pulp in the apex of the filter paper and wash the residue, consisting of tungstic acid in insoluble matter with 2% HCl solution. Wash the residue in the filter back into the beaker with a fine jet of water, using as little water as possible, add about 10 c. c. of strong $(NH_4)OH$, warm until the tungstic acid dissolves and filter through the same filter as before into a platinum dish, wash with dilute $(NH_4)OH$ (10% strong ammonia 90% water) to entirely remove tungstic acid from the filter.

Set the ammonia solution to evaporate and in the meantime proceed with the examination of the insoluble silicious residue, which in some ores may still contain a little tungsten. Ignite it in a platinum crucible, cool, add 5 c. c. HF and 2 drops $H_2SO_4$ and slowly evaporate to dryness to expel silica. Add 2 or 3 grams of $Na_2Co_3$ to the crucible and fuse well. Cool, dissolve fusion in water and filter. The aqueous solution contains as sodium tungstate whatever tungsten may have been in the insoluble residue. Acidulate it with HCl, add 2 or 3 c. c. of cinchonine solution and let stand at a temperature of 50° C. or thereabouts for two or three hours. If any tungsten precipitate appears, filter it off, wash with very dilute cinchonine solution, dissolve in ammonia and add this solution to the main solution in the platinum dish which has now been evaporated to dryness, or nearly so. Continue the evaporation to dryness and heat the residue gently over a bunsen flame until ammonia salts are decomposed, finally heat strongly for a minute, leaving a residue of tungstic oxide which also may contain a little silica and traces of other impurities. Treat the residue in the dish with 2 c. c. of HF and 2 drops $H_2SO_4$ bringing the solution into contact with all of the residue, evaporate to dryness and ignite gently at first, and finally at the full heat of a good bunsen burner for five minutes, cool in dessicator and weigh. Fuse the residue in the dish with 4-5 grams $Na_2CO_3$ and dissolve the fusion in hot water. The small amount of insoluble matter may consist of traces of iron, manganese or lime, filter it off, wash thoroughly with hot water, ignite the residue in the platinum dish and weigh again. The difference between this weight and the first weight of dish and tungstic oxide is pure $WO_3$.

## Hydrofluoric Difference Method for Tungstic Oxide in Ores and Concentrates. (Ledoux and Company, New York)*

Treat one gram of the finely ground ore in a platinum dish with 10 c. c. hydrofluoric acid, 25 c. c. concentrated hydrochloric acid, and 10 c. c. of 25% sulfuric acid. Heat gently until solution is complete, adding more of each acid except sulfuric, if necessary. Evaporate to

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*Private Communication, 1916.

fumes of $SO_3$, dilute with water, transfer to 400 c. c. beaker, and add 100 c. c. aqua regia. The $WO_3$ can usually be completely removed from the platinum dish by rubbing with a finger cot, but if any stain adheres it can be removed with ammonia and added to the solution. The aqua regia solution is evaporated to 20 c. c., diluted to 250 c. c. with cold water, 10 c. c. cinchonine solution added and the beaker set aside for two hours to allow the precipitate to settle. Filter, wash with water containing cinchonine, and ignite residue at dull red. Treat with hydrofluoric and sulfuric acid and ignite to constant weight. Fuse the residue in the crucible with sodium carbonate, dissolve in water, and filter, washing thoroughly with hot water. The residue is ignited in the same crucible, and weighed, the difference in weight being taken as $WO_3$.

The filtrate from the last carbonate fusion of the $WO_3$ is tested for a possible Al, Ta, Nb, Sn. etc., contamination as follows:

Make filtrate acid with hydrochloric, add 5 grams ammonium chloride, and then add ammonia water until just alkaline, followed by an excess of about 5 c. c. Heat to 60° or until precipitate coagulates, filter, ignite and weigh. The weight of any precipitate thus obtained should, of course, be deducted from the $WO_3$ previously found.

## **Determination of Tungstic Oxide in Ores.** (A. H. Low, Technical Methods of Ore Analysis, 1914)

The following method is in regular use in my laboratory:

In all cases the substance should be ground to the finest possible powder in an agate mortar.

Ores and silicious material.—Weigh 1 gram into an 8-oz. copper flask. Add 4 grams of dry sodium sulphate and 4 cc. of strong sulphuric acid. Heat over a free flame, with the flask in a holder, until the free sulphuric acid has been expelled and a nearly or quite red-hot melt is obtained. Rotate the flask in cooling so as to distribute the melt over the sides. When cold, add 25 c. c. of strong hydrochloric acid and 10 cc. of strong nitric acid. Boil down to about 20 c. c., add 50 c. c. of hot water, heat to boiling, and then allow to stand on the hot-plate until well settled. Filter through a 9-cm. filter and wash ten times with hot, dilute hydrochloric acid, (1:10). Reserve the filtrate. Dissolve the tungstic acid on the filter with a mixture of 2 volumes wood alcohol and 1 volume strong ammonia, and also any adhering tungstsic acid in the flask. Wash with the above mixture at least ten times. Receive the filtrate in a small beaker. Reserve the washed residue. Transfer the filtrate to a platinum dish, evaporate to dryness on a water-bath and ignite the residue. Burn the reserved filter and washed residue in platinum or porcelain and warm the ash for a short time with a little strong sodium hydroxide solution. Dilute sufficiently, filter into a beaker and wash with hot water. Acidify the filtrate with hydrochloric acid. Add to this solution 5-6 cc. of a solution of 25 grams of cinchonine in 200 cc. of 1:1 hydrochloric acid, heat nearly to boiling and then allow to stand on the hot-plate and settle for some time. All these operations may be conducted while the main solution is evaporating. Filter through an 11-cm. ashless filter and wash at least ten times with warm, dilute cinchonine solution (6cc. of the above cinchonine solution to 100 cc. of water). Add, filter and precipitate to the ignited tungstic acid in the platinum dish and again ignite until all the carbon is burned off. The total tungstic acid obtained will usually contain a little silica. Add a few cc. of hydrofluoric acid and evaporate to dryness on a water-bath. Again ignite strongly and weigh as $WO_3$.

In most cases the residual silica will amount to only about 0.0008 gram. It will therefore frequently suffice to dispense with the platinum dish and hydrofluoric acid, making the evaporation in a large porcelain crucible and allowing for the above correction.

## **Determination of Tungstic Oxide in Steels and Alloys.** (W. W. Scott, Standard Methods of Chemical Analysis, 1917)

Low tungsten steel may be decomposed with hydrochloric or dilute sulphuric acid, the greater part of the iron being removed in solution and tungsten remaining behind as metal with a small amount of iron. The residue is then fused with sodium carbonate, the tungstate extracted with water, and tungsten determined gravimetrically. Bearley and Ibbotson recommended the following procedure:

Five grams of the sample are digested with 50 to 100 cc. of concentrated hydrochloric acid just short of the boiling point. The iron is easily attacked, but tungsten is not. On adding a few drops of concentrated nitric acid the ferrous chloride changes to the ferric form and tungsten is visibly acted upon until the clear orange-colored ferric chloride blackens again, showing that some ferrous chloride has reformed. By repeating the addition of nitric acid as required, for converting all of the iron to the ferric state and adding a slight excess the sample completely passes into solution in a few minutes. The essential points of the process consist in the presence of sufficient hydrochloric acid to keep the tungstic oxide in solution until decomposition is complete, and maintaining the strength of the acid during the decomposition. The smaller the excess of acid over necessary requirements, the greater the economy of material, and of time occupied in the subsequent evaporation. No more oxidant is used than is necessary to completely oxidize the iron and tungsten. If the acid solution of the metal is boiled until the tungstic acid begins to separate out, and then diluted with at least twice its volume of hot water and again boiled, all the oxide is precipitated except 2 or 3 milligrams. The oxide, $WO_3$, is generally contaminated with silica, which may be removed by volatilization with hydrofluoric acid and it contains traces of ferric iron, which may be estimated by fusion of the residue with sodium carbonate and extracting the tungsten with hot water; the iron remaining may be ignited and weighed and the weight subtracted from that of the previously weighed oxides $WO_3$ and $Fe_2O_3$.

In tungsten-molybdenum steels 90 cc. of strong hydrochloric acid and 10 cc. of concentrated nitric acid are recommended. The solution is evaporated to pastiness and then taken up and boiled with dilute hydrochloric acid (1:4), tungsten and silica remaining undissolved and molybdenum and iron passing into the filtrate.

Steel containing a high percentage of tungsten is extremely hard, so that it is practically impossible to get filings or borings without contaminating the sample with material from the cutting tool. The substance is best prepared by hammering into a coarse powder in a steel mortar. These coarse particles are not readily decomposed by the usual acid treatment or by the alkali carbonate and nitrate fusion. Opening up of the material may be easily accomplished by fusion with potassium acid sulphate.

About 0.5 gram of the coarse powder is heated with ten times its weight of $KHSO_4$ over a low flame, with covered crucible, the flame being removed if the action becomes violent. The melt is cooled slightly and an additional 5 grams of bisulphate added and the treatment repeated. Finally a third 5 gram portion of the acid sulphate is added and the material heated to a cherry redness for a few minues. About fifteen or twenty minutes are sufficient to decompose the material. The heating should be conducted cautiously so that only a gentle evolution of gas occurs, and the mass kept in a molten state until the black particles of steel have entirely dissolved. The mass is now cooled, the crucible and cover placed in 50 to 75 c. c. of water and boiled to disintegrate the fused mass. The liquid is treated with 20 cc. of concentrated hydrochloric acid until the precipitated tungstic acid is yellow. After settling, the precipitate is filtered off and washed with 10% ammonium nitrate solution. The residue is then dissolved in hot dilute ammonium hydroxide, the ammonium tungstate then evaporated in a weighed platinum crucible to dryness, then covered with a watchglass and the residue heated to decompose completely the ammonium salt. Tungstic oxide, $WO_3$, remains and is so weighed.

Should silica be present in the sample it will contaminate the oxide, $WO_3$. It is removed by volatilization with hydrofluoric acid. A small amount of tungsten passes into the filtrate from the acid treatment, which is recovered by repeated evaporation with hydrochloric acid.

**Ferro-Tungsten Alloys** may be dissolved by covering 1 to 2 grams of the alloy placed in a platinum dish with hydrofluoric acid and adding nitric acid in small portions, the dish being kept covered during the intervals between the additions. When the energetic action subsides 10 to 15 cc. of strong sulphuric acid are added and the material digested until the decomposition is complete. The mixture is now evaporated to $SO_3$ fumes over low flame. (Air blown over the solution assists evaporation.) The residue is collected on a filter and washed well, then ignited and weighed as $WO_3$.

**Specific Gravity Methods for Ores.** It is frequently desirable to know the approximate percentage of tungsten or tungsten trioxide in an ore, when a chemical laboratory or an analyst are not available. The method of estimating the approximate tungsten content by determination of the specific gravity of the ores has been much used in various tungsten districts. The method much used in the Boulder field, as described by Hess 915(a) is given below.

The Wolf Tongue Mining Co. originated a method which has been used by it and others on the ferberite ores of the Boulder field with excellent results, and the constants used there have been found serviceable in other fields. The mode of operation is as follows:

The articles needed are a flask holding about 1500 cubic centimeters of water and scales weighing in grams up to 3 or 4 kilos. The flask is counterbalanced, then 1,500 grams of water is weighed into it and the height marked on the neck.

For determinations, 1,300 grams of water is weighed into the flask and then dry ore is poured in until the water is raised to the 1,500 gram (c. c.) mark. This means, of course, that the ore occupies 200 cubic centimeters and that an equal bulk of water weighs 200 grams.

The weight of water in the flask, 1,300 grams, is subtracted from the total weight, and the difference, which is the weight of the ore, is divided by 200 grams, the weight of the water displaced, thus giving the specific gravity, which is compared with a table giving the equivalent percentage of $WO_3$.

At the Wolf Tongue mill the table has been elaborated so that weights may be directly read into percentages by referring to the table, as shown below.

The figures given are, of course, not exact specific gravities but are approximations close enough to give valuable data as to the probable metallic content of the ore. Such a method is applicable wherever there are no other heavy minerals in the ore and wherever the gangue is of fairly constant composition. Corrections would have to be made for the use with particular ores. For example, the specific gravity of the Boulder ferberite is 7.499, or say, 7.5, and the specific gravity of scheelite is about 6, so that for equally high percentage the scheelite ore, if free from heavy minerals, such as galena, pyrite, and hematite, will have a somewhat lower specific gravity.

### PERCENTAGE OF TUNGSTEN TRIOXIDE INDICATED BY WEIGHTS OF 200 CUBIC CENTIMETERS OF FERBERITE ORE PLUS 1,300 CUBIC CENTIMETERS OF WATER, IN BOULDER FIELD, COLO.

| Weight of ore and water (grams). | Specific gravity corresponding to weight of ore. | Specific gravity for given percentages of ore. | Percentage of ore. | Weight of ore and water (grams). | Specific gravity corresponding to weight of ore. | Specific gravity for given percentages of ore. | Percentage of ore. |
|---|---|---|---|---|---|---|---|
| 1,815 | 2.575 | ....... | ....... | 2,165 | 4.325 | 4.323 | 44 |
| 1,820 | 2.600 | ....... | ....... | 2,170 | 4.350 | ....... | ....... |
| 1,825 | 2.625 | 2.650 | ....... | 2,175 | 4.375 | 4.383 | 45 |
| 1,830 | 2.650 | 2.650 | ....... | 2,180 | 4.400 | ....... | ....... |
| 1,835 | 2.675 | ....... | ....... | 2,185 | 4.425 | ....... | ....... |
| 1,840 | 2.700 | ....... | ....... | 2,190 | 4.450 | 4.448 | 46 |
| 1,845 | 2.725 | 2.724 | 1 | 2,195 | 4.475 | ....... | ....... |
| 1,850 | 2.750 | 2.748 | 2 | 2,200 | 4.500 | ....... | ....... |
| 1,855 | 2.775 | 2.772 | 3 | 2,205 | 4.525 | 4.513 | 47 |
| 1,860 | 2.800 | 2.796 | 4 | 2,210 | 4.550 | ....... | ....... |
| 1,865 | 2.825 | 2.821 | 5 | 2,215 | 4.575 | 4.578 | 48 |
| 1,870 | 2.850 | 2.847 | 6 | 2,200 | 4.600 | ....... | ....... |
| 1,875 | 2.875 | 2.873 | 7 | 2,225 | 4.625 | ....... | ....... |
| 1,880 | 2.900 | 2.899 | 8 | 2,230 | 4.650 | 4.643 | 49 |
| 1,885 | 2.925 | 2.925 | 9 | 2,235 | 4.675 | ....... | ....... |
| 1,890 | 2.950 | 2.951 | 10 | 2,240 | 4.700 | 4.709 | 50 |
| 1,895 | 2.975 | 2.979 | 11 | 2,245 | 4.725 | ....... | ....... |
| 1,900 | 3.000 | 3.007 | 12 | 2,250 | 4.750 | ....... | ....... |
| 1,905 | 3.025 | 3.035 | 13 | 2,255 | 4.775 | 4.783 | 51 |
| 1,910 | 3.050 | 3.063 | 14 | 2,260 | 4.800 | ....... | ....... |
| 1,915 | 3.075 | ....... | ....... | 2,265 | 4.825 | ....... | ....... |
| 1,920 | 3.100 | 3.096 | 15 | 2,270 | 4.850 | 4.858 | 52 |
| 1,925 | 3.125 | 3.129 | 16 | 2,275 | 4.875 | ....... | ....... |
| 1,930 | 3.150 | 3.162 | 17 | 2,280 | 4.900 | ....... | ....... |
| 1,935 | 3.175 | ....... | ....... | 2,285 | 4.925 | 4.933 | 53 |
| 1,940 | 3.200 | 3.195 | 18 | 2,290 | 4.950 | ....... | ....... |
| 1,945 | 3.225 | 3.228 | 19 | 2,295 | 4.975 | ....... | ....... |
| 1,950 | 3.250 | ....... | ....... | 2,300 | 5.000 | 5.008 | 54 |
| 1,955 | 3.275 | 3.263 | 20 | 2,305 | 5.025 | ....... | ....... |
| 1,960 | 3.300 | 3.296 | 21 | 2,310 | 5.050 | ....... | ....... |
| 1,965 | 3.325 | 3.329 | 22 | 2,315 | 5.075 | 5.088 | 55 |
| 1,970 | 3.350 | 3.362 | 23 | 2,320 | 5.100 | ....... | ....... |
| 1,975 | 3.375 | ....... | ....... | 2,325 | 5.125 | ....... | ....... |
| 1,980 | 3.400 | 3.395 | 24 | 2,330 | 5.150 | ....... | ....... |
| 1,985 | 3.425 | 3.432 | 25 | 2,335 | 5.175 | 5.177 | 56 |
| 1,990 | 3.450 | ....... | ....... | 2,340 | 5.200 | ....... | ....... |
| 2,000 | 3.475 | 3.471 | 26 | 2,345 | 5.225 | ....... | ....... |
| 2,005 | 3.500 | 3.510 | 27 | 2,350 | 5.250 | ....... | ....... |
| 2,010 | 3.525 | ....... | ....... | 2,355 | 5.275 | 5.266 | 57 |
| 2,015 | 3.550 | 3.549 | 28 | 2,360 | 5.300 | ....... | ....... |
| 2,020 | 3.575 | ....... | ....... | 2,365 | 5.325 | ....... | ....... |
| 2,025 | 3.600 | 3.588 | 29 | 2,370 | 5.350 | 5.355 | 58 |
| 2,030 | 3.625 | 3.629 | 30 | 2,375 | 5.375 | ....... | ....... |
| 2,035 | 3.650 | ....... | ....... | 2,380 | 5.400 | ....... | ....... |
| 2,040 | 3.675 | 3.673 | 31 | 2,385 | 5.425 | ....... | ....... |
| 2,045 | 3.700 | ....... | ....... | 2,390 | 5.450 | 5.444 | 59 |
| 2,050 | 3.725 | 3.717 | 32 | 2,400 | 5.475 | ....... | ....... |
| 2,055 | 3.750 | 3.761 | 33 | 2,405 | 5.500 | ....... | ....... |
| 2,060 | 3.775 | ....... | ....... | 2,410 | 5.525 | ....... | ....... |
| 2,065 | 3.800 | 3.805 | 34 | 2,415 | 5.550 | 5.553 | 60 |
| 2,070 | 3.825 | ....... | ....... | 2,420 | 5.575 | ....... | ....... |
| 2,075 | 3.850 | 3.850 | 35 | 2,425 | 5.600 | ....... | ....... |
| 2,080 | 3.900 | 3.899 | 36 | 2,430 | 5.625 | ....... | ....... |
| 2,085 | 3.925 | ....... | ....... | 2,435 | 5.650 | 5.639 | 61 |
| 2,090 | 3.950 | 3.948 | 37 | 2,440 | 5.675 | ....... | ....... |
| 2,095 | 3.975 | ....... | ....... | 2,445 | 5.700 | ....... | ....... |
| 2,100 | 4.000 | 3.997 | 38 | 2,450 | 5.725 | ....... | ....... |
| 2,105 | 4.025 | ....... | ....... | 2,455 | 5.750 | 5.745 | 62 |
| 2,110 | 4.050 | 4.046 | 39 | 2,460 | 5.775 | ....... | ....... |
| 2,115 | 4.075 | ....... | ....... | 2,465 | 5.800 | ....... | ....... |
| 2,120 | 4.100 | 4.094 | 40 | 2,470 | 5.825 | ....... | ....... |
| 2,125 | 4.125 | ....... | ....... | 2,475 | 5.850 | 5.851 | 63 |
| 2,130 | 4.150 | 4.155 | 41 | 2,480 | 5.875 | ....... | ....... |
| 2,135 | 4.175 | ....... | ....... | 2,485 | 5.900 | ....... | ....... |
| 2,140 | 4.200 | 4.211 | 42 | 2,490 | 5.925 | ....... | ....... |
| 2,145 | 4.225 | ....... | ....... | 2,495 | 5.950 | 5.957 | 64 |
| 2,150 | 4.250 | ....... | ....... | 2,500 | 6.000 | ....... | ....... |
| 2,155 | 4.275 | 4.267 | 43 | 2,505 | 6.025 | ....... | ....... |
| 2,160 | 4.300 | ....... | ....... | 2,510 | 6.050 | 6.060 | 65 |

The details of a similar method used in the Atolia field are given as follows: 915(a)

The apparatus used by me in making these specific gravity determinations was a small scale for weighing out from 1 to 4 kilos of the scheelite ore. I had a 2,000 cubic centimeter glass graduate which was about 18 or 20 inches in height and some 2½ inches in diameter. I filled this with water, generally for convenience to the 1,000 cubic centimeter mark, and then introduced the charge of 1 or more kilos. The displacement of the ore was noted and the specific gravity calculated from it. Then by reference to my chart, which was being made more accurate all the time by reason of the various analyses to check the specific gravity, I was able to get at an extremely close idea of the content—so close in fact, that I latterly came to rely more on it than on analyses, more particularly for the reason that at that time many chemists used different schemes and there were many discrepancies between them for a time.

Later I made also the accompanying table of specific gravity as against $WO_3$ content and did not then have to refer to the chart.

It may be of interest to note that I always required scheelite ores to be clean—that is, with the usually accompanying magnetite removed, as it is quite evident that otherwise my specific gravity determinations would have been vitiated.

The table compiled by Mr. Draper and Mr. F. H. Lerchen is as follows:

### PER CENT OF TUNGSTEN TRIOXIDE INDICATED BY SPECIFIC GRAVITY OF SCHEELITE ORES OF THE ATOLIA FIELD

| Specific gravity. | Per cent. | Specific gravity. | Per cent. | Specific gravity. | Per cent. | Specific gravity. | Per cent. |
|---|---|---|---|---|---|---|---|
| 3.00 | 15.40 | 4.77 | 61.80 | 5.19 | 68.00 | 5.60 | 73.20 |
| 3.10 | 18.40 | 4.78 | 62.00 | 5.20 | 68.10 | 5.61 | 73.30 |
| 3.20 | 21.20 | 4.79 | 62.00 | 5.21 | 68.20 | 5.62 | 73.40 |
| 3.30 | 24.50 | 4.80 | 62.10 | 5.22 | 68.40 | 5.63 | 73.50 |
| 3.40 | 28.00 | 4.81 | 62.20 | 5.23 | 68.50 | 5.64 | 73.60 |
| 3.50 | 31.20 | 4.82 | 62.40 | 5.24 | 68.60 | 5.65 | 73.70 |
| 3.60 | 34.00 | 4.83 | 62.80 | 5.25 | 68.70 | 5.66 | 73.80 |
| 3.70 | 37.00 | 4.84 | 63.00 | 5.26 | 69.00 | 5.67 | 73.90 |
| 3.80 | 39.60 | 4.85 | 63.20 | 5.27 | 69.10 | 5.68 | 74.00 |
| 3.90 | 42.20 | 4.86 | 63.30 | 5.28 | 69.20 | 5.69 | 74.10 |
| 4.00 | 44.80 | 4.87 | 63.40 | 5.29 | 69.40 | 5.70 | 74.20 |
| 4.10 | 47.30 | 4.88 | 63.60 | 5.30 | 69.60 | 5.71 | 74.32 |
| 4.20 | 49.60 | 4.89 | 63.70 | 5.31 | 69.70 | 5.72 | 74.44 |
| 4.30 | 51.60 | 4.90 | 63.80 | 5.32 | 69.80 | 5.73 | 74.56 |
| 4.40 | 54.00 | 4.91 | 64.10 | 5.33 | 70.00 | 5.74 | 74.68 |
| 4.50 | 56.20 | 4.92 | 64.20 | 5.34 | 70.10 | 5.75 | 74.80 |
| 4.51 | 56.40 | 4.93 | 64.30 | 5.35 | 70.20 | 5.76 | 74.92 |
| 4.52 | 56.70 | 4.94 | 64.40 | 5.36 | 70.40 | 5.77 | 75.04 |
| 4.53 | 57.00 | 4.95 | 64.50 | 5.37 | 70.60 | 5.78 | 75.16 |
| 4.54 | 57.30 | 4.96 | 64.70 | 5.38 | 70.70 | 5.79 | 75.28 |
| 4.55 | 57.50 | 4.97 | 64.80 | 5.39 | 70.80 | 5.80 | 75.40 |
| 4.56 | 57.60 | 4.98 | 65.00 | 5.40 | 71.00 | 5.81 | 75.54 |
| 4.57 | 57.80 | 4.99 | 65.20 | 5.41 | 71.10 | 5.82 | 75.68 |
| 4.58 | 58.00 | 5.00 | 65.40 | 5.42 | 71.20 | 5.83 | 75.82 |
| 4.59 | 58.20 | 5.01 | 65.50 | 5.43 | 71.30 | 5.84 | 75.96 |
| 4.60 | 58.40 | 5.02 | 65.60 | 5.44 | 71.40 | 5.85 | 76.10 |
| 4.61 | 58.60 | 5.03 | 65.80 | 5.45 | 71.50 | 5.86 | 76.24 |
| 4.62 | 59.00 | 5.04 | 66.00 | 5.46 | 71.60 | 5.87 | 76.38 |
| 4.63 | 59.20 | 5.05 | 66.10 | 5.47 | 71.70 | 5.88 | 76.52 |
| 4.64 | 59.30 | 5.06 | 66.30 | 5.48 | 71.80 | 5.89 | 76.66 |
| 4.65 | 59.50 | 5.07 | 66.40 | 5.49 | 71.90 | 5.90 | 76.80 |
| 4.66 | 59.80 | 5.08 | 66.60 | 5.50 | 72.00 | 5.91 | 76.94 |
| 4.67 | 60.00 | 5.09 | 66.80 | 5.51 | 72.10 | 5.92 | 77.08 |
| 4.68 | 60.10 | 5.10 | 66.90 | 5.52 | 72.24 | 5.93 | 77.22 |
| 4.69 | 60.20 | 5.11 | 67.00 | 5.53 | 72.36 | 5.94 | 77.36 |
| 4.70 | 60.40 | 5.12 | 67.10 | 5.54 | 72.48 | 5.95 | 77.50 |
| 4.71 | 60.60 | 5.13 | 67.20 | 5.55 | 72.60 | 5.96 | 77.64 |
| 4.72 | 60.70 | 5.14 | 67.30 | 5.56 | 72.72 | 5.97 | 77.78 |
| 4.73 | 61.00 | 5.15 | 67.60 | 5.57 | 72.84 | 5.98 | 77.92 |
| 4.74 | 61.20 | 5.16 | 67.70 | 5.58 | 72.96 | 5.99 | 78.06 |
| 4.75 | 61.40 | 5.17 | 67.80 | 5.59 | 73.08 | 6.00 | 78.20 |
| 4.76 | 61.60 | 5.18 | 67.90 | | | | |

Runner (652) (915a) has drawn curves showing the relation of specific gravity and tungstic oxide content for wolframite from a number of localities. The results from these curves are not as accurate as from the tables worked out for particular deposits, as in the preceding methods.

The following equation given by Runner can be applied to the ore from any particular field and tables or curves of specific gravity and tungstic oxide content can be worked out.

Assuming the density (d) of the gang to be 2.65, of wolframite to be 7.35, of scheelite to be 6.0 and the $WO_3$ content of wolframite

74.58%, and of scheelite 80%, the $WO_3$ content of ores is computed by means of the following formulas:

$$d_O = \frac{(x \times d_M)}{100} + \left(d_G \times \frac{(100 - x)}{100}\right) \text{ or } x = \frac{100 \times (d_O - d_G)}{(d_M - d_G)}$$

where $x/100 = \%$ by vol. of mineral in ore; $d_O$=sp. gr. of the ore; $d_M$=sp. gr. of the pure ore-mineral; $d_G$=sp. gr. of the gang; $x \times d_M/d_O = \%$ by wt. of mineral in ore (W); $W \times \%\ WO_3$ in ore. minerals = % $WO_3$ in ore. The $WO_3$ content of 18 ores as detd. by chemical analysis and by the computation method are reported in a table, showing a mean difference (except in the presence of $SnO_2$) of 0.65%. The method is not applicable to ores containing cassiterite, unless the content of the latter is constant and can be figured with the gangue. Runner recommends that the density be determined by means of a pycnometer, using rather coarsely ground ore, freshly boiled $H_2O$, and removing air under the pump. An ordinary flask with a mark on neck may be used for less accurate determinations. Curves may be drawn showing the ratio of density of tungsten minerals to the richness in $WO_3$. The method is recommended for rapidly obtaining approximate results.

In all of these specific gravity methods the assumption is made that either the gangue material is quartz, or rock of low specific gravity, and that it remains somewhat constant. The presence of heavy minerals such as cassiterite, barite and so forth, will of course, vitiate the results. It is said (915a) that one dealer was ruined in 1916 by purchasing ore on the specific gravity basis which had been "salted" with barite.

# PART II.

## A BIBLIOGRAPHY OF TUNGSTEN

By Miner Louis Hartmann

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## INTRODUCTION

The phenomenal rise in importance of tungsten in the last few years has created a demand for reliable information concerning this metal. The literature of the subject is widely scattered thru the technical periodicals and much that has been written is merely a brief restatement of facts taken from older, more complete descriptions. In making a special study of the subject of tungsten during the last three years the author has felt the need of a bibliography, and in the following pages is presented as complete a list of references as is permitted by the library facilities available.

The subject has been divided into ten general sections, with sub-divisions as follows:

I. Early References.
  (a) Earliest references to wolfram.
  (b) Important early references.

II. Preparation of tungsten metal and its important commercial compounds.

III. Properties of tungsten.
  (a) Physical properties of the metal.
  (b) Chemical behavior of the metal.
  (c) Atomic weight.

IV. Uses of metallic tungsten.
  (a) Uses of tungsten in iron alloys.
  (b) Uses of tungsten in non-ferrous alloys.
  (c) Uses of tungsten in incandescent lighting.
  (d) Uses and preparation of ductile tungsten.
  (e) General and miscellaneous uses of tungsten.

V. Compounds of tungsten.

- (a) Oxides.
- (b) Acids.
- (c) Tungstates.
- (d) Bronzes.
- (e) Tungsten with the halogens.
- (f) Tungsten and sulfur.
- (g) Tungsten and nitrogen.
- (h) Tungsten and hydrogen.
- (i) Tungsten and phosphorus.
- (j) Tungsten and arsenic.
- (k) Tungsten and zirconium.
- (l) Tungsten and aluminum.
- (m) Tungsten and boron.
- (n) Tungsten and carbon.
- (o) Tungsten and silicon
- (p) Organic compounds.

VI. Analytical chemistry of tungsten.

- (a) Qualitative detection.
- (b) Quantitative detection.
- (c) Quantitative determination of tungsten in ores.
- (d) Quantitative determination of tungsten in steel and other alloys.
- (e) Analysis of metallic tungsten and tungsten compounds.
- (f) Tungsten compounds as reagents.
- (g) Quantitative separation of tungsten from other elements.
    1. Arsenic and phosphorus.
    2. Silicon.
    3. Tin.
    4. Molybdenum.
    5. Vanadium.
    6. Columbium and tantalum.
    7. Titanium.
    8. Antimony.
    9. Manganese.
    10. Miscellaneous Separations.

VII. Mineralogy of tungsten.

VIII. Geological occurrence of tungsten minerals.

- (a) United States.
    - (1) Alaska.
    - (2) Arizona.
    - (3) California.
    - (4) Colorado.
    - (5) Connecticut.
    - (6) Idaho.
    - (7) Missouri.
    - (8) Montana.
    - (9) Nevada.
    - (10) New Mexico.
    - (11) Oregon.
    - (12) South Dakota.
    - (13) Texas.
    - (14) Washington.
- (b) Foreign.
    - (1) Australia.
    - (2) Bohemia.
    - (3) Burma.
    - (4) Canada.
    - (5) China and Japan.
    - (6) England.
    - (7) France.
    - (8) Germany.
    - (9) Greenland.
    - (10) Italy.
    - (11) Malay States.
    - (12) New Zealand.
    - (13) Portugal.
    - (14) Russia.
    - (15) South Africa.
    - (16) South America.
    - (17) Spain.
    - (18) Sweden.
- (c) Miscellaneous geological references.

IX. Mining and milling tungsten ores.

X. Miscellaneous.
  (a) General reviews.
  (b) Miscellaneous references concerning tungsten.
  (c) Tungsten production and markets.

The abbreviations for periodicals are, as far as possible, the same as those used in "Chemical Abstracts" (See Chemical Abstracts 11, pp. VII-XXV, 1917). The volume number is given first in bold face type, followed by the page numbers, and the year in parenthesis. In case the series is given, it is placed in paranthesis, preceding the volume number; parts of volume in Roman numerals follow the volume number. In some cases where the exact title was not known the contents have been indicated in place of the title.

The classification of references has necessarily been made largely from the titles rather than from the contents, but as far as possible, cross references to different sections have been given when the article was known to contain information relative to more than one section. Certain references have been repeated when they were considered very important in more than a single section.

The patent literature has been omitted entirely, largely because of incomplete library facilities. It seemed best not to publish any patent references unless the list was known to be fairly complete.

The author will appreciate any corrections or additions to the following list of references to the literature of tungsten.

Rapid City, South Dakota.
May, 1918.

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## ERRATA

Page 14, line 25, "wolframites" should read "wolframite."
Page 15, line 13, insert "series" after "wolframite."
Page 16, line 29, "spahalerite" should read "sphalerite."
Page 20, line 20, "has" should read "have."
Page 22, line 10, "lense" should read "lens."
Page 28, line 3. omit "rich."
Page 42, line 7, "thyolites" should read "rhyolites."
Page 43, line 14, "central part" should read "north central part."
Page 44, line 32, "or" should read "of."
Page 49, line 20, "types 2 and 4" should read "types 3 and 4."
Page 80, line 27, "based" should read "basal."

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# SOUTH DAKOTA SCHOOL OF MINES

Bulletin No. 13

DEPARTMENT OF GEOLOGY

# THE WHITE RIVER BADLANDS

By

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Rapid City, South Dakota
November, 1920

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# THE WHITE RIVER BADLANDS

(A revised reprint of South Dakota State School
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Formations of the Black Hills Region)

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Members at date of authorization:
T. W. Dwight, President
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The picture which geology holds up to our view of North America during the Tertiary ages are in all respects, but one, more attractive and interesting than could be drawn from its present aspects. Then a warm and genial climate prevailed from the Gulf to the Arctic Sea; the Canadian highlands were higher, but the Rocky Mountains lower and less broad. Most of the continent exhibited an undulating surface, rounded hills and broad valleys covered with forests grander than any of the present day, or wide expanses of rich savannah, over which roamed countless herds of animals, many of gigantic size, of which our present meager fauna retains but a few dwarfed representatives. Noble rivers flowed through plains and valleys, and sea-like lakes, broader and more numerous than those the continent now bears, diversified the scenery. Through unnumbered ages the seasons ran their ceaseless course, the sun rose and set, moons waxed and waned over this fair land, but no human eye was there to mark its beauty, nor human intellect to control and use its exuberant fertility. Flowers opened their many-colored petals on meadow and hill-side, and filled the air with their perfumes, but only for the delectation of the wandering bee. Fruits ripened in the sun, but there was no hand there to pluck, nor any speaking tongue to taste. Birds sang in the trees, but for no ears but their own. The surface of lake or river whitened by no sail, nor furrowed by any prow but the beast of the water-foul; and the far-reaching shores echoed no sound but the dash of the waves and the lowing of the herds that slacked their thirst in the crystal waters.

J. S. NEWBERRY.

# PREFACE

Is it of interest to you that the White River Badlands are the most famous deposits of the kind in the world? Do you know that aside from their picturesque topography they tell a marvelous nature story; a story of strange climate, strange geography, and strange animals; of jungles, and marshes, and tranquil rivers, of fierce contests for food, and life, and supremacy; of a varied series of events through ages and ages of time showing the working-out of well-laid plans with no human being to help or interfere? Most people know something of these things but generally it is in an indefinite piecemeal way. Except to scientific men the Badlands, instead of affording the intellectual delight that they should, are commonly little else than a sterile wonder.

This book is written in order that the intellectually alert, the indifferent thinker, the old and the young, irrespective of educational advantage or technical training may have opportunity to get a clearer and more comprehensive idea of this wonderful part of nature's handiwork.

The landscape views given herein, have never been surpassed, it is believed, for clearness of expression or for detail of configuration and the reproductions of the animals, made by the best vertebrate paleontologists of America, are marvels of beauty and accuracy. Among the pictures of animals both in fossil form and restored to life and activity as they were in their ancient White river home are: Brontotherium, the huge thunderbeast; Metamynodon, the bulky rhinoceros; Moropus, the grotesque chalicothere; Mesohippus, the three toed horse; Oreodon, the ruminating hog; Poebrotherium, the ancestral camel; Protoceras, the six-horned herbivore; Hoplophoneus, the savage-tooth tiger; Stylemys, the large dry land tortoise; Crocodilus, the old-time crocodile; and many others long since vanished from earth's activity. The book indicates why the camel of that time had no pads on his feet and the deer no antlers on his head, why the saber-tooth had his enormously vicious teeth, why dogs had retractile claws like the cat, why the horse had three toes on each foot instead of one, and many other things of like kind.

Geologists and paleontologists have been engaged for three-quarters of a century in unravelling the intricate story of these strange lands and I have drawn liberally from the published works of these men. My gratitude for this material is hereby most gratefully acknowledged. Some of the more important publications consulted are listed under the heading, Bibliography. Those wishing a more complete record of papers with annotations on the same should consult my Bibliography of the Geology and Mining Interests of the Black Hills Region, published as South Dakota School of Mines Bulletin No. 11, 1917. I have endeavored in the text or in the figures and plate descriptions to indicate in proper way the source of material used.

It is an especial pleasure to record here the favors extended by Professor Henry F. Osborn of the American Museum of Natural History, by Professor W. B. Scott of Princeton University, and by The Macmillan Company of New York City in permitting the use of many excellent figures and plates from the two great books, Osborn's Age of Mammals in Europe, Asia, and North America, and Scott's History of Land Mammals in the Western Hemisphere. These books deserve a large audience. They should be consulted by all who wish acquaintance with mammalian progress, and particularly by those interested in our White River Badlands, the classic vertebrate fossil ground of America.

The subject is of absorbing interest but I have endeavored to treat it without exaggeration, sensation or cheapness. The present book while following somewhat closely the plan and wording of the earlier publication is arranged with a little more consideration for the general reader. The revised form freed from technical references and faunal lists in the body of the book and with a more generous use of figures and plates should be readily and entirely assimilated. It is believed especially that the general reader and teachers and high school students interested in natural history subjects should find the information valuable and inspirational.

CLEOPHAS C. O'HARRA.

November 4, 1920.

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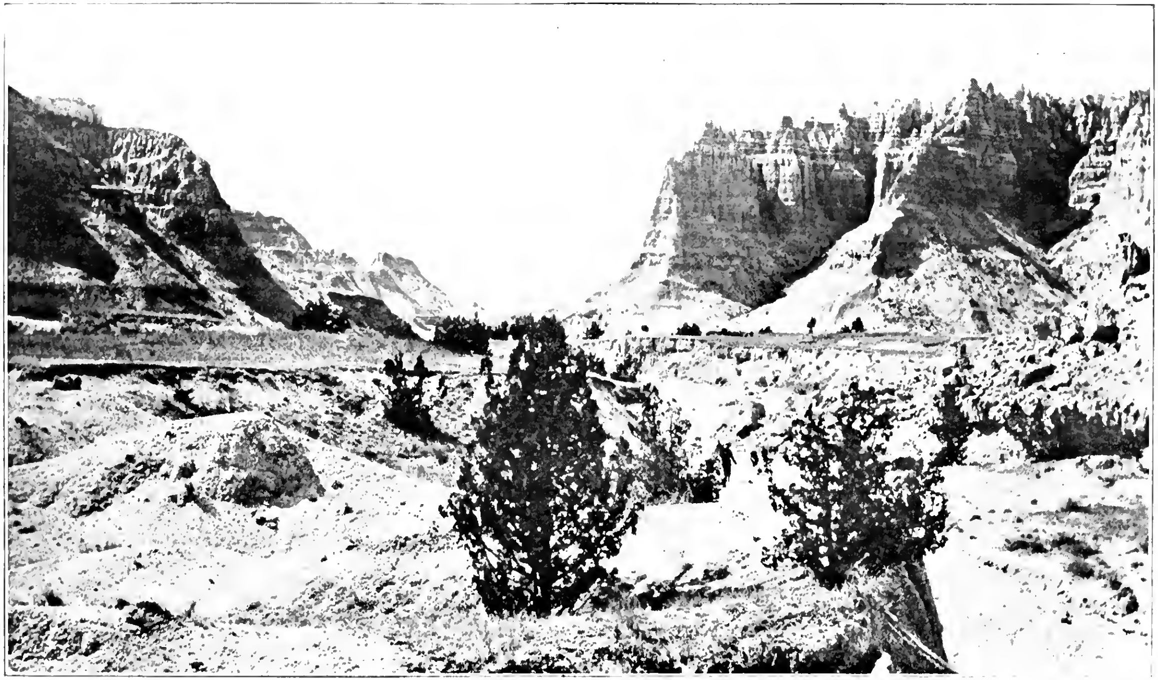


Photograph by O'Harra, 1909.

The Gateway, School of Mines Canyon, at northwest base of Sheep Mountain, Pennington County, South Dakota.

# The White River Badlands

## THEIR IMPORTANCE AND DISTRIBUTION

The White River Badlands constitute the most important badland area of the world. They lie chiefly in southwestern South Dakota but a prominent arm known as Pine Ridge extends through northwestern Nebraska into eastern Wyoming. Most of the drainage is by way of White river, hence the name. The area is very irregular and there are many outliers particularly to the west and northwest of the central portion. Southward geological formations similar to those of White river extend over much of Nebraska and eastern Colorado but here, except along the forks of the Platte the badland feature is not prominent.

Originally the badland formations made up a vast earth blanket stretching for hundreds of miles north and south along the eastern slope of the Rocky Mountain front. Their greatest plainsward extension cannot now be definitely determined, but in South Dakota they reach beyond the Missouri to near the James river valley. They seem to have entirely surrounded the Black Hills and of this uplift only the higher portions remained uncovered. From these restricted areas and from the rising Rocky Mountains detrital materials had opportunity throughout a long period to add their volume to the deposits of the bordering lowlands. Later this vast series of sediments was elevated and was gradually trenched by innumerable streams and most of the material washed away. Along with these changes the badland topography developed and has continued to develop to the present time.

The Badlands do not readily lend themselves to accurate definition nor to brief description. They are in consequence a much misunderstood portion of American territory. The name is a literal translation of the *Mauvaises Terres* of the early French Canadian trappers who had in turn appropriated the still earlier *Mako Sica* (mako, land; sicha, bad) of the Dakota Indians. It signifies a country difficult to travel through chiefly because of the rugged surface features and the general lack of good water. The term is unduly detractive although apt enough in frontier days when hardships of travel were rigorous even under the best of circumstances.

Much the greater portion of the area within the badland region as commonly understood is level and fertile and is covered with rich wild grasses and recent occupation by thousands of settlers has brought out the fact that over large tracts, especially on the higher tables, good refreshing water may be obtained by sinking shallow wells in the soil and gravel mantle that lies rather widespread on the surface. The country has in years gone by been of much value as an open range for the grazing of cattle and horses. Now that it has been made accessible by railway the land has largely passed from the government to private ownership and farming and dairying on an extensive scale are being carried on. Within little more than a stone's throw of where the early explorers spoke of the region as an inferno for heat and drought men have built homes for themselves and their families and are now raising good crops of vegetables, tame grasses and staple grains.

But the purpose of this book is more particularly to indicate the value of the Badlands as an educational asset. Nowhere in the world can the influences of erosion be more advantageously studied or more certainly or quickly understood. Nowhere does the progress of mammalian life reveal itself with greater impressiveness or clearness. Nowhere do long ago days connect themselves more intimately with the present or leave more helpful answers to our wondering questions as to the nature and import of the earth's later development.

The most picturesque portion of the White River Badlands lies between White river and Cheyenne river southeast of the Black Hills. This is known as the Big Badlands, and the chief topographic features, Sheep Mountain and the Great Wall, high remnants of an extensive tableland now reduced to a narrow watershed, are flanked by a marvelous network of rounded hillocks, wedge slopes, grassy flats, and sheer declivites. (For illustrations of these see the views in the plate section). The Great Wall viewed from White river valley presents a particularly rugged aspect and, like the great wall that it is, stretches for many miles in a nearly east-west direction, disclosing for much of the distance a continuous serrated skyline series of towers, pinnacles and precipitous gulches. Sheep Mountain, the cedar covered top of which overlooks all of the surrounding country, presents a view that is hopelessly indescribable. One side leads gently down to a high intricately etched grass-covered flat covering a few cramped square miles. In all other directions everything is strange and wierd in the extreme. Far away cattle or horses may be seen feeding on levels of green and here and there distant dots in ruffled squares indicate the abodes of happy homesteaders. Immediately about all is still. Until recently the sharp eye could occasionally detect a remnant bunch of mountain sheep, once numerous in this locality, but quickly and quietly they would steal to cover among the intricate recesses of the crumbling precipices. Song birds are present but they are prone to respect the solitude. Only an occasional eagle screams out a word of curiosity or defiance as he sails majestically across the maze of projecting points and bottomless pits. Magnificent ruins of a great silent city painted in delicate shades of cream and pink and buff and green! Domes, towers, minarets, and spires decorate gorgeous cathedrals and palaces and present dimensions little dreamed of by the architects of the ancients.

At first as one looks over the strange landscape there may come a feeling of the incongruous or grotesque but studying more closely the meaning of every feature the spirit of this marvelous handiwork of the Great Creator develops and vistas of beauty appear. Here on Sheep Mountain or on the higher points of the Great Wall the contemplative mind weaves its way into the long geologic ages. There are visions of Cretaceous time. A vast salt sea stretches as a broad band from the Gulf of Mexico to the Arctic regions and slowly deposits sediments that are destined to form much of the great western plains of the continent. Strange reptiles sport along the shores of this sea and myriads of beautiful shellfish live and die in its mud laden rush-fringed bays. Changes recur, the salt becomes less pronounced, the sea shallows, brackish conditions prevail but the animals and plants with many alterations and much advancement live on. Deep rumblings in the neighboring Black Hills and in the Rocky Mountains with accompanying intrusions of igneous rocks portend widespread changes, the shallowing sea slips away and fresh water marsh-lands and deltas prevail. The Tertiary comes and with the close of its earlier divisions the White River badland formations begin to be deposited. Barriers somewhere are let down and a great horde of animals higher in type than any known before begins to appear. Here in the foreground gently flowing streams push their muddy way through reedy marshlands and vigorous forests and furnish a lazy playground for countless turtles and occasional crocodiles. In favored recesses groups of rhinoceroses may be seen, some heavy of bulk and water loving, others graceful and preferring dry land. Little fleet-footed ancestral horses with names as long as their legs nibble the grass on the hillsides or, by means of their spreading three-toed feet, trot unhindered across the muddy flats, the nearest restraining rider being more than a million years away. Here and there we see a group of predaceous dogs and not infrequently do we get a glimpse of a ferocious tiger-like cat. On the higher ridges, even far within the distant hills and mountains six horned herbivores reveal their inquisitive pose and perhaps anon, like the antelope, show their puffs of white as they scamper from the nearing presence of some stealthy foe. But the "reigning plutocrat" is the titanothere. In great numbers we see his majestice form as he moves among his kin and crops at his leisure the coarse grasses of the lowlands. Here and there are beavers and gophers and squirrels busy with their toil and their play, and hedgehogs and moles and swine and deer and tapirs and camels, and many other creatures too strange to mention without definition. Although the Badlands as we now know them were until recently little frequented by man except in favored places, do not think the country was in the ages gone by a barren waste or a place of solitude. To all these animals it was home. Here they fought for food and life and supremacy. To them the sun shone, the showers came, the birds sang, the flowers bloomed, and stately trees gave convenient shade to the rollicking young of many a creature.

But "everlasting hills' have their day and rivers do not flow on forever. These animals, under a Guiding Providence, having inherited the more essential characters of their ancestors, in turn transmitted to later individuals the features best fitted to serve their purpose in the winning of life's great race. One by one, group by group, they died, the bodies of most of them quickly feeding the surrounding elements but a chosen few, tucked away by the kindly hand of nature, remaining as unique monuments of the dawning time of the great mammalian races, are now being revealed as gently by nature again in these the days of man.

## HISTORY OF EXPLORATION

Our first knowledge of the White River badlands worthy of record dates from 1847. Early in this year Dr. Hiram A. Prout of St. Louis described in the American Journal of Science a fragment of the lower jaw of the great Titanothere, he calling it a Paleotherium. A few months later Dr. Joseph Leidy described in the Proceedings of the Academy of Natural Sciences of Philadelphia a fairly well preserved head of what he termed a Poebrotherium. The name implies belief in the ruminating nature of the animal and later investigation, strange as it may seem, showed it to be an ancestral camel. The two specimens referred to were obtained from representatives of the American Fur Company. Their exact locality is not known but it is believed to be somewhere between the present towns of Scenic and Wall.

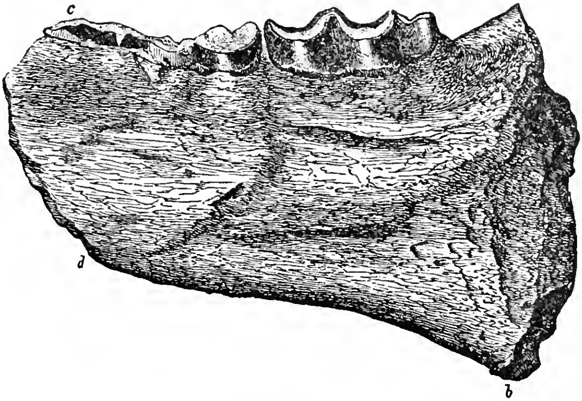


**Figure 1—Fragment of the lower jaw of a Titanothere, the first fossil discovered in the Big Badlands. Described by Dr. H. A. Prout of St. Louis, 1846-47.**

The descriptions of these specimens aroused much interest among men of science and in 1849, Dr. John Evans in the employ of the government under the direction of David Dale Owen of the Owen Geological Survey, visited the region for the purpose of studying its peculiar features and of collecting additional fossils in order to determine the age of the strata. This visit was of the greatest importance and the results were early published in a most careful scientific manner. The report, chiefly the work of Dr. Leidy, who described the fossils and Mr. Evans who through Mr. Owen reported upon the geography and geology, gave to the world the first authentic description of the nature of the badland country. (Plate 4). Thaddeus A. Culbertson visited the region during the following year, 1850, and obtained at the request of the Smithsonian Institution a small but important series of specimens. F. V. Hayden (Plate 8) of the United States Geological Survey of the Territories made several explanatory trips particularly in 1853, '55, '57 and '66. Often in grave danger and hindered by varied hardships he nevertheless succeeded in unraveling in large measure the main geologic features of the country. Plates 5, 6 and 7). All of these parties collected vertebrate fossils of the greatest scientific value and Dr. Leidy (Plate 8) whom I have already mentioned, being recognized as the best fitted man in America to determine the nature of such fossils, was called upon to write their description. Important papers rapidly issued from his pen and each new description served to point out the need of further exploration. He published in 1869 in the Journal of the Academy of Natural

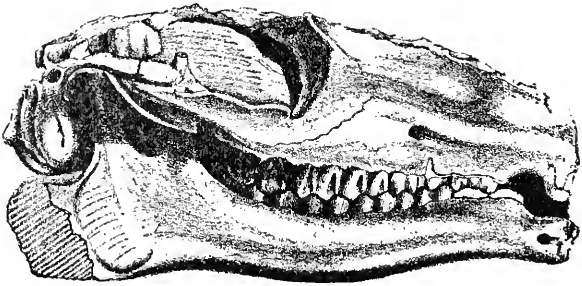
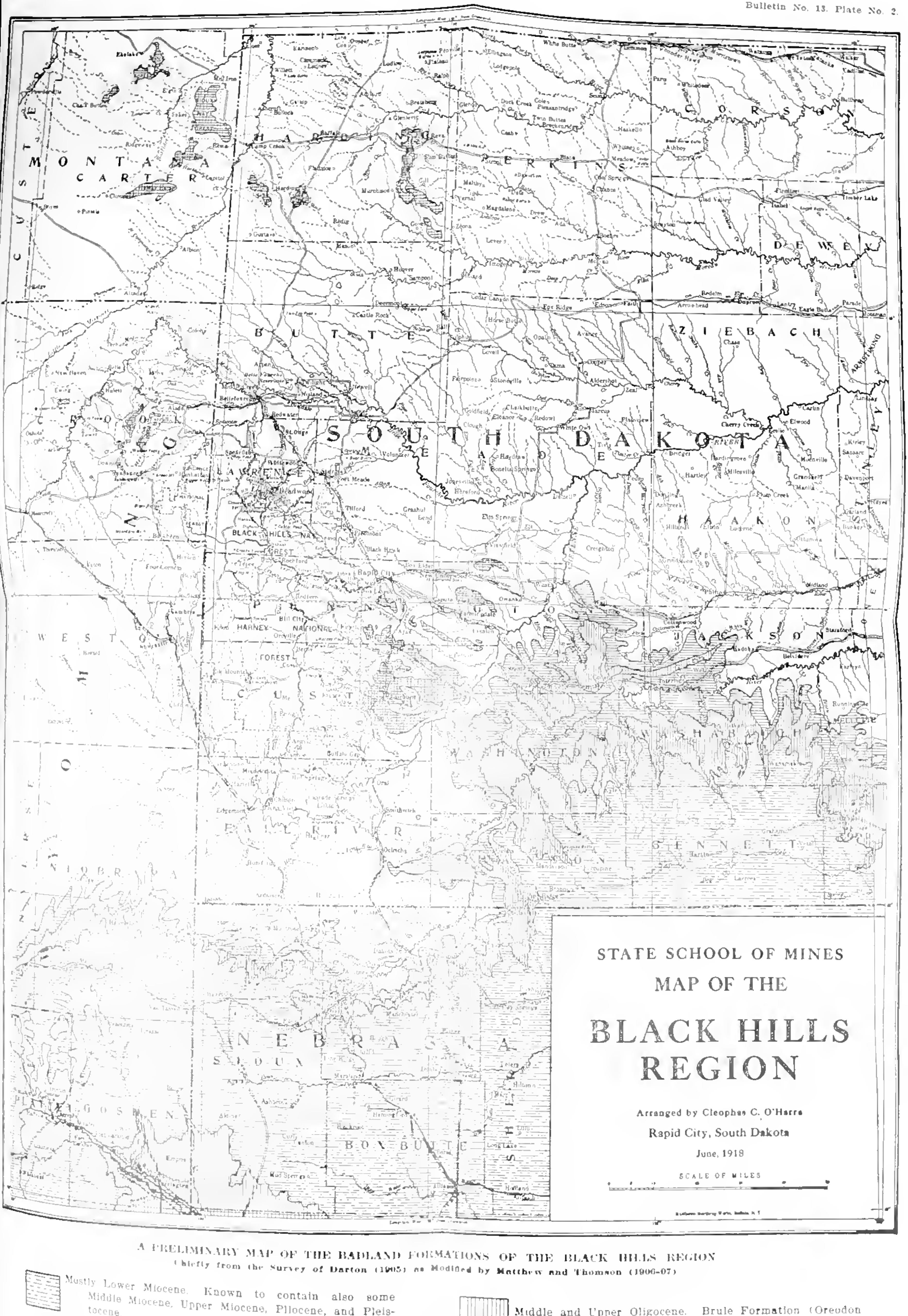


Figure 2—Head of an ancestral camel, *Poebrotherium*, the earliest Badland fossil described by Dr. Joseph Leidy, of Philadelphia, 1847.



A PRELIMINARY MAP OF THE BADLAND FORMATIONS OF THE BLACK HILLS REGION

**Chiefly from the Survey of Darton (1905) as Modified by Matthew and Thomson (1906-07)**

▤ Mostly Lower Miocene. Known to contain also some Middle Miocene, Upper Miocene, Pliocene, and Pleistocene.

▥ Middle and Upper Oligocene. Brule Formation (Oreodon and Protoceras Beds).

▦ Non-differentiated Oligocene (Chiefly Chadron formation).

▤ Lower Oligocene. Chadron Formation (Titanotherium Beds).

Sciences of Philadelphia his monumental work "The Extinct Mammalian Fauna of Dakota and Nebraska." In this large volume he brought together the accumulated information of more than twenty years and in consummate manner established the White River badlands as one of the great fossil vertebrate repositories of the world.

A new epoch in the investigation followed. New men entered the field and institutions not hitherto represented began to send out exploratory and collecting expeditions. Among the institutions were Yale University, University of Princeton, United States Geological Survey, American Museum of Natural History, University of Nebraska, University of South Dakota, Carnegie Museum, Amherst College, Field Columbian Museum and the South Dakota State School of Mines.

The first Yale party, under direction of Professor O. C. Marsh (Plate 8) visited the region in 1870. Professor Marsh, not satisfied with the crude methods of collecting with which the earliest investigators had to content themselves, undertook extensive quarrying for the fossils, and developed also more refined methods of utilizing detached and broken pieces. In this way a number of well-preserved, complete, or nearly complete, skeletons were obtained where before the material was weathered and fragmentary. Complete restorations of skeletons disclose structural features much more readily than detached bones and imperfect fragments, and Prof. Marsh first extensively developed this feature for the fossil vertebrates of the White River and other western badlands. He was thus able to emphasize more easily the nature of these animals and to point out more clearly their profoundly significant relation to present-day life. Prof. Marsh continued field work for many years, the collecting being done sometimes by expeditions directly from Yale, some times by collectors hired for the purpose. Following the first Yale expedition of 1870, other Yale expeditions were in the region in 1871, '73, '74 and hired collectors in 1886, '87, '88, '89, '90, '94, '95, '97, '98. The institution was represented in northwestern Nebraska also in 1908.

In this connection it may be stated that during the years 1886-'90, much of the field work directed by Professor Marsh was done under the auspices of the United States Geological Survey, the materials collected being later transferred to the National Museum. Much of this collecting, particularly during the years 1886, '87, '88, was in immediate charge of Mr. J. B. Hatcher, one of the most original and successful collectors that has ever worked in the badlands.

The University of Princeton was first represented by an expedition under direction of Professor W. B. Scott in 1882. Another expedition directed by Prof. Scott came in 1890. A third came in 1893, directed as before by Prof. Scott, with whom was associated Mr. J. B. Hatcher. A fourth party came in 1894, this time under the full direction of Mr. Hatcher. (Plate 8). The results of these expeditions were of very great importance. The abundant fossil remains collected enabled Prof. Scott to describe in most complete manner a number of the more noted extinct animals and to indicate with more certainty their proper classification and relationship.

The American Museum of Natural History entering the field in 1892, was favored from the very first by important discoveries. Since the first expedition, several parties have

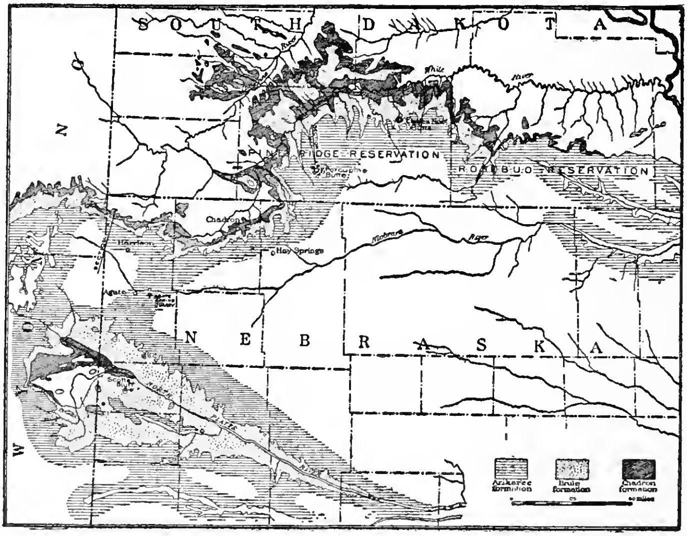


Figure 3—Areal distribution of Oligocene and Miocene exposures in South Dakota, Northwestern Nebraska, and Eastern Wyoming. N. H. Darton, modified by Matthew and Thomson, 1909.

represented this institution in its field investigations. Backed by abundant means and made up of capable investigators, they have been able to carry home a large amount of extraordinarily valuable material. This has given opportunity to establish more accurately the details of stratigraphy and correlation and to indicate with greater certainty the characteristics and habits of the various animals while in the living state. The years in which parties have been in the field, either in South Dakota or northwestern Nebraska are 1892, '93, '94, '97, '03, '06, '08, '11, '12, '13, '14, '16. Under the direction of Prof. H. F. Osborn, (Plate 8), Curator of the Department of Vertebrate Paleontology, earlier a co-worker with Prof. Scott in the Princeton investigations, many of the best preserved skeletons complete in practically every detail and mounted with the greatest skill, have been clothed with flesh, life and activity. Reproductions of a number of these, reference to which is made on other pages, are given in this book.

The University of Nebraska sent expeditions into the field, the parties being under direction of Prof. E. H. Barbour in 1892, '94, '95, and '97, '05, '07, '08 and later. Much of their collecting was done in northwestern Nebraska, but a considerable part of it in South Dakota and Wyoming. Prof. J. E. Todd of the University of South Dakota, spent a brief time in the field in 1894. He made a second visit, accompanied by several students in 1896. The University has more recently carried on additional investigations but the publications issued have been largely in connection with the fauna and flora of the present day.

New impetus was given the geological and paleontological work, particularly among the Miocene formations of northwestern Nebraska and eastern Wyoming, by the inauguration in 1902 of explorations by the Carnegie Museum of Pittsburg. This has continued to the present time. Mr. Hatcher directed much of the earlier work, while later, Mr. O. A. Peterson has had charge of it. This museum, as in the case of the American Museum, has been particularly successful, and many new and strange species have been discovered and described. A discovery of special note is that of the rich and important bone deposits near Agate Springs found in 1904.

Amherst College sent a party into the region under directon of Prof. F. B. Loomis in 1903 and another in 1907. Field Columbian Museum was represented by a party under Curator O. C. Farrington in 1904. The United States Geological Survey renewing its investigations in 1897 under Mr. N. H. Darton continued work in the region for several years, the chief purpose being to study the various geological formations with reference to underground water resources.

Reference has been made to the fact that the South Dakota badlands extend across the southern boundary of the state through northwestern Nebraska into eastern Wyoming. The northwestern Nebraska area has in recent years

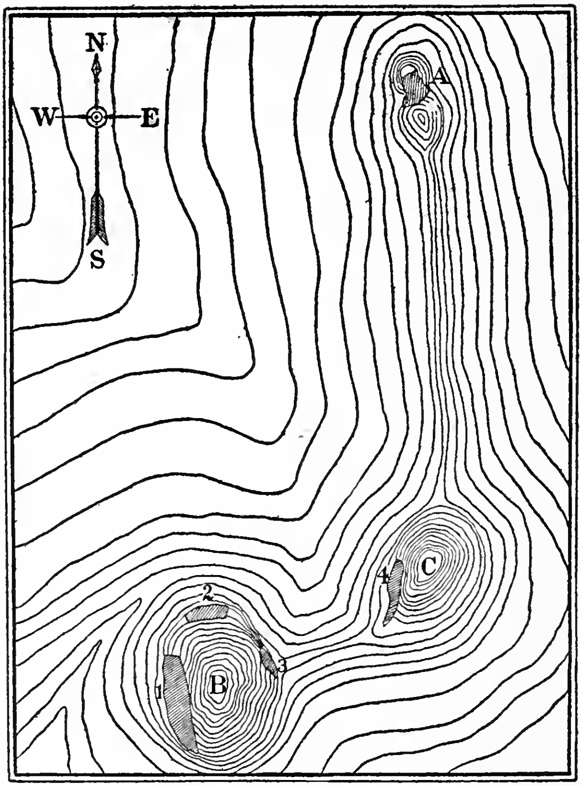


Figure 4—The Agate Spring fossil quarries, Sioux county, Nebraska, and their related topography. Holland and Peterson, 1914. A, First excavation, B, Carnegie hill, C, University hill. Amherst hill lies about two miles east of this.

attracted much attention, due in large measure to the extraordinary deposits found on the James Cook ranch near Agate Springs on the Niobrara river approximately forty miles south of Ardmore, South Dakota. Osborn states that they are the most remarkable deposits of mamalian remains of Tertiary age that have ever been found in any part of the world. It is in connection with these deposits that most of the later White River badland work of the museums and other educational institutions has been done. The bones are not only extremely abundant and well preserved but complete or nearly complete skeletons are fairly common and in several instances considerable groups of good skeletons have been found in little disturbed condition. Three small hills in which quarries have been worked in the search for bones have been designated as Carnegie Hill, University Hill and Amherst Hill, these having been first opened, in the order given, by representatives of the respective institutions, Carnegie Museum, University of Nebraska, and Amherst College.

The South Dakota State School of Mines has nearly every year, beginning with 1899, sent a party into the badlands either to Sheep Mountain or to some place along the Great Wall. Aside from the publication by the institution in 1910 of a summary description under the title "The Badland Formations of the Black Hills Region" the chief purpose of these visits, covering generally only a few days, has been to give students an opportunity to study physiographic processes and topographic types. The visits have served to give name to what is perhaps the ruggedest drainage feature of all the White River badlands, namely, School of Mines canyon. (See Plates 1, 91, 92, 94, 95, 96, and others). This cuts a deep gash into the highest part of Sheep Mountain and connects through a picturesque gateway with Indian creek an affluent of Cheyenne river.

In addition to the expeditions equipped by the several institutions, private collectors have obtained large quantities of valuable material and these specimens, either directly or through dealers, have found their way into the best museums, both at home and abroad. Now that access to every part of the White River badlands is readily gained, investigators are constantly visiting the region and activity in the development of knowledge concerning these wonderful deposits has perhaps never been more vigorous nor better planned than it is at the present time. Each succeeding year enhances the quality and importance of the investigation and doubtless this will continue for many years to come.

Figure 5—North America during the time when the Pierre (Cretaceous) shales in the form of mud were being laid down in the sea. Schuchert, 1908. White represents land areas; diagonal lines Pacific and Atlantic ocean areas; horizontal lines Arctic conditions; vertical lines Gulf conditions; black represents formation outcrops.

## CLASSIFICATION AND CORRELATION OF THE DEPOSITS

The history of the earth since the advent of life on its surface is commonly divided into certain time-divisions called eras. Beginning with the oldest, these are the Archeozoic, the Proterozoic, the Paleozoic, the Mesozoic, and the Cenozoic.* Each of these eras is divided into shorter time-divisions known as periods, varying somewhat among authors. For example the Paleozoic may be divided into the Cambrian, Ordovician, Silurian, Devonian, Mississipian, Pennsylvanian, and Permian periods; the Mesozoic into Triassic, Jurassic and Cretaceous; the Cenozoic into the Tertiary and Quaternary. The periods may in turn be divided into epochs, as for example, the Tertiary into the Paleocene, the Eocene, the Oligocene, the Miocene, and the Pliocene epochs; the Quaternary into the Pleistocene, or Glacial epoch, and the Recent or Human epoch. The rocks laid down during the various epochs or periods are spoken of as being grouped into formations (not to be confused with the ill-defined expressions often used for any natural oddity) the name of each formation being usually derived from some town, stream, tribe of people, or other feature of local interest where the formation was first carefully studied and described. The Black Hills and the Badlands together form a nearly continuous series from very old rocks to the very youngest. The following section in order of deposition, the oldest being at the bottom shows the various formations of this part of the country:

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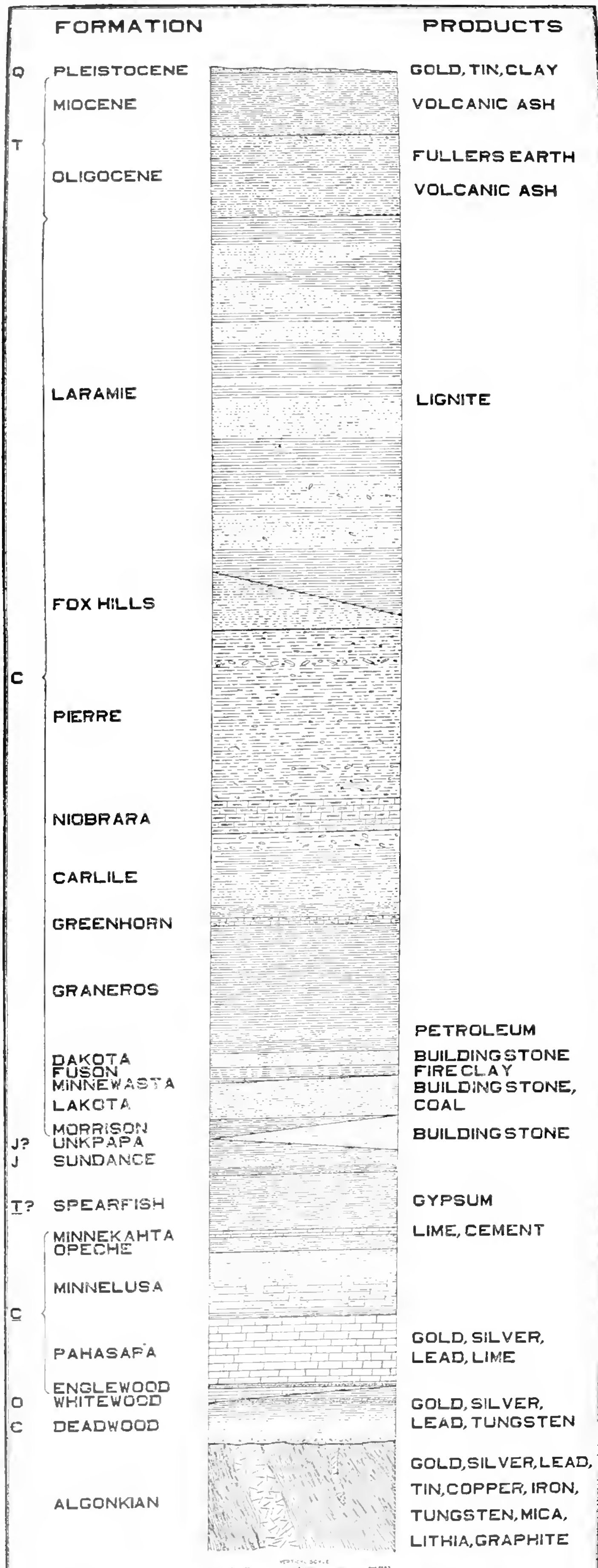
*I regret the apparent advisability of following conservative classification rather than joining present events with anticipated conditions and adding the beautifully expressive term "Psychozoic Era," the Age of Man, introduced by Prof. Joseph LeConte many years ago and used by him in the various editions of his elements of Geology.

## Table of Geologic Divisions for Western South Dakota

| | | | |
|---|---|---|---|
| Cenozoic | Quaternary | | Recent alluvial (flood plain) deposits.<br>Older high-level gravels, sands and clays. |
| | Tertiary | Pliocene | Not sub-divided. |
| | | Miocene | Nebraska Beds<br>Sheep Creek Beds<br>Arikaree |
| | | Oligocene | Brule<br>Chadron |
| | | Eocene | Ft. Union Beds |
| | | | ? Lance Formation |
| Mesozoic | Cretaceous | | Laramie<br>Fox Hills<br>Pierre<br>Niobrara<br>Carlile<br>Greenhorn<br>Graneros<br>Dakota<br>Fuson<br>Minnewasta<br>Lakota<br>? Morrison |
| | Jurassic | | ? Unkpapa<br>Sundance |
| | Triassic | | ? Spearfish |
| Paleozoic | Carboniferous Permian | | Minnekahta<br>Opeche |
| | Pennsylvanian | | Minnelusa |
| | Mississippian | | Pahasapa<br>Englewood |
| | Devonian | | [Not represented?] |
| | Silurian | | [Not represented?] |
| | Ordovician | | Whitewood |
| | Cambrian (Saratogan) | | Deadwood |
| Proterozoic | Algonkian | | Not yet differentiated |
| Archeozoic | | | [Not represented] |



# COLUMNAR SECTION
OF THE
# BLACK HILLS REGION

DRAWN BY ZAY JEFFRIES 10

## Table of Geologic Divisions for Western South Dakota

| | | | |
|---|---|---|---|
| | Quaternary | Recent alluvial (flood plain) deposits.<br>Older high-level gravels, sands and clays. | |
| Cenozoic | | Pliocene | Not subdivided. |
| Me | | | |
| Pal | | | |
| Pro | | | |
| Arcneozoic | | [Not represented] | |

The rock formations of the White River badlands represent a late time in geologic history. From the earliest days of their exploration they have been recognized as of Tertiary age and of non-marine character. The particular horizon within the Tertiary to which the various subdivisions should be referred have been less easy to determine. Leidy in his earliest studies of the extinct animals considered the beds as Eocene. Fuller study indicated to him and others a wider range in age than was first suspected and many features showed a later Tertiary character. As a result they became designated as Miocene and Pliocene, then as Lower Miocene and Pliocene, the Miocene (or lower Miocene) be-

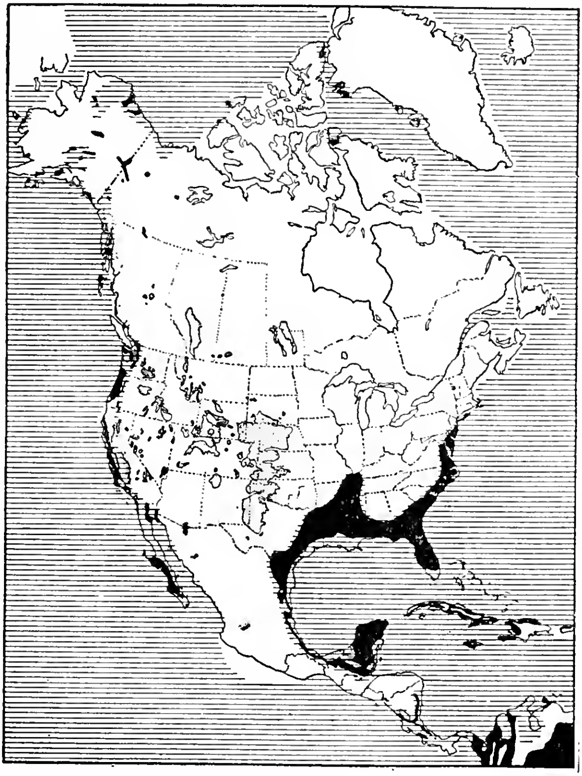


**Figure 6**—Map of North America in the Tertiary period, Black areas represent known exposures of marine Tertiary; lined areas, sea; dotted areas, non marine formations. Scott.

ing often referred to as the White River group. Later as the methods of correlation became more refined and as representative fossils came more abundantly and in better condition from the hands of the collectors, giving better opportunity for comparison with similiar fossils in other parts of the world, the lower beds were found to be equivalent to the Oligocene and the upper beds to the Miocene, chiefly Lower Miocene. This is now the accepted correlation. Pliocene deposits are know to occur along and to the

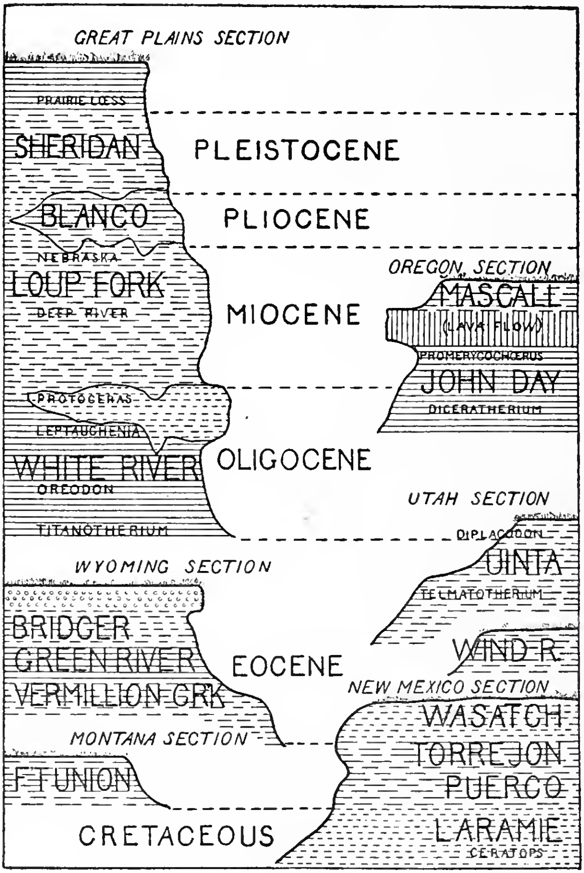


Figure 7—Diagram showing the chronological and stratigraphic succession of the Cretaceous, Tertiary, and Pleistocene formations of the western states, in which fossil mammals are found. Osborn. 1907.

south of the South Dakota-Nebraska boundary line and Pleistocene gravels are found in occasional places.

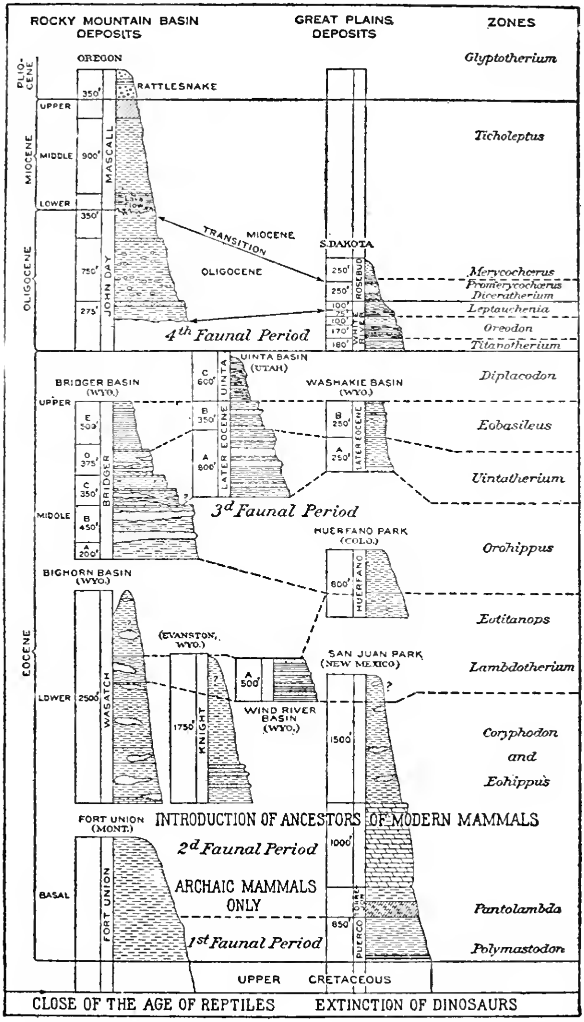


**Figure 8**—Diagram showing the successive and overlapping Tertiary formations of the Rocky Mountain region, with names of the important life zones. Osborn. 1909.

An important work of investigators has been to further subdivide the deposits and to correlate in so far as possible the resulting subdivisions. Hayden early attempted a subdivision and with marked success so far as information then at hand would allow. Later workers with better means at their command have made corrections and added new features until now the main history is fairly well outlined.

The present classification shown of some local and conflicting peculiarities is given herewith and this is followed by an idealized birdseye view of the Big Badlands by Osborn in which the thickness of the beds and the chief characteristics are given.

### GENERALIZED GEOLOGIC SECTION OF WHITE RIVER BADLANDS

| | | | |
|---|---|---|---|
| Pliocene | | Little White River Beds | Hipparion Zone |
| Upper Miocene— 50-200 ft. | | Nebraska Beds | Procamelus Zone |
| Middle Miocene— —— ft. | | Sheep Creek Beds | |
| Lower Miocene— 600-900 ft. | Arikaree Formation | Harrison Beds | Merycochoerus Zone with Daemonelix Sandstone. |
| | | Monroe Creek Beds | Chiefly Promerycochoerus Zone with Gering Sandstone. |
| Upper Oligocene— 150-250 ft. | Brule Formation | Protoceras Beds | Leptauchenia Zone (Plains fauna) with Protoceras sandstone (Forest and Fluviatile fauna) |
| Middle Oligocene— 200-400 ft. | | Oreodon Beds | Oreodon Zone (Plains fauna) with Metamynodon sandstone (Forest and Fluviatile fauna.) |
| Lower Oligocene 0-180 ft. | Chadron Formation | Titanotherium Beds | Titanotherium Zone |

## NATURE OF THE DEPOSITS

The rock materials of the White River badlands vary in different localities and in the different beds. The older deposits are chiefly fine partially consolidated clays interlaid with occasional irregular beds of coarse argillaceous sands and gravels. Concretions are abundant and they often grade into fairly continuous sandstone. Clay dikes occur frequently and are widely distributed. In certain localities thin veins of hard bluish-gray chalacedony check the softer sediments in great profusion. Limestones are not common but among some of the marginal outcrops particularly those toward the Black Hills they reach importance. Likewise near the Black Hills conglomerates are occasionally of con-

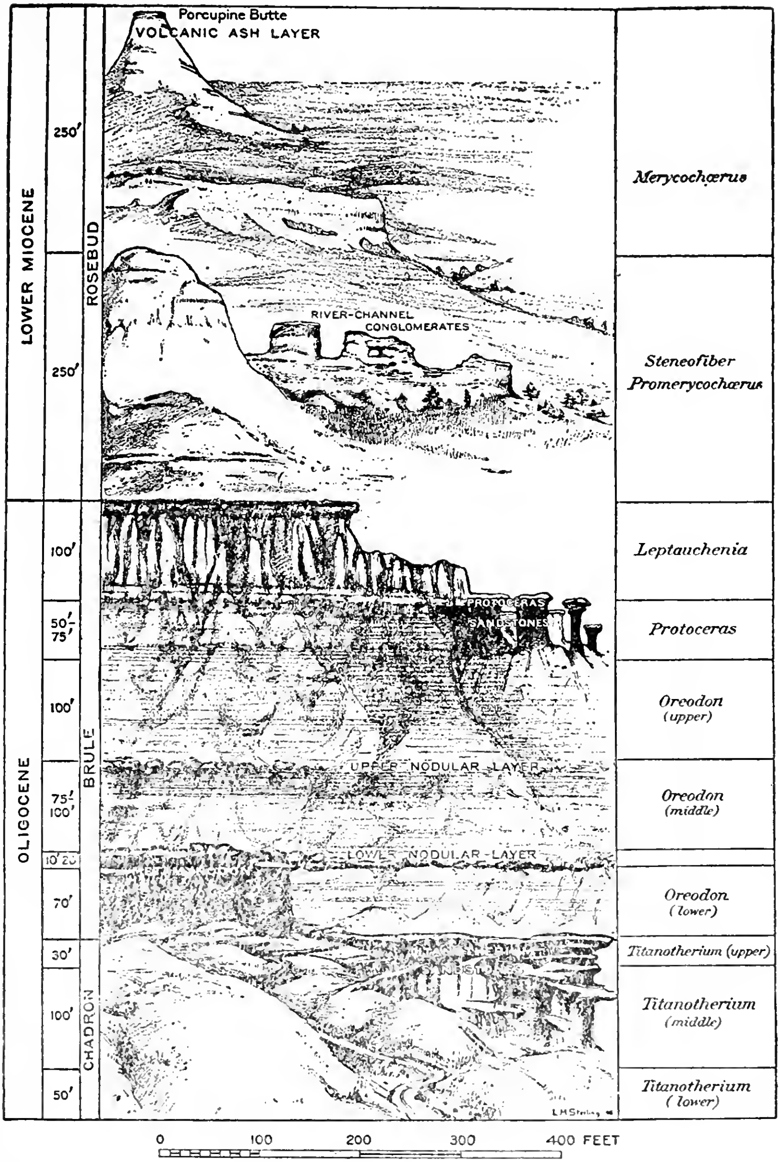


Figure 9—Idealized birds-eye view of the Big Badlands, showing channel and overflow deposits in the Oligocene and Lower Miocene. Looking southeast from the Black Hills. Osborn, 1909.

sequence. Volcanic ash occurs at certain horizons and one or two beds in the later formations cover considerable areas.

The several geological formations have particular characteristics that serve to distinguish them in the field. In view of the importance of these formations the makeup of each is here described in some detail beginning with the Chadron which is the oldest. The others follow in the order of their age.

## OLIGOCENE

### *The Chadron Formation*

The Chadron formation, better known by the much older term, the *Titanotherium beds,* from the name of the large extinct animals, whose bones occur in it so abundantly, receives its name from the town of Chadron in northwestern Nebraska. The formation is best developed and has been most studied in and near the Big Badlands of South Dakota, but is of importance along the northerly facing escarpment of Pine Ridge in South Dakota, Nebraska and Wyoming. Owing to the slight dip of the strata away from the Black Hills, the Pine Ridge outcrop, lying as it does at the base of the high escarpment, passes quickly beneath younger formations and leaves only a long narrow east-west band for observation. In and near the Big Badlands the White and Cheyenne rivers and their tributaries have cut deeply into and across the deposits, and there the Chadron is exposed over a large territory. The beds are known to underlie an extensive area of later formations within and beyond the Black Hills region and are well exposed in the valley of North Platte river in western Nebraska, and of South Platte river in northeastern Colorado.

The formation is made up chiefly of a sandy clay of light greenish-gray color, with generally coarser sandy materials at or near the bottom, including sometimes deposits of gravel or conglomerate several feet thick. The beds immediately above the gravels are often of a yellowish, pinkish, reddish, or brownish color, and Mr. Darton states that in northwestern Nebraska, near Adelia, the red color is especially prominent. Aside from this the color in the main is a greenish white, the green showing as a very delicate tinge on weathered slopes, but a distinctly deeper olive green in fresh exposures. The clays sometimes partake of the nature of fullers' earth, but generally they contain more or less sand. In most of the beds little cementing material is present, although the clays are often quite compact. Occasionally thin persistent bands of knotty, grayish limestone or lime clay concretions are found. These weather to a chalky white, and although seldom prominent individual bands may sometimes be traced over considerable areas. Concerning the sandy layers within the Big Badlands, Hatcher says:

"The sandstones are never entirely continuous, and never more than a few feet thick. They present every degree of compactness, from loose beds of sand to the most solid sandstones. They are composed of quartz, feldspar, and mica, and are evidently of granitic origin. When solidified the cementing substance is carbonate of lime.

"The conglomerates, like the sandstones, are not constant, are of very limited vertical extent, never more than a few feet thick. They are usually quite hard, being firmly held together by carbonate of lime. A section of the beds taken at any point and showing the relative position and thickness of the sandstones, clays and conglomerates is of little value, since these vary much at different and quite adjacent localities."*

The total thickness of the formation within the Big Badlands is approximately 180 feet. Hatcher and others subdivide the formation in that locality as follows: Lower, 50 feet; Middle, 100 feet; Upper, 30 feet. The sub-divisions are based on the nature of the Titanotheres found at the various horizons. Along Pine Ridge the formation is much thinner. Darton gives it as approximately 30 to 60 feet.

## THE BRULE FORMATION

The Brule formation, like the underlying Chadron formation, outcrops chiefly in the Big Badlands and along the northward facing escarpment of Pine Ridge. As now commonly understood, it may for the Big Badlands be best considered under its two subdivisions, namely, the Oreodon Beds, constituting the lower part, and the Protoceras Beds, constituting the upper part.

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*Hatcher, J. B. The Titanotherium Beds. Am. Nat., Vol. 27, 1893, pp. 204-221.

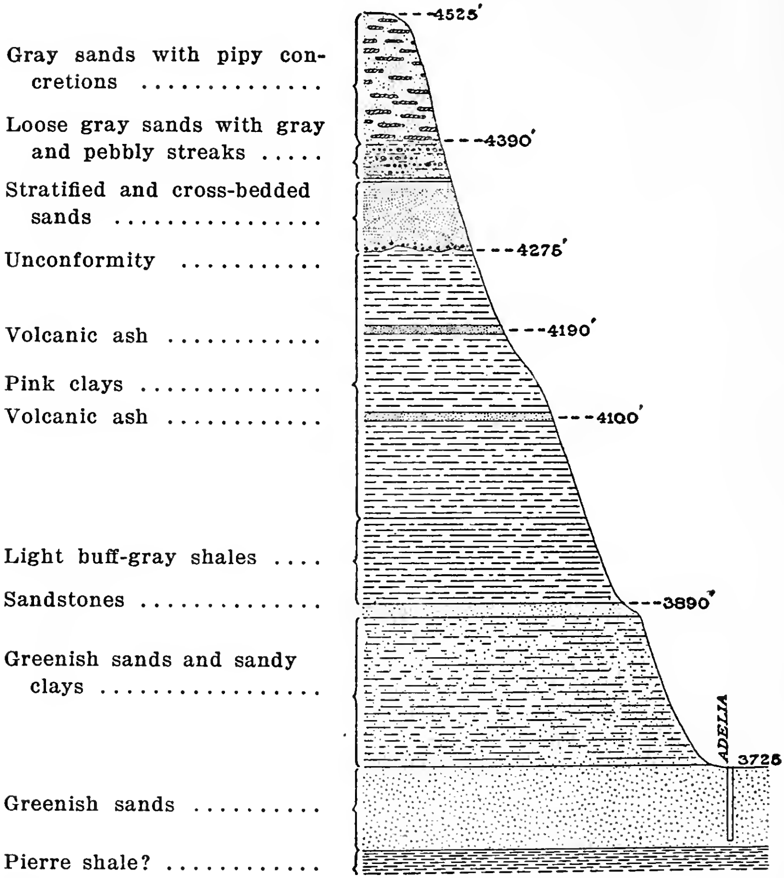

Figure 10—Section from Round Top to Adelia, Sioux county, Nebraska. Above the Pierre shale to 3725 is Chadron formation, 3725 to 4275 is Brule, 4275 to 4390 is Gering, 4390 to 4525 is Arikaree. Darton, 1905.

*The Oreodon Beds.* The Oreodon beds, so named because of the abundant remains of Oreodons found in them, are made up chiefly of massive arenaceous clays, lenticular sandstones, and thin layers of nodules. A particular feature of the beds is the color banding. The general color is a gray or faint yellow, but this is often much obliterated by horizontal bands showing some shade of pink, red or brown. They are present in greater or less prominence over large areas, particularly in the Big Badlands, and in places become a rather striking feature. Their thickness varies from an inch or less to occasionally several feet. Sometimes they are repeated in rapid succession without great contrasts in color. More often a few bands stand out with prominence, especially if moistened by recent rains and, seen from some commanding point, may be traced for long distances.

The sandstones being of a lenticular nature are often absent or of little consequence, but in many localities they reach considerable thicknesses. One series near the middle of the bed is of particular importance. It reaches in the Big Badlands a thickness of twenty feet or more, and according to Wortman, covers an area approximately twelve miles in length and a mile or a mile and a half in width. It contains fossil remains in abundance of the ancestral rhinoceros, Metamynodon, hence is commonly known as the Metamynodon sandstone.

Of the nodular layers, one just above the Metamynodon sandstone is of paramount importance. For description of this I quote from Mr. Wortman, 1893: "There is one layer found in the Oreodon Beds which is highly characteristic and is perhaps more constant and widely distributed than any other single stratum in the whole White River (Oligocene) formation. This is a buff-colored clay carrying numerous calcareous nodules in which are imbedded remains of turtles and oreodons. The fossils are almost invariably covered with a scale of ferruginous oxide when first removed from the matrix, and are of decidedly reddish cast. Upon this account this stratum is known to the collector as the 'red-layer.' It is situated somewhere between 40 and 50 feet above the top of the Titanotherium beds and can almost always be easily identified. It varies in thickness from 10 to 20 feet, and in some rare instances it is replaced by sandstone. I have also found it without the nodules in places, but this is also quite a rare occurrence."

Another tolerably constant fossiliferous nodular layer occurs at from 75 to 100 feet above the nodular layer just described. This higher horizon was provisionally considered as marking the top of the Oreodon beds. The present tendency is to extend the Oreodon beds upward so as to include the series of non-fossiliferous clays about 100 feet thick, lying just above the upper nodular layer. The total thickness of the beds in the vicinity of Sheep Mountain is from 250 to 300 feet. The stratigraphy in Pine Ridge differs in some important respects lithologically from that of the Big Badlands and the exact equivalent there of the Oreodon beds does not yet seem clear.

*The Protoceras Beds.* The Protoceras beds, earlier considered as part of the Oreodon beds, were first differentiated by J. L. Wortman as a result of field work done during the summer of 1892 for the American Museum of Natural History. The name is derived from the characteristic and highly interesting extinct animal, the Protoceras, which occurs in the sandstones of these beds in considerable abundance.

Lithologically the beds are made up of isolated patches of coarse, lenticular sandstones, fine-grained clays, and nodular layers. The sandstones occur in different levels and are usually fossiliferous. They are seldom continuous for any great distance and often change abruptly into fine-grained barren clays. Immediately overlying the sandstones there is a pinkish colored nodule-bearing clay, containing abundant remains of Lepthauchenia and other forms, hence the name Leptauchenia zone often used in connection with these beds. The Protoceras beds have been clearly differentiated only in the Big Badlands. Elsewhere the lithologic conditions do not generally serve to indicate their presence, hence if they occur outside of the Big Badlands, the determination of their areal distribution must in a large measure await the study of the paleontologist. The total thickness of the beds, including with them the Leptauchenia clays, is approximately 150 to 175 feet.

## LOWER MIOCENE

### *The Arikaree Formation*

The Arikaree formation, first designated as such by Darton, receives its name from the Arikaree Indians, who were at one time identified with the area in which it is most largely developed. Its greatest development is in Pine Ridge and southward. It is of Lower Miocene age and lies uncomformably on the Brule and in places overlaps the margins of that formation.

The Arikaree is largely a soft sandstone, varying in color from white to light gray. Calcareous concretions occur throughout the formation in abundance. They are usually of cylindrical form and are often more or less connected into irregular sheets. It is to this feature especially that the Pine Ridge escarpment and other prominent topographic features of that part of the country are due. For the manner of development of these concretionary forms, the reader is referred to the discussion of concretions and sand-calcite crystals elsewhere in this paper.

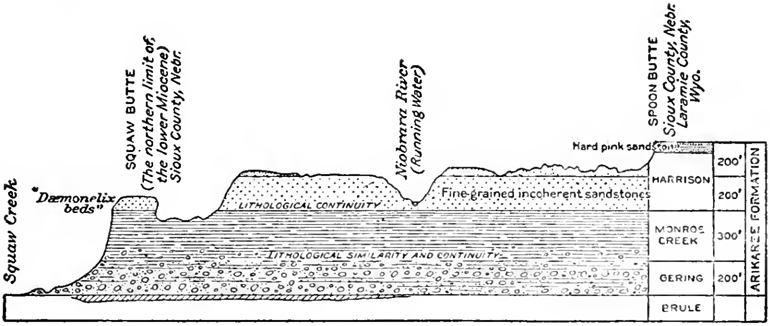

Figure 11—Diagramatic section of the Arikaree on the Nebraska-Wyoming line west of Harrison. Osborn, modified from Peterson, 1906-09.

The Arikaree has not been carefully defined for all the area where it has been found, and owing to the variable nature of the formation in different localities a number of terms in this connection need to be referred to and defined. Darton in his studies in western Nebraska some years ago, differentiated certain sands and standstones, lying below the Arikaree deposits, as the Gering formation. More recent study seems to show that much of this material is little more than non-continuous river sandstones and conglomerates that traverse the lower Arikaree clays and occupy in places irregular channels in the partly eroded upper Brule formation, the relation to the Arikaree clays being in such places much as that of the Titanotherium, Metamynodon and Protoceras sandstones to the clays in which they severally occur. The general tendency at present seems to be to consider them as a special depositional phase of the lower part of the Arikaree. According to Hatcher, the Arikaree in Sioux County, Nebraska, and Converse County, Wyoming, is lithologically and faunally divisible into two easily distinguishable horizons, namely, the Monroe Creek beds, below, and the Harrison beds above.

*The Monroe Creek Beds.* The Monroe Creek beds, Hatcher states, are well shown in the northern face of Pine Ridge at the mouth of Monroe Creek Canyon, five miles north of Harrison, where they overlie the Gering sandstones, and are composed of 300 feet of very light colored, fine-grained, not very hard, but firm and massive sandstones. The thickness decreases rapidly to the east and increases to the west. The beds are generally non-fossiliferous, though remains of Promerycochoerus are found in it, hence the name Promerycochoerus zone.

*The Harrison Beds.* The Harrison beds receive their name from Harrison, in the vicinity of which town the beds are well exposed. As stated by Hatcher, they are composed of about 200 feet of fine-grained, rather incoherent sandstones, permeated by great numbers of siliceous tubes arranged vertically rather than horizontally. They are further characterized by the presence, often in great abundance, of those peculiar and interesting, but as yet not well understood, fossils known as Daemonelix, (hence called Daemonelix beds by Barbour, who first studied them), and by a considerable variety of fossil mammals belonging to characteristic Miocene genera.

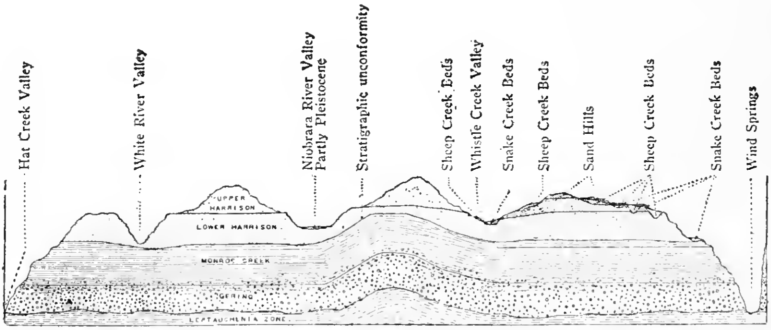

Figure 12—Section from Hat creek south through Sioux county to Wind Springs, a distance of approximately fifty miles. Cook, 1915.

Later investigation has shown that in some places the division is not readily made on lithologic features alone, but that the formation can in all places be separated faunistically into lower and upper levels as indicated. The section by Osborn, modified from Peterson, shows the relations of the Nebraska-Wyoming line west of Harrison. (Figure 15).

*The Rosebud Beds.* The Arikaree has been studied with much care near Porcupine Butte and farther east on White river by representatives of the American Museum of Natural History. Matthew and Gidley, who first collected fossils there, designated the series of strata as the Rosebud beds. These beds are believed to be approximately equivalent to the Arikaree formation as the latter is now coming to be understood, but exact relations have not yet been fully determined over any very large section of the country. Matthew describes the beds in their typical eastern locality as follows: "The western part of the formation attains a thickness estimated at 500 feet on Porcupine creek, a southern tributary of White river. The base is taken at a heavy white stratum which appears to be identical with the stratum capping the White River formation on Sheep Mountain in the Big Badlands. This stratum can be seen extending interruptedly across the river to Sheep Mountain, about twenty miles distant, capping several intervening buttes and projecting points of the underlying formation. The Rosebud beds at the bottom approximate the rather hard clays of the upper Leptauchenia beds, but become progressively softer and sandier towards the top, and are capped at Porcupine Butte by a layer of hard quarzitic sandstone. Several white flinty, calcareous layers cover the beds, one of which, about half way up, was used to divide them into Upper and Lower. The stratification is very variable and inconstant, lenses and beds of soft fine-grained sandstone and harder and softer clayey layers alternating with frequent channels filled with sandstones and mud-conglomerates, all very irregular and of limited extent. The hard calcareous layers are more constant. A bed of volcanic ash lies near the top of the formation, and there may be a considerable percentage of volcanic material in some of the layers further down. These volcanic ash beds should in theory be of wide extent, and may be of considerable use in the correlation of the scattered exposures on the heads of the different creeks—a very difficult matter without their aid.

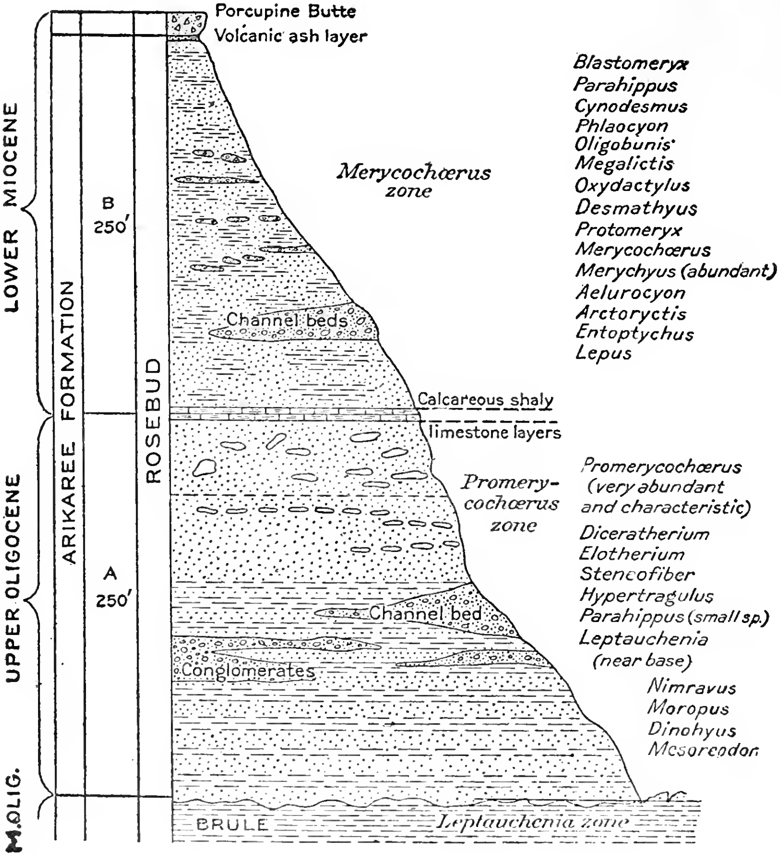

Figure 13—Columnar section from Porcupine Butte northward toward White river as observed by Matthew and Thomson in 1906. Osborn, 1912.

The beds form the upper part of the series of bluffs south of White river on the Pine Ridge and Rosebud Reservations, and are exposed in the upper part of the various tributary creeks."*

For a section of these beds see Figure 13, from U. S. Geol. Survey Bulletin No. 361, p. 70, Cenozoic Mammal Horizons of Western North America, etc., by Osborn and Matthew.

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*Matthew, W. D. A Lower Miocene Fauna from South Dakota. Am. Mus. Nat. Hist., Bull., Vol. 23, 1907, pp. 169-219.

## MIDDLE MIOCENE

The Middle Miocene, so far as I am aware, has not been identified within the area covered by the Black Hills map, except in the southern part, chiefly in Nebraska. Strata of this age have been studied fifteen or twenty miles south-southwest of Agate Springs, and they have there yielded a limited fauna. Matthew and Cook designate them as the *Sheep Creek beds*, and describe them briefly, as follows: "They consist of soft fine-grained sandy 'clays' of a light buff color, free from pebbles, and containing harder calcareous layers. Their thickness is estimated at 100 feet. Near the top is a layer of dark-gray volcanic ash, two feet thick."

## UPPER MIOCENE

*The Nebraska Beds.* The Nebraska beds, Nebraska formation as designated by Scott, are represented in various areas not yet carefully mapped along the Niobrara river, where, as widely scattered river channel and flood plain deposits, they immediately overlie the Harrison beds. Further south they pass beneath or blend into the Oglalla formation, which covers so much of western and southwestern Nebraska. They have been studied by Hatcher and by Peterson. Hatcher describes them as consisting of a series of buff colored sandstones of varying degrees of hardness and unknown thickness, with occasional layers of siliceous grits, which protrude as hard undulating or shelving masses from the underlying and overlying softer materials. Peterson states that the thickness cannot be greater than 150 or 200 feet, and he gives a section near the Nebraska-Wyoming line showing only 70 feet. The beds have afforded many interesting fossils of vertebrates, some of which are described elsewhere in this publication.

## PLIOCENE

Pliocene strata are found irregularly distributed on the eroded surfaces of Upper Miocene beds bordering Little White river valley and the valley of the Niobrara. They contain important fossils but the beds have not been carefully mapped. As a consequence local names have been used to designate the beds in the several localities where fossil hunting has been carried on. Among these names are Snake Creek, Oak Creek, Little White River, Niobrara River and Spoon Butte.

The beds are of Lower Pliocene age and are of especial stratigraphic value in that Pliocene mammals are not well known in North America and the mammalian fauna which the beds have yielded has helped materially in filling in the gap.

## GEOLOGIC SECTION OF THE BIG BADLANDS

| | Approximate estimate thickness of the beds | Characteristic Species and General Nature of the Rock |
|---|---|---|
| Protoceras Beds | 100 feet | Leptauchenia layer; nodule-bearing, pink-colored clays widely distributed. |
| | 50-75 feet | Coarse sandstones, occupying different levels, not continuous. |
| Oreodon Beds | 100 feet | Light colored clays. Few fossils. |
| | 75-100 feet | Nodulous clay stratum. Bones white.<br>Sandstones and clays. Bones rusty colored. |
| | 10-20 feet | Oreodon layer; nodule-bearing, very constant and widely distributed. Numerous Oreodons and turtles imbedded in nodules. Bones always covered with scale of ferruginous oxide. "Red layer" of collectors. |
| | 70 feet | Metamynodon layer; sandstones, sometimes replaced by light colored barren clays. Bones usually rusty colored.<br>Reddish gritty clay, sometimes bluish. Bones white. |
| Titanotherium Beds | 30 feet | Clays, sandstones and conglomerates. |
| | 100 feet | Clays, toward the base often reddish, or variegated. The prevailing color, however, is a delicate greenish white. Bones are always light colored or white, sometimes rusty.<br>Clays and sands, sometimes fullers earth. |
| | 50 feet | |

## MANNER OF DEPOSITION

Geologists who first studied the badland formations of the western plains early formulated the theory that the deposits were collected by streams from the highlands of the Rocky Mountains and the Black Hills and were laid down as sediment in great fresh water lakes. These lakes were thought to have varied in position and extent in the different periods of time during which the several formations were being deposited. They were believed in general to have had their origin in certain structural changes, either a slight depression along the western side or the elevation of some drainage barrier on the east, and to have been obliterated by the development of new drainage channels accompanied possibly by general uplift, and by the progressive aridity of the climate.

More recently doubts began to be entertained as to the accuracy of this attractive lacustrine theory, more detailed study disclosing many facts at variance with the usual conditions of lake deposition, both with reference to the physical character of the deposits and to the nature, condition, and distribution of the fossil remains found in them. There now seems to be abundant evidence for the belief that the deposits were of combined lagoon, fluviatile, floodplain and possibly eolian origin instead of having been laid down over the bottom of great and continuous bodies of standing water as was first supposed.

The lacustrine theory originated in the earlier accepted idea that all horizontally bedded sedimentary rocks were deposited in bodies of comparatively still water, either marine, brackish, or fresh. It was believed that the fine-grained banded clays were deposited in the quiet deeper waters of the lake, that the sandstones and conglomerates were deposited along the shores and about the mouths of tributary streams, and that the wide distribution of the animals now found as fossils was accomplished by the drifting about in the lake of the decaying bodies washed down by the inflowing streams. The fossils obtained by the earlier students of the region showed a general lack of an aquatic fauna. As a result the idea developed that the waters of this great lake although receiving the drifting bodies of land animals were themselves of such a saline or alkaline nature that they were incapable of supporting life.

It has more recently been shown that the waters were not only not saline, but that they were eminently fitted for the support of aquatic life and in fact in some localities did support such life, both plant and animal in great abundance.

It seems that the topography of the plains region during deposition of the badland materials was nearly level, the slope then as now being very gentle from the Rocky Mountains and the Black Hills. Broad streams found their way slowly across this great tract and developed upon it a net work of changing channels, backwaters, lagoons and shallow lakes interspread here and there with reed-bearing marshes and grass-covered flats. Climatic changes gradually brought about conditions of aridity, the rivers and other water bodies dwindled and wind-driven materials began to assert their prominence. Thus the clays, sandstones, conglomerates, fullers earth, eolian-sands and even the volcanic dust, wind-borne from far away craters in the Rocky Mountains or the Black Hills, are all accounted for and the life conditions of the time are in reasonable measure made plain.

## GEOLOGIC HISTORY

The rocks of the earth's crust retain to a marked extent a record of their history. Sometimes this is indicated by composition, sometimes by manner of erosion, sometimes by relation to one another, sometimes by fossil contents, et cetera. Often several such characters are available in the same formation. In such cases the history may be unraveled with much fulness.

A detailed history of the Tertiary of the Black Hills region may not be entered upon here, but a brief review of the general physical changes is desirable in order that the setting of conditions and activities discussed elsewhere may be better understood.

Preceding the deposition of the Tertiary rocks, that is during the Cretaceous period, the Black Hills region had for a long time been surrounded and largely if not wholly covered by a great sea. In this sea countless marine organisms flourished and died. The sea from time to time, and particularly near the close of the period, tended through a brackish to a fresh water nature. Approximately coincident with the full development of fresh water conditions the Black Hills region was subjected to disturbance, profound elevation took place and a more active erosion was inaugurated. The history here for a time is not well disclosed but beginning with the Oligocene the conditions become more evident. By that time the streams had become sluggish and muddy and by meandering had developed vast flood plains across which they shifted their lazy way and deposited and redeposited the debris obtained from the higher lands to the west· Following the Oligocene there was further uplifting and erosion was correspondingly quickened but the general history continued much as before.

The climate for a considerable time in the history of the deposition seems to have been moist to a marked degree. Later a more arid condition prevailed and it was then that transportation and deposition by wind became a feature of importance.

The great disturbances in the early part of the Tertiary resulting in the pronounced doming of the Black Hills region and the uplifting of the Rocky Mountain front were accompanied and followed by profound igneous intrusion. The White River region was influenced only in a general way by the disturbances and no volcanic outbursts occurred there. However some of the igneous material within the Rockies and possibly some also in the northern Black Hills connecting with the throats of vigorous volcanoes was from time to time hurled high above the surface. Here favorable winds, catching up the finely divided fragments, bore them far to the eastward and there gently dropped them as thin widespread ashen blankets to become an integral and interesting portion of the general badland deposits.

Subsequent to the Pleiocene the history of the White River badlands is largely one of rapid weathering and vigorous erosion.

## PHYSIOGRAPHIC DEVELOPMENT

The White River badlands are the result of erosion, controlled in part by climatic conditions and in part by the stratigraphic and lithologic nature of the deposits. There is a too frequent lack of appreciation of the work of common disintegrating and carrying agents and many an individual speculates upon the mighty upheavals and the terrific volcanic forces that to him have produced the wonderful ruggedness of the badlands, when the real work, so far at least as immediate topography is concerned, wholly apart from the forces of vulcanism, have been performed under a kindly sun and through benevolent combination by ordinary winds and frosts and rains, and to a lesser degree by plants and animals. What the earliest beginning may have been is not known. Suffice it to say that then, as now, the sun shone, the winds blew, and the rains came, and such irregularities as may have existed influenced in some degree the earliest run off. Season by season the elements weakened the uplifted sediments, and little by little the growing streams cut the yielding surface. In time lateral tributaries pushed their way into the interstream areas and these tributaries in turn developed smaller branches, the series continuing with ever increasing complexity to the delicate etching at the very top of the highest levels. All the important streams give indications of an eventful history, but for this there is little opportunity for discussion here. Cheyenne river and White river are the chief factors today in the production and continuation of the badland features, and of these, White river clings most closely to its task. The Cheyenne has already cleared its valley of the badland deposits except in the important locality southeast of the Black Hills and in the western Pine Ridge area beyond the headwaters of White river and even in these areas the main stream has cut entirely through the formations and in most places deeply into the underlying black Cretaceous shales. White river, on the other hand, for more than fifty miles of its middle course, meanders across a wide alluvial bottom, underlain by badland sediments, while its many branched head and all of the larger tributaries from the south and many from the north continue to gnaw vigorously into deposits that retain much of their original thickness.

Among the innumerable tributaries within the badlands proper, few are of great length, but many are of note in the physiography of the region, in the history of early day travel, and in the yielding of important specimens to the fossil hunter. Of those leading from the Badlands to the Cheyenne river, the following are important and often referred to in the scientific literature: Bull creek, Crooked creek, Sage creek, Hay creek, Bear creek, Spring crek, Indian creek, Little Corral draw, Big Corral draw, Quinn draw, and Cedar draw. Nearer the head of the river are Hat creek, Old Woman creek, Lance creek, and others. Three streams rising east of the Big Badlands and north of the Great Wall flow eastward between Cheyenne river and White river and form the head of Bad river. These are Cottonwood, White Water and Buffalo creeks. The White river tributaries from the north are short, and of these Cain creek, Cottonwood creek, and Spring creek rising near the heart of the Big Badlands are the most important. The White river tributaries on the south are numerous, and of considerable size. Well known ones within the Pine Ridge Indian reservation, are: Pass creek, Eagle Nest creek, Bear in the Ledge creek, Corn creek, Pumpkin creek, Yellow Medicine creek, Medicine Root creek, Porcupine creek, Wounded Knee creek, and White Clay creek. Little White river is the most important of all the streams flowing into White river. It rises west of Manderson in the southern part of Pine Ridge reservation and flows eastward and northward into and through the Rosebud Indian reservation. Many valuable fossils have been found among the outcrops exposed along its valley.

The southern slopes of Pine Ridge are drained by Niobrara river. This river rises in Wyoming and flowing eastward approximately parallels Pine Ridge and the South Dakota-Nebraska state line. It may for our purpose here serve to mark the southern limit of the area described.

In addition to the streams certain features need mention because of their commanding position. These are Pine Ridge, Porcupine Butte, Eagle Nest Butte, Sheep Mountain, and The Wall,“ the latter being more fully designated by the various local names: Sage creek wall, White Water wall, and Big Foot wall. Besides these, the following passes or natural roadways, well known to all the travelers within the Big Badlands, are of historic importance and of physiographic significance: Sage Creek pass, Big Foot pass, Cedar pass, Chamberlain pass, et cetera.

Less noted in the literature, but of much importance, are the numerous mesas or tables. They stand at various heights up to three hundred feet or more above the basins or valleys. Some of these are of large size and those east of the Cheyenne river have been given individual names by the people who have settled upon them. The larger ones are Sheep Mountain table, about six miles south-southwest of Scenic; Hart table, between Indian creek and Spring creek; Kube table, between Spring creek and Bear creek; Seventy-one table, between Bear creek and Hay creek; Quinn table, between Hay creek and Sage creek; Crooked Creek table, between Sage creek and Bull creek; Lake Flat between Bull creek and the headwaters of Cottonwood creek; White River table, at head of Quinn draw. The last named lies within the Pine Ridge Indian reservation and is of historic interest in that it was used as a fortress by the Indians during the Indian outbreak of 1891.

The chief factors in badland development are these: first, a climate with a low rainfall more or less concentrated into heavy showers; second, scarcity of deep rooted vegetation; third, slightly consolidated nearly homogenous fine-grained sediments lying at a considerable height above the main drainage channels, the occasional hard layers or beds that may be present being thin and in horizontal position. All of these favor rapid, steep, and diversified sculpturing. As already stated, the White and the Cheyenne rivers, not far separated from each other, serve as the main drainage channels for the Badlands and, having cut far below the topmost mesas or tables, afford abundant opportunity for rapid run off. The vegetation is scanty. Rich, short grasses are abundant over large areas, but these have not sufficient root-strength to prevent cutting. The gnarled cedars of the higher points also lack such strength, for even these often wage a losing fight and especially in the elongating gulches and on the narrowing tables they progress toward inevitable destruction.

The rock material is largely an excessively fine clay, not thoroughly indurated, sometimes massive, sometimes laminated. Sandstones occur locally in some abundance, especially in the upper beds, but never of great thickness and seldom of much lateral extent. Concretions are common and these as well as the sandstones accentuate the irregularity of erosion. The bare clay slopes under the influence of occasional rains and the beating suns, generally show a spongy surface, the loosening porous clay often extending to a depth of several inches. This feature is common on the sloping surface of the Oreodon beds and is especially characteristic of the rounded hillocks of the Titanotherium beds. This preliminary loosening of the clay, explains perhaps more than any other one feature, the surpassing ease with which the countless tiny channels are formed and how it is that the streams become turbid with every passing shower.

Any hard layer that may be present tends to resist erosion and this at once initiates surface irregularities. The unconsolidated clays being more rapidly removed, the harder stratum soon stands out in distinct relief and later by undercutting, a precipice develops. Joints often accelerate the erosion along certain vertical planes and the result is the development sometimes of cave-like excavations and sometimes of columnar masses. Columns are likely to develop also in connection with hard strata made up of concretionary masses. They are especially abundant in the Protoceras beds, where concretionary masses and jointed sandstones are both abundant.

Generally the transportation lags perceptibly behind the disintegration and as a consequence a thin fan of sediment clings to the base of every pillar, mound or table. The full extent of these alluvial fans is often not fully discerned. Being formed by the conjoint action of many little streams and made up of excessively fine sediment, their surface slope is low and one readily confuses the alluvial materials with the undisturbed beds on which they lie. As may be readily inferred, there is much transient carrying of sediments and much meandering of maturer streams. A single season or even a single freshet often makes important changes in a stream's position and there is a decided tendency in the medium sized streams to quickly develop box-like trenches. Cheyenne river and White river are active throughout the year, and during the rainy season they flow in large volume, but the tributary streams coming from the badlands are dry much of the time. Some are able to struggle along in continuous flow for a little while after the rainy reason, but later in most of them little is left but dusty sands and stingy pools of water, the latter clear if strongly alkaline, otherwise turbid to the consistency of mud porridge.

## CONCRETIONS, SAND CRYSTALS, DIKES, VEINS AND GEODES

*Concretions.* A concretion is a spherical, cylindrical, elliptical, or nodular body produced by the tendency of certain mineral constituents to orderly aggregate about a common center within an embedding rock mass. The discovery in the White River badlands several years ago of what are known as sand or sand-calcite crystals has added much to our knowledge of concretionary development and has served well to indicate the local conditions with reference to these abundant and interesting forms.

Concretions vary greatly in size, shape, composition, manner of distribution and method of growth. They are common in the Great plains formations. In some of the Cretaceous and Tertiary beds they may be found in prodigious numbers. They occur in many places and in various horizons and of all sizes up to several feet in diameter. Any horizon which contains the concretions at all is likely to contain many of them and often they coalesce horizontally and form continuous strata. More frequently they are separate and, being harder than the surrounding material, they often tend under the influence of erosion to become the caps of earth pillars. The material of which they are made is generally an arenaceous clay with calcium carbonate as a cementing material, but iron oxide is often times present in considerable quantity.

*Sand Crystals.* The sand crystals are made up of approximately sixty per cent of sand and about forty per cent of calcium carbonate. The former occurs as an inclusion, while the latter, the mineralizing agent, is the crystal proper. The size varies in length from a quarter of an inch or less to fifteen inches. They occur chiefly in the Arikaree formation, which is largely a soft sandstone. Much of the rock is concretionary, and not a little of it is in cylindrical or pipe-like masses, often many feet or yards in length. These often disclose evidence of some internal molecular or crystalline arrangement and weathered specimens not infrequently show a radiate or rosetted structure, due to the tendency of lime-salts to crystallize according to the laws governing calcite as far as the interference in the part of the sand grains will allow. (Plate 52).

The first discovered and most noted locality is on Pine Ridge Reservation at Devils Hill, near Corn creek, about twenty miles south of White river. Concerning their occurrence here, Prof. Barbour, who has visited the locality, says: "The mode of occurrence of these crystals seems most unusual and remarkable. In a bed of sand scarcely three feet thick, and so soft as to resemble the sand on the seashore, occur these crystals in numbers which can best be figured in tons. We dug them out with our bare hands. They are mostly single crystals, with numerous doublets, triplets, quadruplets and multiplets. In other words every form from solitary crystals to crowded bunches and perfect radiating concretions were obtained. It was a matter of special interest in the field to note that at the bottom of the layer the bulk of these sand-lime crystals are solitary; one foot higher there is an evident doubling of the crystals, until within another foot they are in loosely crowded clusters, a little higher in closely crowded continuous clusters, pried out in blocks with difficulty; still higher they occur in closely crowded concretions in contact with one another, making nearly a solid rock. A little higher this mineralizing process culminates in pipes, compound pipes and solid rocks composed wholly of crystals but so solidified that their identity is lost, and is detected only by a certain reflection of light, which differentiates the otherwise invisible units by showing glistening hexagonal sections. There could not have been a more gradual and beautiful transition, and all confined to a bed six or eight feet in thickness."

The relation of the crystals to concretions, as indicated above, discloses an important step in the development of concretions in general, and doubtless to some such cause as this crystallographic tendency is due the development of all of the concretions of the Badland strata.

*Dikes and Veins.* Dikes and veins are ordinarily elongate, vertical, or nearly vertical rock or mineral masses occupying fissures in a pre-existing rock. The filling body, if intruded as an igneous rock while in the molten condition, is commonly referred to as a dike. If filled in by a slow process of deposition from aqueous solution it is known as a vein. It is now recognized that fissures sometimes become filled with broken (clastic) material derived from adjacent or nearby rock masses without any immediate influence either of heat or of solvent action. These clastic bodies are known as dikes also.

Many writers have commented upon the nature and abundance of the dikes and veins in the Badlands. Although constituting minor features of the landscape they are nevertheless extremely abundant in places and not infrequently they display themselves in an interesting and complicated manner. The dikes are made up generally of a soft greenish sand or sandy clay. This usually wears away a little more readily than the enclosing strata but sometimes it resists weathering better and then the dike projects above the general surface. The prevailing attitude is nearly perpendicular and the dike outcropping in a straight line may occasionally be traced across gulches and draws and over ridge and pinnacle and mound for a mile or more. The thickness is commonly not more than a few inches but it sometimes reaches two or three feet. The dikes are supposed to occupy preexisting cracks, the material having been forced in from below by hydrostatic pressure or by the weight of the superincumbent strata. It is possible that in some cases the material may have come from above.

The veins are chiefly chalcedony. They resemble the dikes so far as concerns position and form and, aside from the fact that they were deposited from solution, are believed to have much the same history. They average thinner than the dikes, are much harder, and are in many places more abundant. They resist weathering much better than the enclosing clays, hence commonly present a jagged line above the surface. As the supporting clay becomes loosened and is carried away the thin chalcedony breaks into platy angular fragments and these falling upon the surrounding surface protect it from further erosion much as would a shingle roof.

*Geodes.* Geodes are spheroidal masses of mineral matter formed by deposition of crystals from some mineral solution on the walls of a rock cavity. The growth is constantly inward toward the center. If the process of deposition has continued sufficiently long, the crystals reach across the depositional space, interlock with each other, and the geode becomes solid. Often the crystals project only part way, leaving a considerable cavity and then the geode when broken presents a crystal lining of much beauty and interest. Commonly the geodes are more or less siliceous, especially in the outer portions and, resisting weathering better than the enclosing rock mass, may often be found freed from the matrix lying on the disintegrating surface. Not infrequently crystal fragments become detached within the shell, and these, striking against the inner walls when the geode is shaken, serve to make a sound. For this reason the geodes are often referred to locally as rattle stones.

Many geodes have been collected from the Big Badlands. The diameter varies from one inch or less to several inches. The prettiest ones of rather small size are found near Imlay. They have commonly an irregular shell of chalcedony more or less filled with bright clear-cut white or colorless quartz crystals, the latter varying from microscopic size to one-half inch or more in length. The finer white crystals much resemble white sugar, hence the name sugar geodes. Selenite (crystalized gypsum) is occasionally present. The origin of the geodes is doubtless closely connected with the origin of the chalcedony veins described above.

### DEVIL'S CORKSCREWS (*Daemonelix*)

Among the interesting materials of the badland deposits few have given rise to more speculations as to their origin than what are known as the Devil's Corkscrews of the Harrison beds. Devil's Corkscrews, or Daemonelix, as they are technically called, have been known by the early residents of northwestern Nebraska for many years but it was not until 1891 when Prof. Barbour made a collecting trip to Harrison and the Badlands that these strange objects were brought to the attention of scientific men. What they really represent or how they were formed is still a matter of conjecture. The more typical forms are upright tapering spirals and they twist to the right or to the left indiscriminately. The spiral sometimes encloses a cylindrical body known as the axis but it is more often without the axis. Sometimes the spiral ends abruptly below but more often there projects from the lower part one or two obliquely ascending bodies placed much as the rhizomes of certain plants. The size of the well developed form varies considerably. The height of the corkscrew portion often exceeds the height of a man while the rhizome portion is ordinarily about the size of one's body.

They are known to occur especially between the head waters of White and Niobrara rivers chiefly in Sioux county, Nebraska, but extend westward to Lusk, Wyoming, and eastward to Eagle Nest Butte, South Dakota. The vertical range of strata carrying them is approximately 200 feet. In certain localities they are found in the greatest profusion, sometimes stretching like a forest over many acres and sometimes so closely placed that they are inextricably entangled and fused together. (Plate 47).

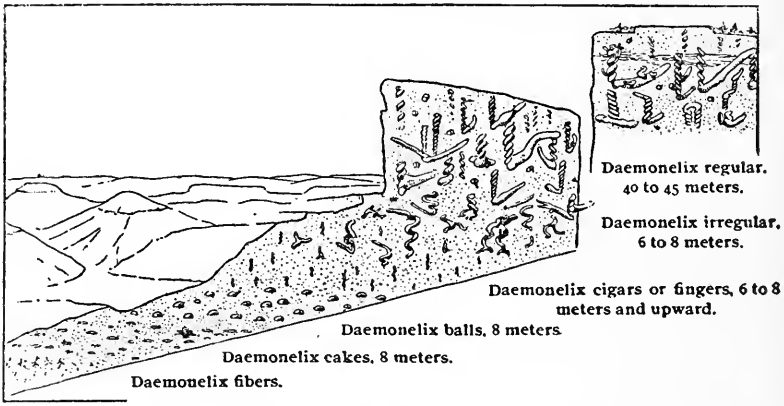

Figure 14—Diagramatic section showing the relative positions of the several forms in the Daemonelix series according to Barbour, 1896.

Prof. Barbour who has given these interesting forms most study considers them as representing some kind of plant life and has apparently found much to corroborate this view. Some have considered that they represent low plant organisms such as algae, others that they may be remains of higher plants, in which all has decayed away except the cortical layer. Still others and these with much reason have considered them as casts of well preserved burrows of animals. Among the earliest to suggest the latter idea were Dr. Theodore Fuchs of Germany and Prof. Cope. More recently Mr. O. A. Peterson emphasized the latter view as a result of the finding of numerous fossils of burrowing rodents within the corkscrews. (See Figures 15 and 53).

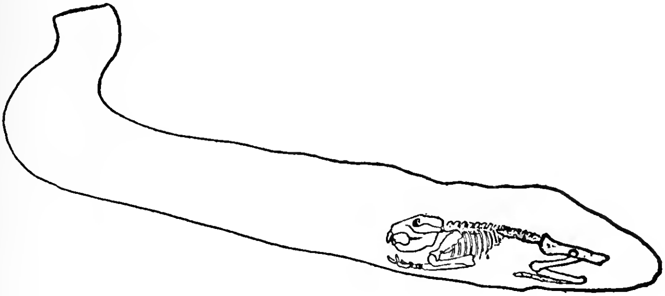

**Figure 15—Field sketch of a weathered rhizome containing the type specimen of the burrowing rodent, *Steneofiber barbouri*. Peterson, 1905.**

## ECONOMIC MINERAL PRODUCTS

The White River badlands have not attracted particular attention as a source of mineral wealth. Sandstones and limestones are found in various places but they seldom meet the requirements of a high grade building stone. They are nearly always thin-bedded and generally are more or less argillaceous. The sandstones are often of coarse or irregular texture and poorly cemented.

Clays occur in unlimited abundance and analyses show that they could be utilized if desired, in various ways, particularly in the manufacture of brick and cement. Some of the clays especially those near the bottom of the Titanotherium beds have the property of decolorizing or clarifying oils, hence are known as fullers earth.

Prof. Heinrich Ries of Cornell University, gives the following analyses for the localities mentioned, analyses 1, 2, 3, 6 being of material from near Fairburn, and analyses 4 and 5 of material from near Argyle.

**Analyses of Fullers' Earth From the Titanotherium Beds.**

| Constituent | 1 | 2 | 3 |
|---|---|---|---|
| | Per cent | Per cent | Per cent |
| Silica ($SiO_2$) | 68.23 | 60.16 | 56.18 |
| Alumina ($Al_2O_3$) | 14.93 | 10.38 | 23.23 |
| Ferrous oxide (FeO) | 3.15 | 14.87 | [a] 1.26 |
| Lime (CaO) | 2.93 | 4.96 | 5.88 |
| Magnesia (MgO) | 0.87 | 1.71 | 3.29 |
| Loss on ignition | 6.20 | 7.20 | [b] 11.45 |
| Total | 96.31 | 99.28 | 101.29 |

a—$Fe_2O_3$ b—$H_2O$.

| Constituent | 4 | 5 | 6 |
|---|---|---|---|
| | Per cent | Per cent | Per cent |
| Silica ($SiO_2$) | 55.45 | 57.00 | 58.72 |
| Alumina ($Al_2O_3$) | 18.58 | 17.37 | 16.90 |
| Ferrous oxide (FeO) | 3.82 | 2.63 | 4.00 |
| Lime (CaO) | 3.40 | 3.00 | 4.06 |
| Magnesia (MgO) | 3.50 | 3.03 | 2.56 |
| Loss on ignition | 8.80 | 9.50 | 8.10 |
| Volatile | 5.35 | 5.85 | ......... |
| Alkali | ......... | ......... | 2.11 |
| Moisture | ......... | ......... | 2.30 |
| Total | 98.90 | 98.35 | 98.45 |

Volcanic ash has been mentioned in the description of the deposits. It occurs rather widely distributed over the country. A prominent bed lies near the top of Sheep mountain and extends outward from it for many miles along the walls and the remnant buttes that are high enough to retain it. Other beds are found near and within the neighboring Black Hills and here some effort has been made to place the material upon the market. Deposits of a similar nature in Nebraska have been worked for many years. The ash when not mingled with other sediment is nothing more than minute angular fragments of natural glass and these having sharp cutting edges give to the ash a value as a polishing powder or in the prepared state is an important constitutent of abrasive soaps.

The fossil bones found in the badland deposits, like the bones of present day animals, generally contain much phosphate. There is little reason, however, to believe that the phosphate can be utilized commercially. Men speak of the abundance of the fossil bones, but it should be stated that this is more particularly from the viewpoint of the scientist interested in their educational value rather than that of the manufacturer of commercial bone products. There seems never to have been any very great tendency for the phosphate to leach out from the bones and concentrate into beds.

For those interested in the chemical nature of the bones, I give the following analyses made many years ago by Dr. Francis V. Greene from material collected by the Owen Survey and published in the American Journal of Science, 1853, also analyses made recently in the State School of Mines laboratories by Mr. George Enos.

**Analyses of Badland Fossils (Greene)**

| Constituent | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| | Per cent | Per cent | Per cent | Per cent |
| Phosphoric Acid ($P_2O_5$) | 33.98 | 39.15 | 35.97 | 31.19 |
| Silica ($SiO_2$) ......... | 0.09 | 0.48 | 0.79 | 0.26 |
| Ferric Oxide ($Fe_2O_3$) .. | 1.77 | ......... | ......... | ......... |
| Fluorine (F) ........ | 0.40 | 0.04 | 1.42 | 2.46 |
| Magnesia (MgO) ...... | 0.33 | 0.22 | 0.53 | 1.14 |
| Lime (CaO) .......... | 49.77 | 51.80 | 51.23 | 50..83 |
| Potash ($K_2O$) ........ | 0.31 | 0.24 | 0.23 | 0.28 |
| Soda ($Na_2O$) ......... | 1.13 | 1.28 | 0.75 | 1.57 |
| Baryta (BaO) ........ | 0.36 | ......... | ......... | 1.10 |
| Chlorine (Cl) ......... | ......... | ......... | ......... | 0.02 |
| Sulphuric Anhydride ($SO_3$) ........... | 0.88 | 1.01 | 1.51 | 2.19 |
| Carbonic Acid ($CO_2$) .. | 4.08 | 3.17 | 2.83 | 2.77 |
| Water ($H_2O$) ........ | 2.04 | 0.62 | 2.10 | 1.97 |
| Organic Matter ....... | 5.67 | 2.54 | 2.66 | 4.09 |
| Total ............ | 100.81 | 100.55 | 100.02 | 99.87 |

In the above anaylses, No. 1 is that of a Titanothere bone, No. 2 of a Titanothere tooth (enamel), No. 3 of a Titanothere tooth (dentine), No. 4 of an Archaeotherium (Elotherium) bone.

**Analyses of Badland Fossils (Enos)**

| Composition | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| | Per cent | Per cent | Per cent | Per cent |
| Silica ($SiO_2$) | 8.96 | 2.10 | 23.78 | 71.80 |
| Phosphoric Anhydride ($P_2O_5$) | 46.30 | 33.40 | 20.00 | 4.34 |
| Iron and Aluminum Oxides | 1.97 | 2.80 | 5.00 | .18 |
| Lime (CaO) | 27.17 | 20.00 | 24.10 | 8.80 |
| Magnesia (MgO) | .50 | 32.36 | 1.44 | 3.22 |
| Soda ($Na_2O$) | 6.08 | .14 | .04 | 2.80 |
| Potash ($K_2O$) | .65 | .80 | .72 | 1.16 |
| Baryta (BaO) | .08 | ......... | 3.80 | ......... |
| Chlorine (Cl) | Trace | ......... | ......... | ......... |
| Fluorine (F) | ......... | ......... | ......... | ......... |
| Sulphuric Anhydride ($SO_3$) | .56 | .97 | .42 | .25 |
| Carbon Dioxide ($CO_2$) | 4.65 | 5.90 | 18.70 | 7.19 |
| Water at 110°C | 1.40 | 1.32 | 2.04 | ......... |
| Organic Matter | 1.17 | ......... | ......... | ......... |
| Total | 99.49 | 99.79 | 100.04 | 99.74 |

Remarks:—

No. 1 is part of the upper tooth of a brontothere.

No. 2 is part of lower tooth of a young titanothere.

No. 3 is part of lower jaw with teeth (oreodon) and matrix.

No. 4 is a coarse sandstone with clay pebbles and bone fragments from Protoceras beds.

The above specimens are all from the Big Badlands of South Dakota.

## FOSSILS

Fossils as generally understood are the parts of animals and plants living before the present era that have been buried in the rocks and preserved by natural causes. The manner and degree of preservation vary greatly. The essential thing is the sealing up of the remains in the rocks so that destruction and decay may be prevented. Animals such as the ice-entombed mammals of Siberia and the amber enclosed insects of the Baltic, are practically perfect as the day they were buried, but they are exceptional. Generally only the hard parts, such as bones or teeth, or shells remain. Not infrequently these are replaced particle by particle by new mineral matter of some kind, particularly silica or pyrite, then they become petrifactions. Sometimes only the form, or the impression of the original parts are preserved, hence the terms molds and casts. Occasionally the relics are limited to footprints, or trails, or burrows, or borings or eggs.

Animals living in the water or frequenting marshy places for food and drink are more easily and more quickly buried beneath sediments, hence their fossils are usually more abundant. The bodies of dry land animals are subjected to the vicissitudes of sun and rain and wind, and frost, and are often feasted upon by scavenger birds and beasts and insects. Furthermore their burial is commonly brought about only during flood season. All of these tend to the destruction or dismemberment of the various parts. Again, even if once nicely buried, they may later be obliterated by metamorphism or be destroyed by disintegrating and denuding agencies. As a result of all this, the history of certain groups of animals is meagre in the extreme and doubtless hordes of species have left no worthy evidence of their ever having lived.

## EXTINCTION, EVOLUTION AND DISTRIBUTION OF ANIMALS

The progress of animal organisms is constantly directed toward the goal of perfection. Each individual shares in the improvement but the perfection to be attained consists not so much in the exquisite relation the various organs bear to one another as it does in the harmony that the animal in all its characters shows to its environment.

When life began, and how, no one knows. It is evident that in the beginning it was represented by very simple forms. These, because of varying conditions, were followed in orderly sequence by creatures of growing complexity. All animals pass through innumerable vicissitudes and existence is a constant struggle. Those best fitted to meet difficulties tend to survive and leave posterity. It thus happens that advantageous variations are perpetuated and those of less use are eliminated. In this way changes occur, characters are modified, and life forms sooner or later take on an appearance and a nature quite different from their ancestors.

Just as individuals suffer distress and destruction so, sometimes, entire animal groups battling for position in life's long race and gaining for a time supremacy in their field are in turn oppressed and in the end obliterated by the contending forces. Of the animals described in this book several groups are wholly extinct, no relatives of any reasonable nearness being found living today. Notable among such are the Titanotheres, the Oreodons and the Moropus. Reference to the extinction of others is given in connection with their description.

Often extinction is apparent rather than real and the seeming obliteration may be only the normal expression of constant change. For example, in the horse, camel, rhinoceros and other families the consecutive changes may be traced through a long continued series of replacements by the process of gradual development. Again the seeming extinction may be only a migration from the locality in

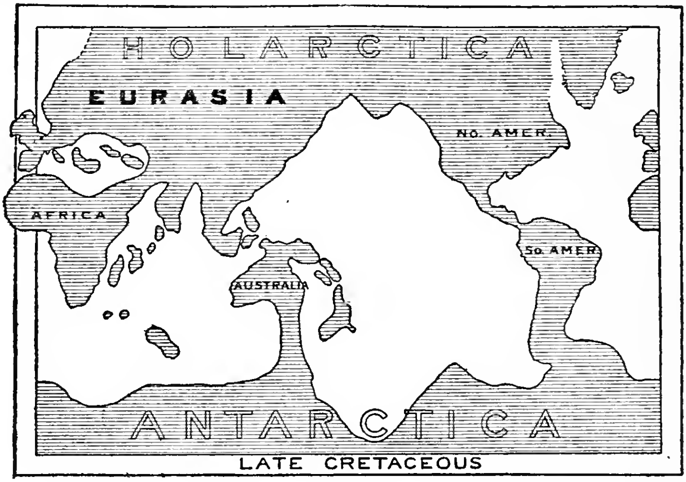

Figure 16—Land areas of the world during Late Cretaceous and Basal Eocene time. Period of extinction of the great Reptilia. A time of elevation, favoring an interchange of archaic life between South and North America, also between North America and Europe. South America probably united with Australia via Antarctica, allowing an interchange of carnivorous and herbivorous marsupials. A partial community of fauna between North America and Eurasia with Africa. Rearranged from W. D. Matthew, 1908. H. F. Osborn: The Age of Mammals in Europe, Asia, and North America, 1910. Published by The Macmillan Company. Reprinted by permission.

question and in the new environment activity may continue as favorable as before.

In case of actual extinction it is often not possible to ascertain the immediate causes. Sometimes the extinction is due wholly to conditions external to the animals themselves, such as unfavorable climate, alteration of food supply, ravages of disease, encroachment of hostile species, insect pests, et cetera. Again extinction may be due largely to lack of internal adaption or adaptability, for example, the teeth may be fitted for too little variation of food, or the brain may be deficient in size or quality so that the animal lacks resourcefulness, alertness and enterprise.

Figure 17—Land areas of the world during Oligocene time. A period of continental elevation and reunion followed by the reestablishment of connections between the life of the New and Old Worlds. Central Europe submerged or partly archipelagic. African mammals and birds partly similar to those of Europe. Madigascar united with Africa. South America entirely separated, its mammals developing independently. Australia entirely separated. Closing the Oligocene, another long interval of separation between North America and Europe. Rearranged after W. D. Matthew, 1908. H. F. Osborn. The Age of Mammals in Europe, Asia and North America, 1910. Published by the Macmillan Company. Reprinted by permission.

The distribution of animals is closely related to their development and has been in large measure controlled by geographical conditions. A study of paleogeography shows that the several continents have had a varied career. Changes have taken place in them through all the ages and migration roads and barriers, in long procession, have formed and disappeared. With the advent of mammalian life interest in these physiographic changes increases and their interpretation is made with greater assurance of accuracy.

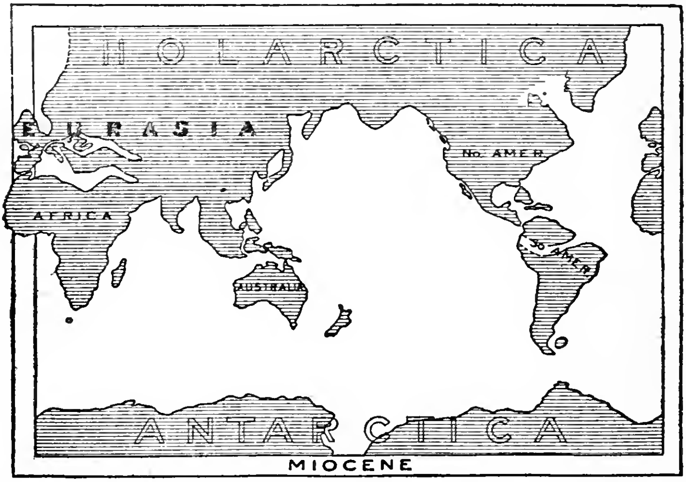

Figure 18—Land areas of the world during Miocene time. A period of continental elevation and emergence, consequently of renewed land connections and migrations. Africa broadly united with Europe across the Arabic peninsula, and a typical Asiatic fauna roaming westward into Europe and Africa. Asia connected with the East Indies and the Philippine Islands. Florida elevated at the close of the Miocene. South America divided into northern and southern halves by a broad gulf, the northern half perhaps connected with North America. Australia entirely separated from Asia. Rearranged after W. D. Matthew, 1908. H. F. Osborn: The Age of Mammals in Europe, Asia and North America, 1910. Published by The Macmillan Company. Reprinted by permission.

Life in the older geologic time was simple. The forms increased in complexity as the ages came and passed. Primitive mammals appeared during the Mesozoic but not until the

Cenozoic did they reach importance. They then became the ruling type and the Cenozoic, for this reason is often called The Age of Mammals. (See Plate 9).

In early Tertiary time North America was apparently not connected by land with South America. It was, however, connected with Asia by way of Alaska and with Europe by way of Greenland and Iceland. These land bridges and the Panama region are known to have changed greatly during and subsequent to the Tertiary and a fair understanding of their influence will explain many perplexing features of animal and plant distribution.

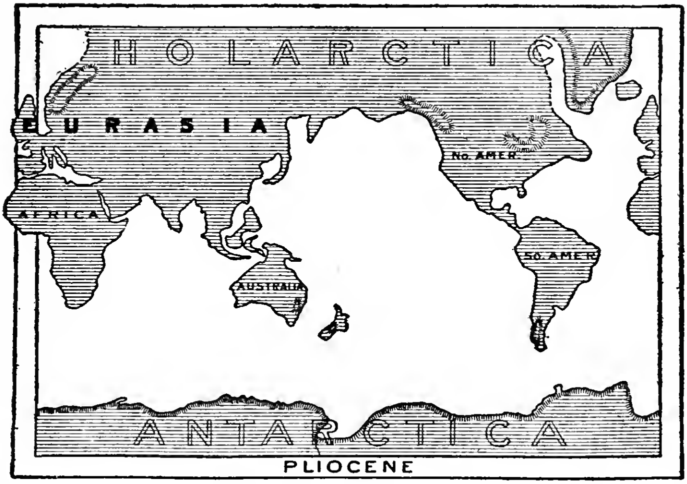

Figure 19—Land areas of the world during Pliocene time. A period of continued continental elevation especially in Europe and Eastern North America. Seasons of aridity or summer drought, increased aridity of the Great Plains of North America. South America connected with North America by migration routes which allowed free interchange of mammals. Australia still united with New Guinea and Tasmania. Rearranged after Matthew, 1909. H. F. Osborn. The Age of Mammals in Europe, Asia and North America, 1910. Published by The Macmillan Company. Reprinted by permission.

## THE COLLECTING AND MOUNTING OF FOSSIL BONES

In the earliest explorations in the Badlands little careful effort was made to secure complete skeletons, the explorer apparently contenting himself with securing only the better heads or other fragments lying on or near the surface. Later extensive digging was resorted to, but for some years this was done in a crude way. The bones are generally more or less broken and disarticulated and when once the fragments become separated the proper assembling of the pieces again becomes a difficult task. In course of time a method of bandaging developed. Now the fragments while being excavated are kept together by laying on with flour paste strips of muslin or burlap or other coarse, loose-woven cloth. Plaster of paris may also be used especially where heavy pieces are involved or where extreme care is necessary. Soft bones are treated with some preparation of shellac or gum to harden them for transportation· Exact location of the skeleton and the relative position of every bone in the skeleton is of the greatest importance. Sketches and photographs are made as the work progresses and all pieces removed are carefully labelled. A knowledge of the stratigraphical horizon is essential to determining much of the relationship and life history of the animal and the proper location of each bone with reference to neighboring bones of the same excavation may serve greatly in the

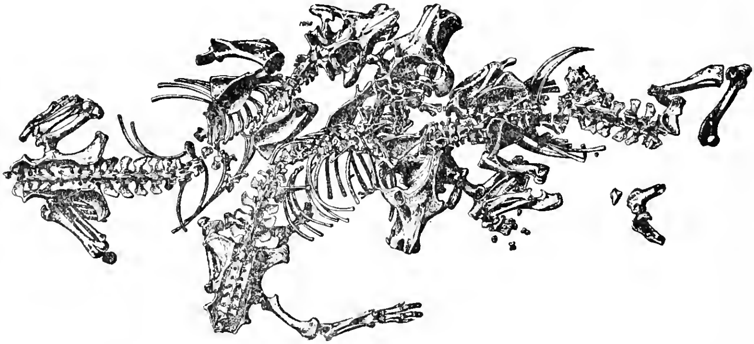

**Figure 20—Group of three *Promerycochoerus carrikeri* skeletons in position as found. Showing the disturbed conditions of the specimens even when the bones are well preserved and the skeletons fairly complete. Peterson, 1914.**

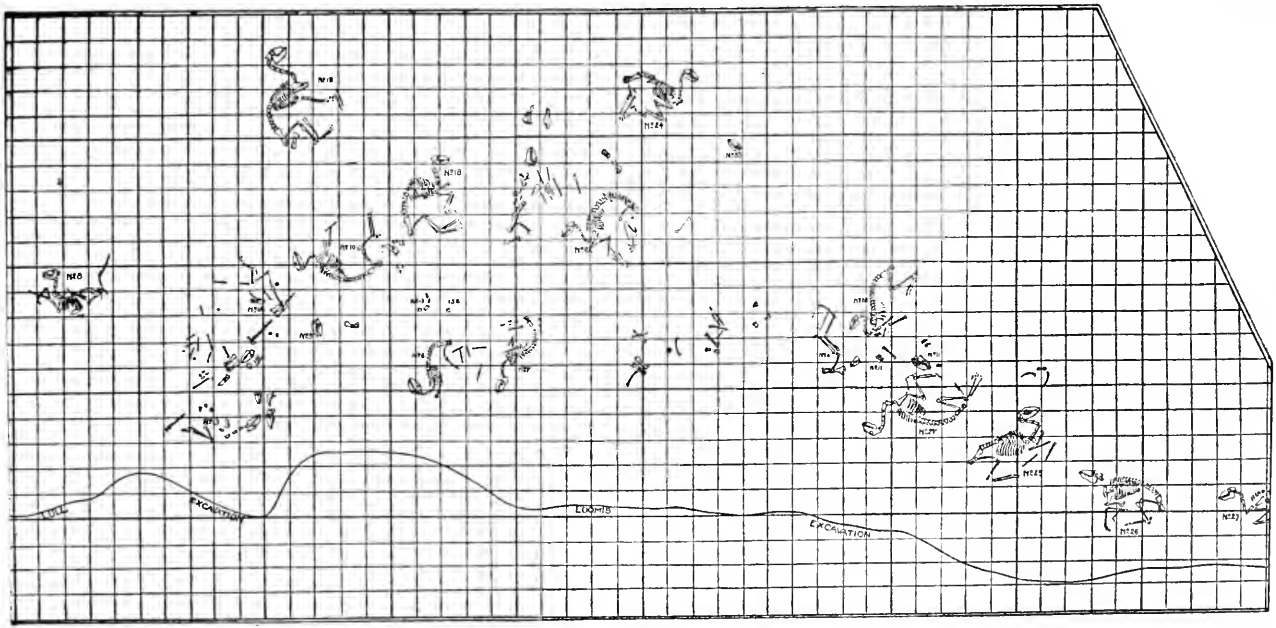

Figure 21—Plan of the Carnegie Museum Stenomylus quarry, Sioux county, Nebraska, showing the remarkably fine array of complete or nearly complete skeletons of ancestral camels excavated there. Peterson, 1911. (Each square represents one square foot.)

mounting of the restored skeleton. Often considerable masses of the enclosing earth or stone are quarried out and shipped to the museum where time and proper instruments will permit a more satisfactory extraction of the bones. (See Plate 10 and Figures 20 and 21).

Reaching the preparator's laboratory the bandages are carefully removed, all useless matrix cleared away and the bone fragments assembled and cemented together. Injured bones are then repaired and missing bones reproduced in some suitable artificial preparation. The mounting is often facilitated by study of the living relatives of the fossil form. Where there is no living animal nearly related, recourse is had to the studies of the rugosities of the bones where the main muscles were attached in life, the facettes of the joints and the general shape and character of the various bones.

All this work, if properly done, requires much patience and skill in manipulation as well as intelligent insight into the general nature of the animal to be mounted. Many weeks or months may be required in the laboratory work alone, the expense of preparation usually far exceeding the time and money spent in collecting the specimens in the field. It may be readily inferred that the money value, to say nothing of the educational importance of the completed skeleton, particularly if it is the type specimen of a new series, is often very great. (Plate 50).

## THE CLASSIFICATION AND NAMING OF EXTINCT ANIMALS

The naming of animals, both living and extinct is closely interwoven with their classification. Classification is a process of comparison. Its object is to bring together the like forms and to separate the unlike. This is best accomplished by comparing the various characters which are the most constant. The natural result is the arrangement of groups within groups in a continuous manner, the various groups being given particular names, as, Kingdom, Subkingdom, Class, Order, Family, Genus, Species, et cetera. The scientific name by which any animal is indicated is formed by combining the generic and specific names much as we combine our own family and Christian name except that in the scientific nomenclature the specific term comes last. To illustrate: The scientific name of the domestic dog is *Canis familiaris* Linnaeus, *Canis* being the name of the genus and *familiaris* the name of the species. The third non-italicized portion may be considered a part of the name although this really refers only to the naturalist who first carefully described and properly named the creature. It is often omitted, especially in the case of fairly common or well known animals or where there is no mistaking the individual who gave the name. In scientific literature, however, and particularly in paleontology where, on account of imperfect material, there is liability of error in determination this is usually given as it not infrequently becomes essential for clearness in referring to the species. Omitting it from the name for the time being, the complete classification of the dog may be represented as follows:

Kingdom, Animalia.
Sub-kingdom, Vertebrata.
Class, Mammalia.
Sub-class, Eutheria.
Infra-class, Monodelphia.
Cohort, Unguiculata.
Order, Carnivora.
Sub-order, Fissipedia.
Family, Canidae.
Genus, Canis.
Species, Familiaris.
Variety, "Shepherd."
Individual, "Shep."

Continuing the illustration the scientific name of the tiger is *Felis tigris* Linnaeus; of the ox, *Bos taurus* Linnaeus; of man, *Homo sapiens* Linnaeus. These names are simple enough when once understood and indeed many names we now look upon as common have been transferred bodily from the scientific generic nomenclature, as for example, rhinoceros, hippopotamus, bison, and mastodon.

It is well known that the common names by which animals now living are designated are often not sufficiently accurate. The name in order to be properly useful must be sufficiently distinctive to indicate clearly the animal to which reference is made. For example, there are five existing species of rhinoceroses, the clear definition of which by common names is perhaps difficult enough, to say nothing of the score or more of fossil forms besides a still larger number of extinct animals closely allied to the rhinoceroses and falling under the general Class, Rhinocerotoidae. Again sometimes the common name is deceptive. For example the well known pronghorn antelope, *Antilocapra americana,* of our western plains is considered by some zoologists as not being an antelope at all. On the other hand our Rocky Mountain goat *Oreamus Montanus* is a member of the true antelope family. True antelopes at the present day inhabit chiefly Europe, Asia and Africa. They include many species, the better known ones being designated in common speech as hartebeests, gnus, elands, gazelles, klipspringers, gemsbocks, springboks, waterbucks, duickerboks, saigas, etc. Several of these are subdivided. For example the duickerboks alone are credited with thirty-eight species. If, therefore, we are going to name animals in conformity with their recognized distinctions, and for clearness of conception there is generally no alternative, then the various duickerbok species must each be given a name—thirty-eight in all. Thus antelope being in reality a misnomer here in this country and losing much of its distinctive significance even in the old world, becomes little more than a loose expression for a great group of animals, some of them no larger than a jack-rabbit, and others comparable in size to a horse.

Generally, in designating the species, the words of the scientific name refer to some important character, or they express some relationship or resemblance, or indicate some fact of distribution or discovery. Sometimes the meaning is obscure in which case it may be necessary to consult the work of the original author for the interpretation. Often, however, the name needs little explanation other than that given by a good comprehensive dictionary.

The generic names are usually of classic origin, most of them being Latinized forms of Greek names. They may be either simple or compound words and they often have modifying or descriptive prefixes or suffixes. The specific names show a somewhat wider latitude of origin than the generic names. Sometimes they are geographical, sometimes personal, oftentimes descriptive. The following names of badland fossils may serve to illustrate the principle: *Procamelus occidentalis* Leidy, an ancestral camel of the new world, described by Leidy; *Magacerops brachycephalus* Osborn, a short headed animal with a great-horned appearance, described by Osborn; *Neohipparion whitneyi* Gidley, a new world, small horse described by Gidley and named in honor of W. C. Whitney; *Protoceras celer* Marsh, a fleet-footed first-horned animal described by Marsh; *Protosorex crassus* Scott, a large sized primitive shrew, described by Scott.

It would lead us too far away to go into the full details of this nomenclature. One additional feature, however, deserves notice in view of its not infrequent perplexity. The individual who first describes a new species is supposed to give it a name which must not conflict with any name used previously for another species. According to the rules governing the matter the name by reason of its priority can not be changed subsequently except for cause. Often in paleontological work where poor or insufficient or aberrant material has been first studied later discoveries have shown errors of description or improper identification in which case a new name may become necessary. The new name, if properly given becomes the accepted name while the old name is referred to as a synonymn. In not a few cases there are several synonyms and not infrequently it is a matter of some conjecture as to just which is the most appropriate under the circumstances.

With rare exceptions the animal life of the White River badlands is restricted to the Vertebrata—the backboned animals. Aside from turtles of which there are many, and a few crocodiles, lizards, and birds eggs, all of the fossil remains of the vertebrates thus far found within the area belong to the great class "Mammalia." The term "Mammalia" includes all hair-clad, vertebrated animals, the females of which are provided with glands for secreting milk for the early nourishment of the offspring. They are the highest of the vertebrates, possessing that happy combination of anatomical and physiological simplicity and complexity tending toward highest efficiency as organisms. They are not only the most important animals of today, but they have been the rulers of the animal world since early Tertiary time. Continuing back in geological history with ever increasing simplicity toward a generalized, omnivorous, allotherian ancestry they may be traced with certainty to Triassic time. Since their beginning multitudinous changes have taken place in the structure and activity of the many species that have originated, developed and died and, as a result, the expression of relationship must often be indefinite or uncertain.

Following the custom of many authors three main subclasses of the Mammalia may be recognized, namely, the Prototheria or primitive mammals, the Metatheria or pouched mammals and the Eutheria or perfect mammals.

The Prototherian mammals are restricted to a few simple forms such as the Echidna (Australian Ant Eater) and the Ornithorynchus (Duck-billed Platypus) which lay large yolked eggs much after the fashion of reptiles and birds. They are not represented in the White River badlands either living or fossil, hence need no further consideration here.

The Metatheria are those intermediate, marsupial mammals which, having only a rudimentary or primitive placental structure, bring forth their young in a very immature state and carry them for a considerable time in a pouch provided for the purpose. The opossum, the kangaroo and the Tasmanian "wolf" are well known representatives. Like the Prototheria the Metatheria are not found in the White River badlands.

The Eutheria include a vast assemblage of forms of all sorts of perfection of development from lowly primitive creatures to man. These are grouped somewhat differently by different authors but all of the fossil forms obtained from the region under discussion fall naturally into four main divisions, namely, the Insectivora (insect eaters) the Carnivora (flesh eaters), the Rodentia (gnawers), and the Ungulata (hoofed mammals), the Ungulata (Herbivora) being represented by two orders, the Perissodactyla (~~even~~- odd toed mammals) and the Artiodactyla (~~odd~~ even -toed mammals).

The Insectivores include moles, hedgehogs, shrews and other small animals of antiquated structure. They are generally plantigrade (walking upon the sole of the foot), the snout is often prolonged into a short proboscis, and their chief food is insects. The Carnivores include animals whose chief food is flesh. They may be terrestrial, arboreal, or aquatic. They have a simple stomach, a well developed brain, toes provided usually with long, sharp claws, and generally they have a body capable of much agility in the capture of prey. They walk either upon the entire sole of the foot or upon the under surface of the toes but never upon the tips of the toes as do the Ungulata. The carnivorous structure is common to all of the class but the carnivorous habit, though general is not universal. Living representatives vary in size from the little active ermine to the powerful grizzly bear. The Rodents include a group of small to moderately large animals the most prominent and universal character of which is their dentition. Canine teeth are absent. The deeply set incisors, separated by a considerable vacant interval from the molars, are long and flat edged and are of paramount importance. Since they lengthen by persistent growth they serve admirably for vigorous chisel-like cutting of hard materials, hence the name "gnawers." The animals are usually plantigrade, often burrowing, not infrequently arboreal, and occasionally acquatic. They are today represented by the squirrels, prairie dogs, rabbits, rats, mice, beavers, porcupines, and a host of others. The Ungulates (Herbivores) are plant-feeding animals with hoofs rather than claws or nails, and with limbs perfected for running and not for climbing and grasping. Viewed from the point of usefulness to man they are the most important of all animals in that they furnish him with food, clothing and working assistance.

## CARNIVORES

The Carnivora may be conveniently divided into three sub-divisions (sub-orders), namely, the Creodonta or primitive carnivores, the Fissipedia or true carnivores, and the Pinnipedia or aquatic carnivores. Of these the Creodonts are found only in the fossil state; the Fissipedes include our common carnivorous animals such as the Canidae (dogs or dog-like creatures) and the Felidae (cat family), and are both fossil and living. They are found in large numbers among the fossils of the badlands. The Pinnipedes include the aberrant animals, the seals and walruses. The Creodonts are represented in the White River badlands by but one family, the Hyaenodonts. The Pinnipedes are not found there at all.

## CREODONTA

The Cerodonts originated in the earliest Tertiary and were evidently the predatory flesh eaters of their time. They were the primitive ancestors of the true carnivores and they held a position relative to contemporary animals similar to that which the true carnivores hold among the animals of today.

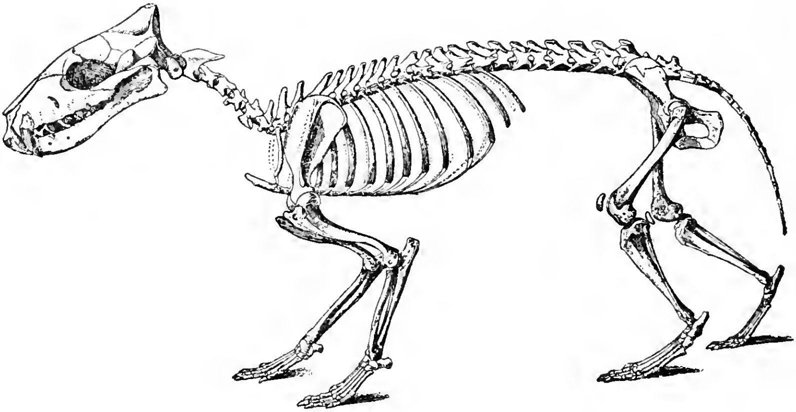

Figure 22—Skeleton of the Oligocene creodont *Hyaenodon cruentus* Scott. 1895.

There were numerous families but of all these only the Hyaenodons, the latest and most specialized are found in the White River badlands. (See Plate 25). The individual fossils are not abundant although several species are represented. The skull of the largest *Hyaendon horridus* indicates an animal of wolf-like appearance approaching in size the present day black bear. The life habits of these animals are not entirely clear. It is not even known whether they were digitigrade or plantigrade. They may have been semi-plantigrade. It has been suggested that they were semi-acquatic but this is quite uncertain. The Hyaenodons, unlike most of the class, seem to have lived on carrion.

## CANIDAE

The Canidae are abundantly represented in the White River badlands. More than twenty species are known. The earliest North American Canidae recognized as such are found in the Upper Eocene. They first appeared in Europe at about this time also and were abundant in both Europe and North America during Oligocene and Miocene times. They are known to have reached India by the early part of the Pliocene and seem to have migrated along the Isthmus of Panama to South America as soon as it emerged from the sea at the dawn of Pliocene time. It is of interest to note in this connection that the nearest living allies of the White River Oligocene and Miocene forms are certain foxes now inhabiting South America.

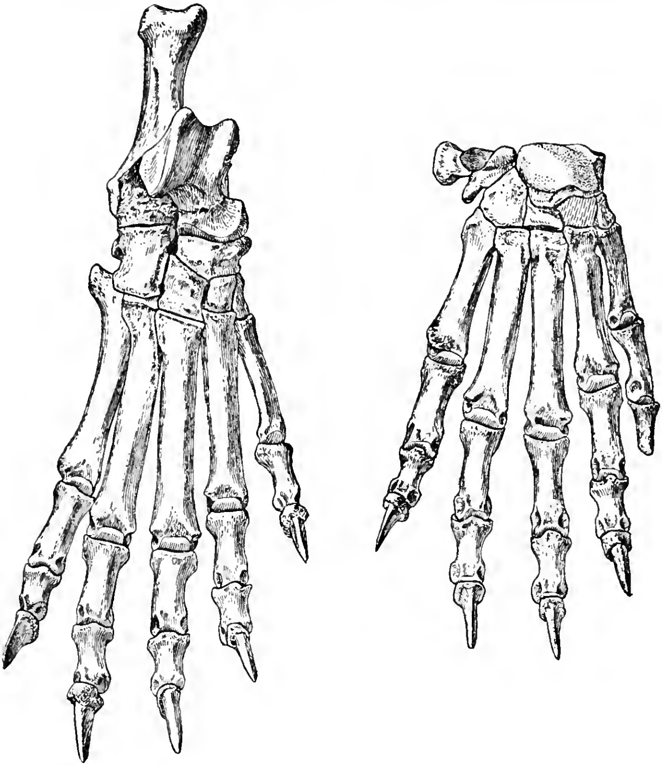

**Figure 23**—Dorsal view of the hind foot and the fore foot of *Daphoenodon superbus*. Peterson, 1910.

According to Cope, the Canidae, so far as concerns structure, occupy a position intermediate between the generalized carnivores, such as the raccoons, and the highest specialized forms, the cats; but in brain character they display superiority to all of the other carnivore families. The chief difference between the Tertiary and the living forms lie in the higher specialization of the latter, particularly as regards foot structure and brain character.

The Canidae seem almost certainly to have descended directly from the early Eocene Creodonta, but so undoubtedly did the Felidae. During the Oligocene time the two families were much generalized and had many characters in

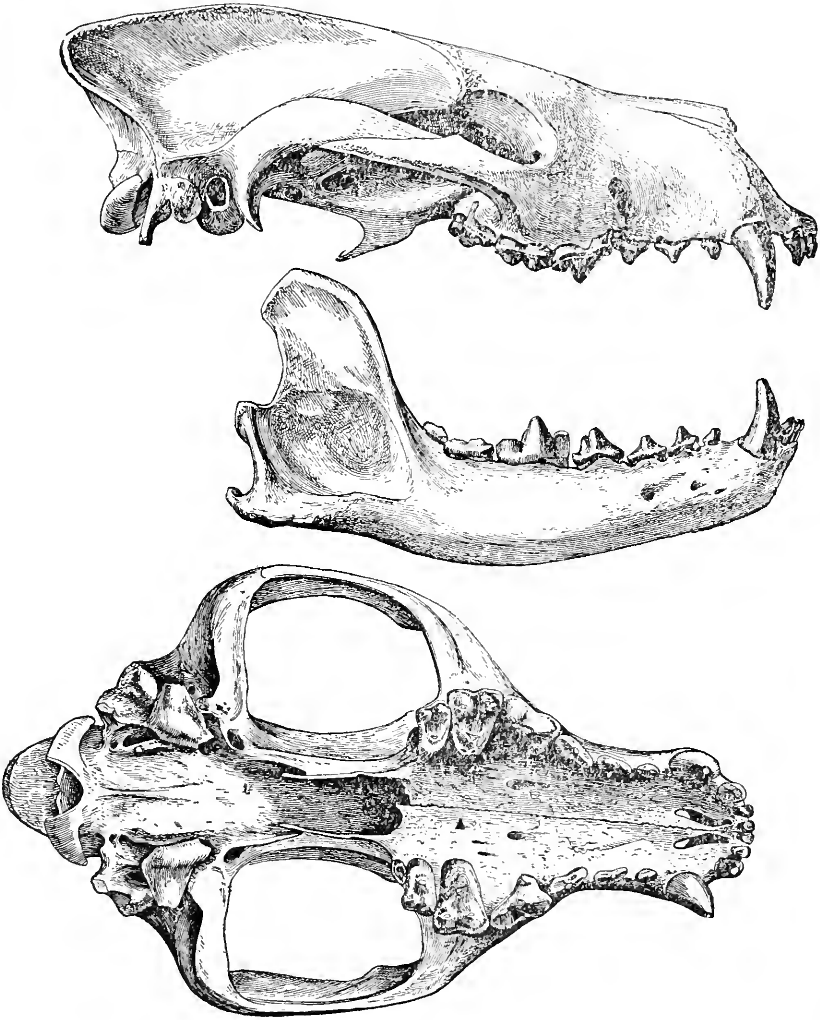

Figure 24—Skull of *Daphoenodon superbus*. Peterson, 1906.

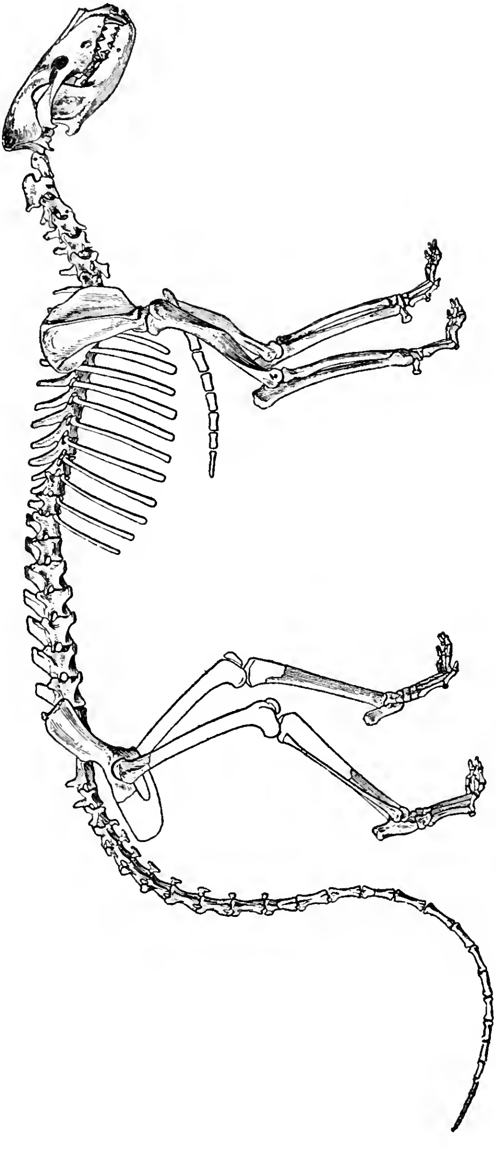

Figure 25—Skeleton of the Oligocene bear dog, *Daphoenodon superbus*. Peterson, 1910.

common, particularly in the dentition, the structure of the skull, the vertebrae, the limbs, and the feet. One feature of surprising interest, first indicated by Prof. Scott, is that some at least of the Canidae had sharp pointed, high, compressed, hooded claws, as in the cats, instead of curved, cylindrical cones, as in the dogs, and had the unmistakable ability of retracting the claws to a greater or less extent.

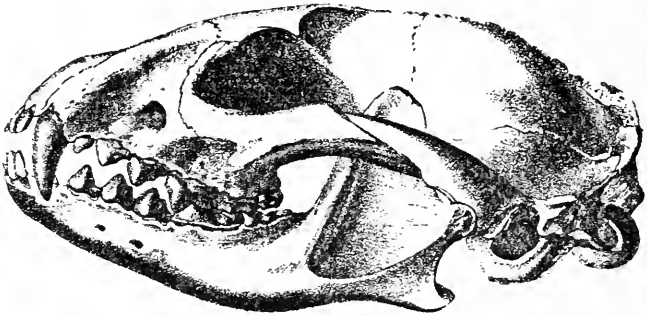

Figure 26—Skull of *Cynodictis gregarius.* Scott, 1898.

Although many specimens of the Canidae have been found in the White River badlands, few complete skeletons have been obtained. Until recent years little had been collected but heads. Of the several species *Cynodictis gregarius, Daphoenus felinus* and *Daphoenus superbus* are the best known. *Cynodictis gregarius* was most abundant and as the name implies seems to have roved the country in packs. It was smaller than the common red fox of the eastern states. *Daphoenus felinus* reached approximately the size of the coyote, while *Daphoenus superbus* was as large as a full grown gray wolf. (See Plate 26). One species, *Ischyrocyon hyaenodus,* includes individuals of larger size. Partial remains of a young individual seem to indicate that the full grown animal would compare favorably with the modern grizzly bear.

Daphoenus seems to represent in pretty fair manner the ancestral stage of the present-day wolf. Cynodictis has many characters resembling those of the modern fox but close relationship has not been proven. A small brain was characteristic of all of the Canidae and this was particularly true of Daphoenus.

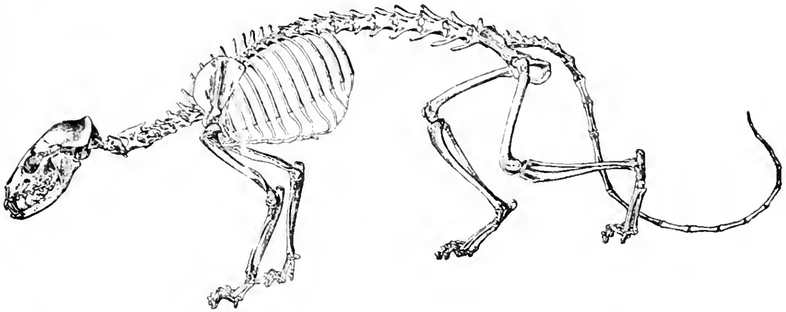

Figure 27—Skeleton of the Oligocene dog, *Cynodictis gregarius*. Matthew, 1901.

## FELIDAE

The cat family is well represented in fossil form in the White River region, although neither the species nor the individuals were so numerous as were the Canidae. Two genera are of particular prominence, namely, Hoplophoneus and Dinictis. These are early forms of what are commonly known as saber-tooth cats or tigers (Machaerodonts), a name given them by reason of two great sword or saber-like canine teeth of the upper jaw. They were not so large as certain later forms of this great group, nevertheless they were vicious creatures and Hoplophoneus, the larger of the

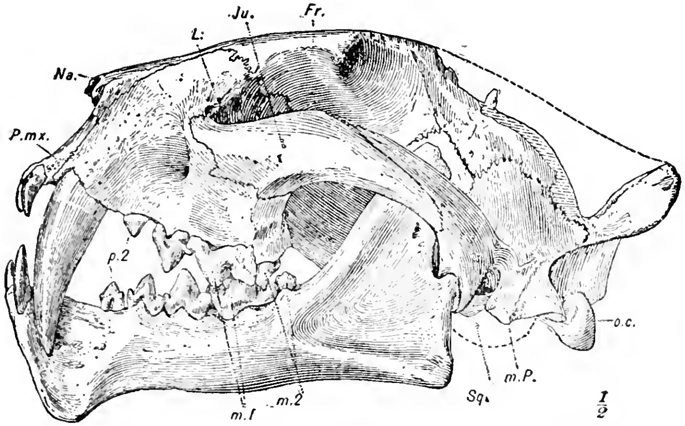

Figure 28—Skull of the Saber-tooth tiger, *Dinictis squalidens*. Matthew, 1905.

two, was doubtless fully as large as the present day leopard and apparently much more powerful. (Plates 27 and 28). The two represent well separated stages in the evolution of saber-tooth cats, and while Dinictis seems to have reached as high a stage of specialization as Hoplophoneus, it was evidently fitted to a somewhat different life.

An important feature of the lower jaw is the extreme downward projection of its anterior portion. This seems to be a co-incident feature necessitated by the unprecedented development of the powerful canine teeth already mentioned.

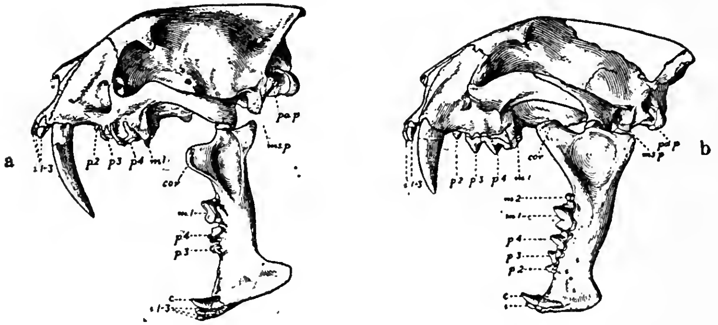

**Figure 29**—Heads of White River Saber-tooth tigers showing open jaws ready for attack. (a) *Hoplophoneus primaevus* (b) *Dinictis squalidens.* Matthew.

These upper canine teeth curve forward and downward nearly parallel with each other, and passing behind the much smaller lower canines, continue approximately to the lowest portion of the anterior downward prolongation of the chin. In general they are laterally compressed and the edges are more or less serrulated. They are implanted by a strong fang and reach two and one-half or three inches in length. In Hoplophoneus, these fangs were very long and slender and the protecting jaw flange was correspondingly deep. Dinictis had shorter canines and a less prominent jaw flange.

The cause of the development of the abnormally powerful upper canines and the uses to which they were put have been the cause of much speculation. (Plates 11 and 12.) W. D. Matthew of the American Museum of Natural History in discussing this indicates that in his opinion there is definite evidence of the adaptation of the canines to a particular method of attack. The head is so shaped that good attachment is allowed for strong muscles, enabling the animal to strike downward with its saber teeth with enormous power and the changes in the cranial portion allowing for the attachment for the increasingly powerful muscles were in strict correlation with the development of the saber-teeth. Along with these changes was the degeneration and change in shape of the lower jaw, allowing the mouth to be opened to an unusual extent so as to give greatest freedom to the saber-teeth in stabbing the prey. Hoplophoneus in addition to his terrible teeth had a strong body, stout neck and legs and highly developed strong retractile claws. His food must have been in large measure the thick skinned rhinoceroses, elotheres, oreodonts, and other similar animals of the time. The lighter proportioned

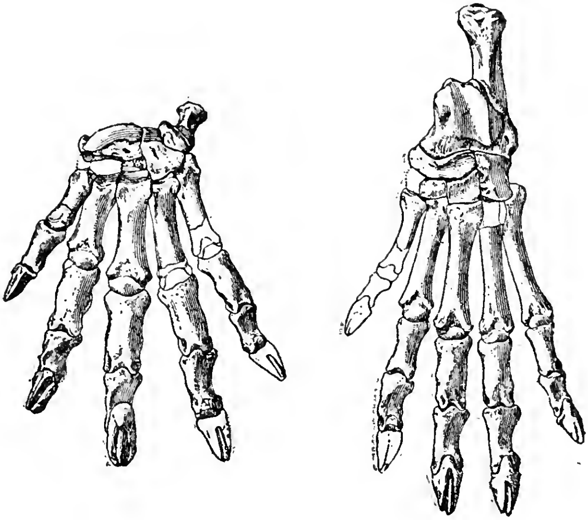

**Figure 30—Dorsal view of the fore foot and the hind foot of *Hoplophoneus primaevus*. Adams 1896.**

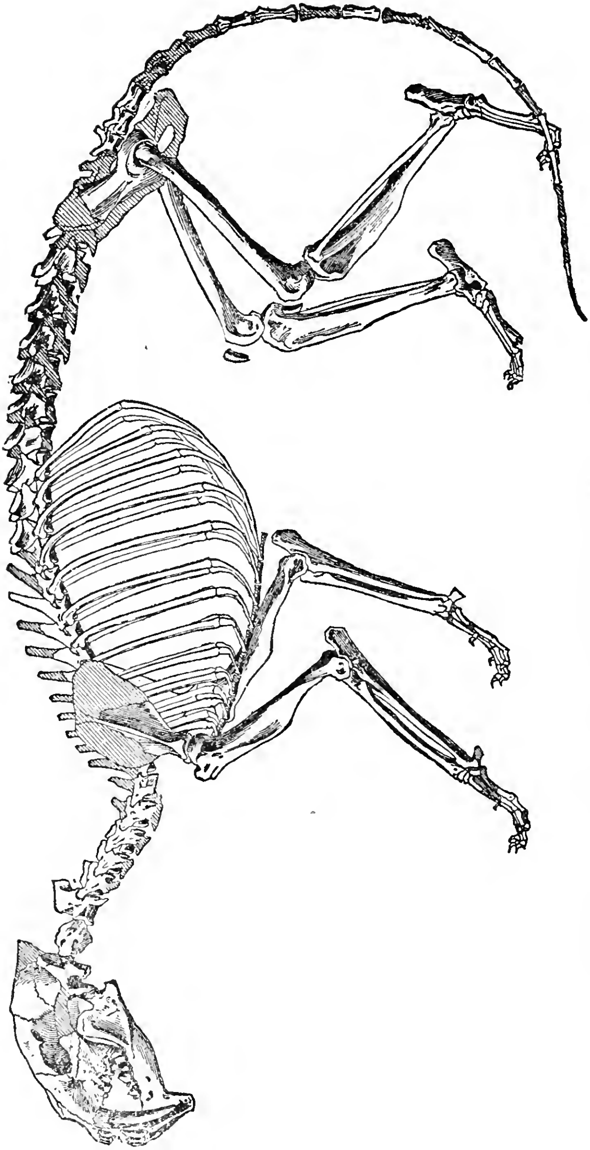

Figure 31—Skeleton of the Oligocene Saber-tooth tiger *Hoplophoneus primaevus.* Scott and Osborn, 1887.

Dinictis, with its less powerful canines, doubtless preyed more successfully on the smaller swift-footed animals, the securing of which demanded superior speed and endurance.

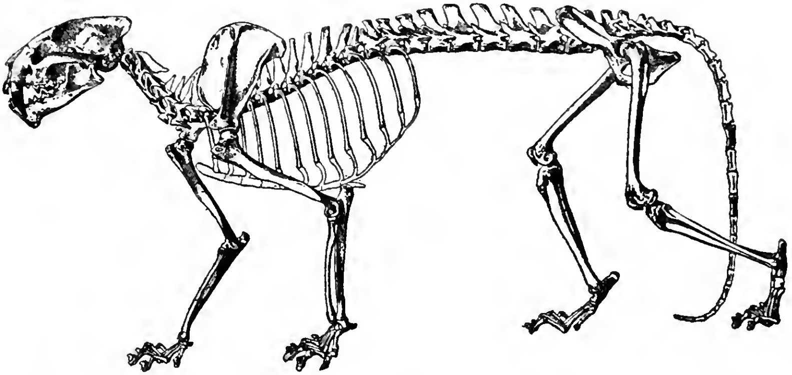

Figure 32—Skeleton of the Oligocene saber-tooth tiger *Dinictis squalidens.* Matthew, 1901.

The White River badlands furnished the earliest discovered remains of Saber-tooth cats in America. Leidy who described the first species gave it the name *Machaerodus primaevus.* Later this was changed to *Drepanodon primaevus*, and still later to *Hoplophoneus primaevus*, the name it now bears. From time to time other species have been discovered until now about a dozen are known. They were all most terrible beasts of prey and one of them *Eusmilus dakotensis*, approaching the size of the African lion was the largest carnivore of its time.

## MUSTELIDAE

The Mustelidae of the present day include such animals as the badgers, minks, martens, weasels, ermines, skunks, otters, and ratels· Fossil members of the family have been found in some abundance. The more ancestral forms continue back to Eocene time, but no clearly defined species have as yet been identified in the White River badlands in rocks older than the Miocene.

None of the remains discovered are complete, and nearly all are more or less mutilated. Those of *Megalictis ferox*, however, are sufficiently characteristic to indicate much of the nature of the animal. They represent a very large musteline. The head is short, wide, and massive, brain small, tail long and powerful, limbs short and stout, feet plantigrade, number of toes five, claws large and non-retractile. The animal is characterized as a gigantic wolverine, equalling a jaguar or a black bear in size, but in proportion more like the ratel. It was evidently predaceous like the wolverine, but seems to have been to some degree of burrowing disposition.

## INSECTIVORES

Remains of insectivorous animals are recognized as far back as earliest Tertiary time, but the fossils are not abundant. The White River badlands have yielded several species, but they are fragmentary. They belong to several families, particularly the hedgehogs, the shrews and the golden moles. The identification of fossil remains of the golden mole in South Dakota brought up certain important questions and speculations. True moles (Talpidae) are now found in the subarctic or temperate zones of all the northern continents, but not in or south of the tropics. However, in the south temperate zone, there are animals which have adopted mole-like habits and superficially resemble the true moles to a greater or less degree. The Chrysochloridae or golden moles of South Africa are of this nature. A similar animal in fossil form has been found in the Upper Miocene of southern South America. The peculiar geographical distribution of certain animals and plants of southern lands has long been a source of speculation and study and this finding of a fossil golden mole in South Dakota so far removed from its present day and fossil relatives, adds a new feature of interest.

## RODENTS

The rodents or gnawers as regards numbers are overwhelmingly predominant among living mammals. Their most prominent and universal character, the dentition, shows the absence of canine teeth and the paramount importance of front teeth or incisors. They appear to have originated in North America in early Eocene time and to have been rather rapidly distributed to the other great land masses of the earth. In the White River region they appear first in the Middle Oligocene, ancestral squirrels, rabbits, beavers, and rats, being represented. The beavers or beaver-like animals continue into the Upper Oligocene, the Lower Miocene and the Upper Miocene. They are particularly abundant in the Lower Miocene. Rabbits occur also in the Lower Miocene as well as certain poorly preserved forms supposed to be related to pocket gophers.

The number of specimens found indicates a considerable abundance of rodents in the region during Tertiary time, and the number of species adds emphasis to this. It happens, however, that but few complete skeletons have been obtained, the best material consisting largely of skulls and lower jaws, and in several of the species named, the description has been based on still more fragmentary material.

The earliest specimens of the rodents obtained were found by Hayden in the Big Badlands, and described by Leidy. With the exception of two other species described many years ago by Cope, little further information became available until the last few years, during which time Mr. Peterson of the Carnegie Museum, and Mr. Matthew of the American Museum of Natural History, each described a number of species. The Carnegie Museum material has come chiefly from northwestern Nebraska and eastern Wyoming, the American Museum material from Little White river.

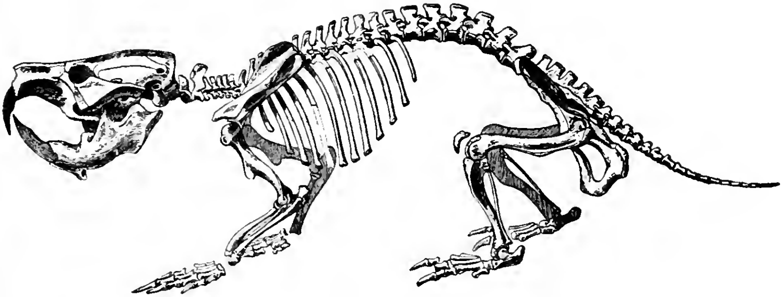

Figure 33—Skeleton of the Lower Miocene burrowing rodent *Steneofiber fossor.* Peterson, 1905.

The commonest fossil is Steneofiber. This is especially abundant in the Lower Rosebud beds of Little White river and in the Harrison (Daemonelix) beds in northwestern Nebraska and in eastern Wyoming. Entoptychus, the gopher-like rodent, seems to be fairly common in the Little White river area also. Peterson found many specimens of

*Steneofiber fossor* in close association with the Devil's Corkscrews of the Harrison beds and, as referred to elsewhere, suggests the reason for the association. This animal was smaller generally than the present day beaver. Its skull is comparatively large, the lower jaws heavy, neck short, limbs and feet powerful, tail round, rather heavy and of moderate length. Peterson states that the limb presents a striking similiarity to that of other burrowing rodents and approaches that of the mole in its position. The elongated and narrow scapula of the mole, the heavy clavicle, the strongly built humerus, and the broad foot with the long and powerful unguals, is rather suggestive of the habits of this animal, which was probably burrowing to a considerable degree. The animal is related to the beaver, but is evidently not in the direct line of ancestry.

## UNGULATES

The order Ungulata (Herbivores) as now constituted includes the mammals once loosely classed as Ruminants, and Pachyderms. The earliest known forms much resemble the primitive Carnivores. The ancestors of both seem to have been omnivorous.

For some reason there appeared very early among the Ungulates a tendency to develop the herbivorous type of tooth and the digitigrade foot (walking upon the tips of the toes). The change in the foot from the five toed plantigrade form progressed along two different lines and thus there were produced two very different types, ,namely, the odd-toed type and the even-toed type. In the odd-toed type the axis of the foot is in the third or middle digit (mesaxonic). Animals of this type are known as Perissodactyls. In the even-toed types the axis of the foot is between the third and fourth digits (paraxonic). Animals of this type are known as Artiodactyls. The horse, the tapir, and the rhinoceros are well known representatives of the perissodactyls. Among Artiodactyls are the camel, lama, deer, giraffe, antelope, ox, sheep, goat, and bison.

## PERISSODACTYLS

Perissodactyls, as above stated, have the axis of the foot in the third or middle digit. They are generally odd toed, the third toe being the largest and sometimes the only functional one. The tapir, an anatomically unprogressive creature, is a partial exception in that it has four toes on the front foot and three toes on the hind foot. Similar exceptions or seeming exceptions occasionally existed in the evolutionary development of other perissodactyls, nevertheless the bisection of the third toe by the median plane of the foot early asserted itself and has continued with firm persistence.

Existing perissodactyls include animals of greatly differing appearance and habits but their skeletal characters indicate with certaintly their relationship and skeletal characters indicate also the wide gap between them and other hoof-bearing creatures.

The perissodactyls constitute a restricted group and although many prehistoric forms are known—in all about five hundred species—living species are confined to the three well known families, rhinoceroses, tapirs, and horses. Of fossil forms the following families are represented in the White river badlands: Titanotheridae, Equidae, Tapiridae, Lophiodontidae, Hyracodontidae, Amynodontidae, and Rhinocerotidae.

The living forms so far as concerns their present natural habitat, with the exception of the American tapirs, are all confined to the Old World. Gidley calls attention to the fact that this is the more interesting since North America seems to have been the birth place or at least the stage for the development, not only of the early representatives of all the living Perissodactyls, but of most of the extinct groups of the order as well and that half the total number of perissodactyl species described have been founded on specimens from the Tertiary and Quaternary formations of this country.

## RHINOCEROTOIDEA

The finding of fossil bones of true rhinoceroses in the Big Badlands by Alexander Culbertson in 1850, and their prompt and accurate identification by Leidy, constitute one of the most interesting, unexpected, and instructive paleontological discoveries of America.

Existing rhinoceroses are confined to Africa, the Indian Archipelago and the southern parts of Asia. These form but a small representation of the numerous ancestry that abounded in North America from Middle Eocene to late

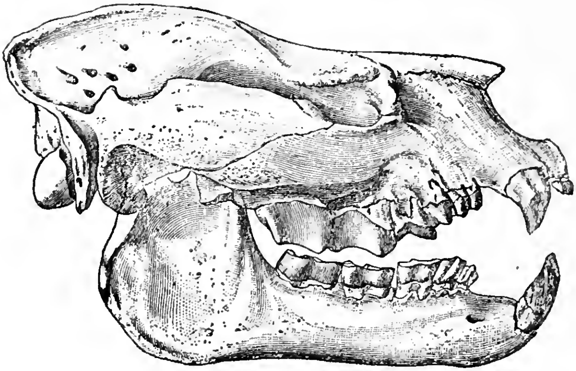

Figure 34—Skull of *Metamynodon planifrons*. Osborn, 1896.

Miocene time and in Europe from Eocene to Pliocene time. There is much reason for believing that the rhinoceros family originated in North America and subsequently spread to the old world but this has not as yet been proven.

All rhinoceroses, living and extinct, are divided by Osborn into three subdivisions, as follows. The Hyracodontidae or cursorial (upland) rhinoceroses; the Amynodontidae (aquatic) rhinoceroses, and the Rhinocerotidae or true (lowland) rhinoceroses. Of these the first two are found only in

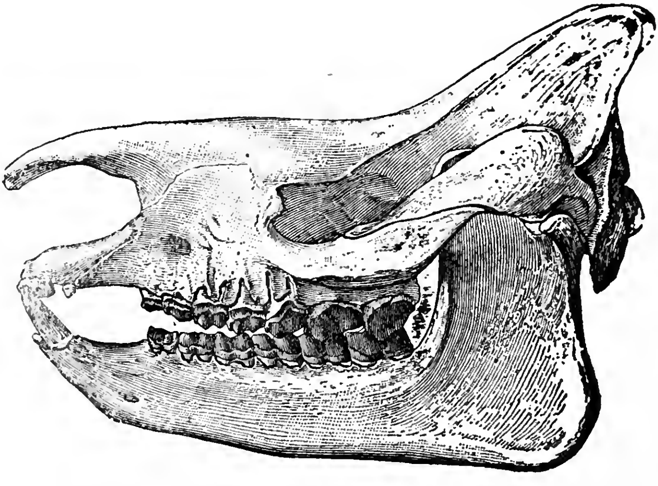

Figure 35—Skull of *Caenopus tridactylus*. Osborn, 1898.

the fossil state, the third is found both fossil and living. In America, the cursorial rhinoceroses are found first in the Middle Eocene, the aquatic rhinoceroses in the Upper Eocene, and the true rhinoceroses in the Lower Oligocene. The first two became extinct here in the Oligocene, but the true rhinoceroses endured until after the close of the Miocene. All three occur in fossil form within the area described in this paper, the cursorial and aquatic species in the Oligocene, chiefly in the Middle Oligocene, the true rhinoceroses throughout both the Oligocene and the Miocene.

The three families differed greatly from one another, both in exterior form and in dental and skeletal structure. The Hyracodonts were small, light chested, swift footed, hoofed, hornless creatures, much resembling the Miocene horses and evidently well-fitted for living on the grass-covered higher lands. (Plates 30 and 38). The Amynodonts were heavily built, short-bodied, hornless animals, with spreading padded feet, four functional toes in front, eyes and nostrils much elevated supposedly for convenience in swimming, canine teeth enlarged into recurved tusks, and a prehensile upper lip, apparently tending toward proboscoid development. (Plates 29 and 30). The animal evidently much resembled the present day hippopotamus, both in build and in habit. One adult skeleton,

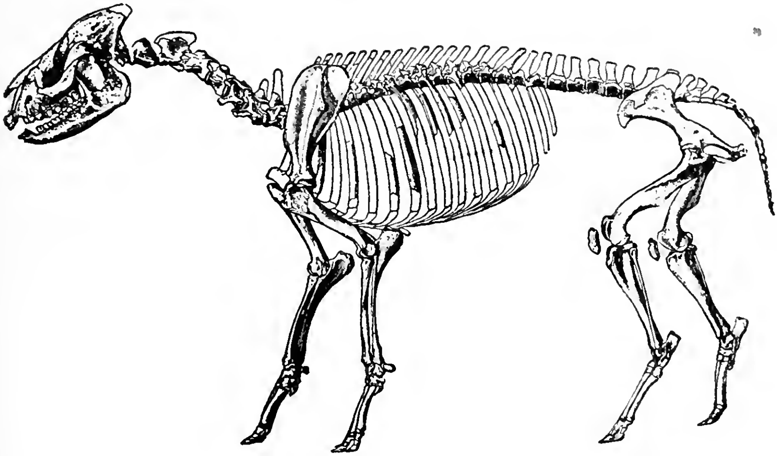

**Figure 36—Skeleton of the small, swiftfooted Oligocene rhinoceros, *Hyracodon nebrascensis*. Osborn, 1898.**

that of *Metamynodon planifrons* in the American Museum of Natural History, measures nine and one-half feet long and four and one-half feet high at the shoulders. The true rhinoceroses began as light limbed, hornless animals, intermediate in proportion between the two just mentioned, and in size and structure were not greatly unlike modern tapirs. During much of their early life history they, like the more primitive Hyracodonts and Amynodonts, were entirely without horns.

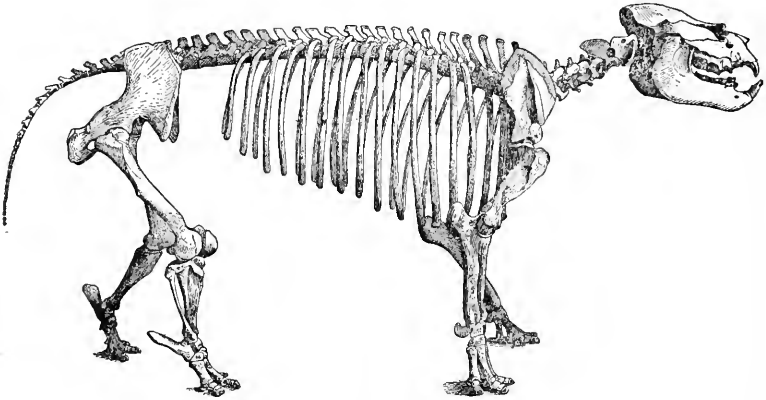

**Figure 37**—Skeleton of the heavy, marsh loving Oligocene rhinoceros, *Metamynodon planifrons*. Osborn, 1898.

The true rhinoceroses constitute in many respects the most important of the three subdivisions and to the paleontologist are of profound interest. They lived in great numbers in the region of the Black Hills during Oligocene and Miocene time, and their skeletons in certain favored localities, particularly in the Big Badlands and in Sioux County, northwestern Nebraska, have been collected in abundance. The Oligocene forms are especially characterized as being without horns, hence the old name Acerathere. (Plate 15). The Miocene forms have generally, but not always, a rudimentary or fairly well developed pair of horns placed transversely across the anterior part of the head, hence the name Dicerathere. (Plate 26). Present day rhinoceroses, it should be remembered, have either no horn or one or two horns, but the arrangement when horns are present is always medial, never transverse. It is of in-

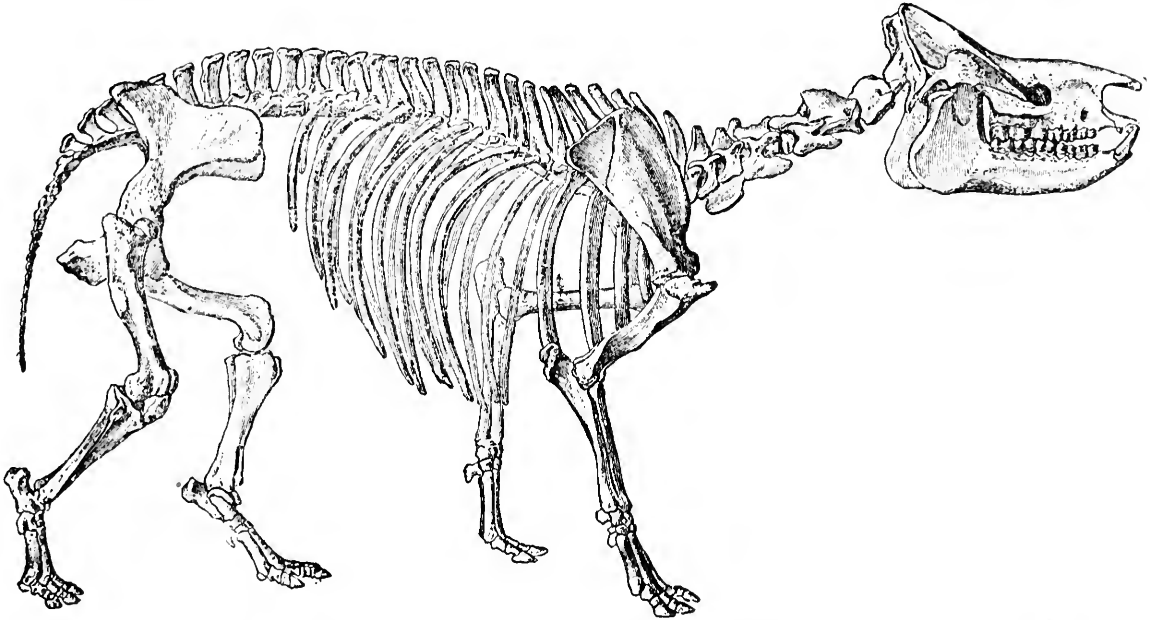

Figure 38—Skeleton of the Oligocene true rhinoceros, *Caenopus tridactylus*. Osborn, 1898.

terest to note also that while all living rhinoceroses have feet that are functionally tridactyl, some of the ancestral true rhinoceroses, at least so far as concerns the front feet, were functionally tetradactyl. This is known to be true of *Trigonias osborni* and is suspected of others. This lessening of the number of functional toes corresponds to similar alterations in other animals and indicates progressive change. Indeed, the rhinoceroses show in many ways gradual transformations, particularly with reference to the feet, the teeth, and the development of horn cores.

Among the Aceratheres *Caenopus mitis* was the smallest, its height at the shoulders being approximately twenty-eight inches. Among the Diceratheres *Diceratherium schiffi* was the smallest. It was also most specialized. The largest of the Aceratheres, in fact the largest of all the true rhinoceroses, seems to have been *Caenopus platycephalus.* It considerably surpassed the present day Sumatran rhinoceros. Among the others *Caenopus copei* was about the size of the American tapir and *Caenopus tridactylus*, measuring seven feet, nine inches in length, and four feet high to top of the rump, was nearly as large as the Sumatran rhinoceros.

## LOPHIODONTIDAE

The lophiodonts, closely related to the ancestral tapirs, are the most generalized of all known perissodactyls. The fossils that have been found are in general very fragmentary but they indicate a group of animals of great interest. Much uncertainty prevails as to the exact relationship of the Lophiodonts, but they are known to have many of the primitive characters of the tapir, the hyracodont, and the horse.

## CHALICOTHERIDAE

The study of fossil bones has oftentimes brought out very unexpected information. The unravelling of the story of the Chalicotheres is a good illustration of this in that it presents a pronounced exception to Cuvier's law of correlation. Certain peculiar foot bones found at Eppelsheim, nearly one hundred years ago were pronounced by Cuvier to be those of a gigantic pangolin (an edentate). These were described by Lartet under the name Macrotherium (Big Beast). Later some skull fragments with teeth found in the same Eppelsheim locality were described under

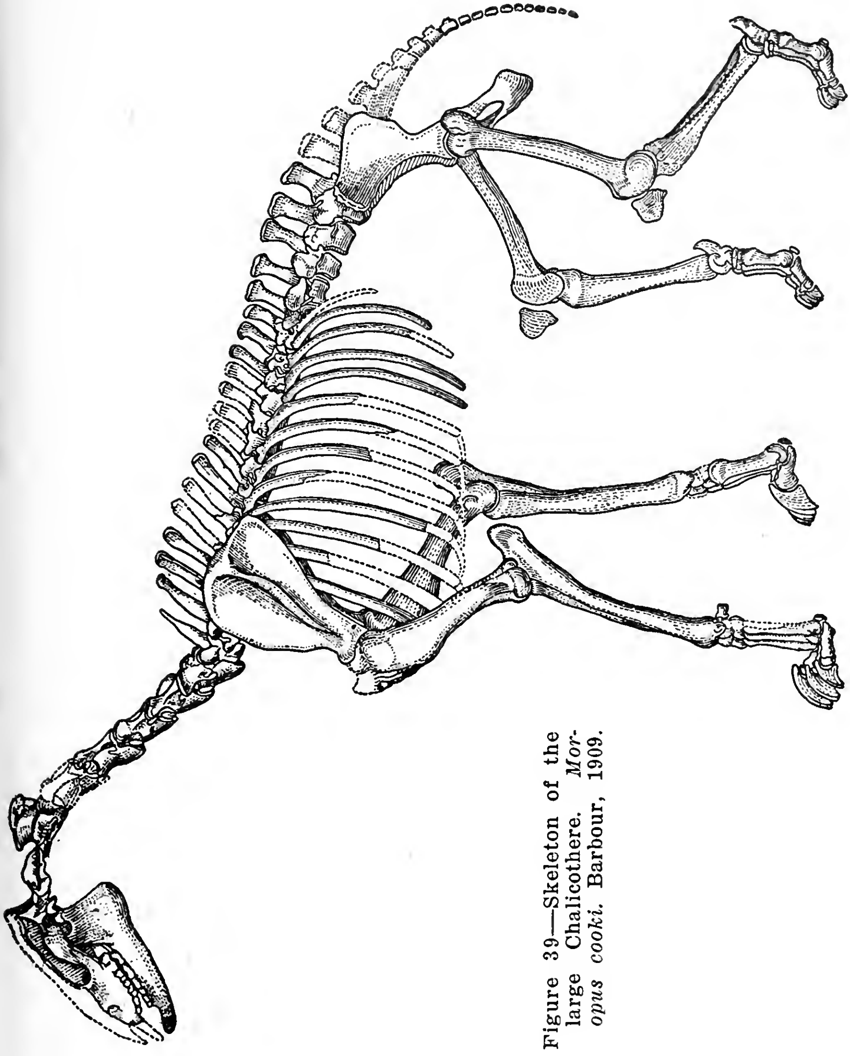

Figure 39—Skeleton of the large Chalicothere. *Moropus cooki*. Barbour, 1909.

the name Chalicotherium (Beast of the Gravel). The teeth were somewhat similar to those of the rhinoceros hence these head parts were regarded as belonging to one of the ungulates. Some paleontologists believed at first that they represented the artiodactyles but later they were generally considered as representing the perissodactyls. The foot bones continued to be regarded as belonging to the Edentates. Filhol, a French paleontologist, in 1887 reflecting upon the fact that Macrotherium foot bones were not uncommon and that Chalicotherium teeth were pretty well known but that no one had discovered feet of the latter nor head of the former, began to suspect that the two represented the same creature. The discovery a little later of nearly complete skeletons under favorable conditions definitely established the correctness of this supposition. It is of interest that in more recent years American discoveries have added greatly to our knowledge of these strange creatures. Several localities have afforded remains of which the most important has been the famous Agate Springs locality in northwestern Nebraska. The deposits are known as the Harrison beds. Director W. J. Holland and Mr. O. A. Peterson of the Carneige Museum in 1909 described in elaborate manner some of the best Agate Springs material found up to that time and summarized in good form the descriptions given in the publications of other investigators. Later the American Museum of Natural History made important discoveries in the Agate Springs locality and in their five summers (1911-1914, 1916) of excavation unearthed there within an area of about thirty-six feet square nearly complete skulls of ten individuals and skeletal parts of seventeen individuals. This material added new information of importance until now the size and nature of the animal are known to a high degree of certainty.

All of the chalicotheres found in the Agate Springs quarries have been designated as belonging to the genus *Moropus*. Several species have been described. The largest is *Moropus elatus*, an animal as large or larger than the African rhinoceros. (Plate 31). Others are considerably smaller.

Moropus in life was evidently very grotesque in appearance. The head resembles not a little that of the horse, or the primitive rhinoceros. The neck is heavier than that of the horse although very similar in shape, while the body has some resemblance in general outline to the rhinoceros. The head is small but the body is heavy and is supported by heavy limbs and feet. The fore limbs are larger than the hind limbs and this gives to the animal a corresponding pose. The feet, terminating in bifid, clawlike bones are especially distinctive, combining in peculiar manner characteristics of the ungulates and apparent characteristics of the Carnivores, and of animals accustomed to digging. (Plates 17 and 32). Osborn says, "Moropus may be characterized as a forest-loving, slow moving animal, not improbably frequently rather swampy ground. The small head, relatively long neck, high fore quarters, short, downwardly sloping back, straight and elongated limbs, suggest a profile contour only paralleled by the forest-loving okapi among existing mammals. The foot structure, of course, is radically different from that of the okapi, but we should not regard it as fossorial, or of the digging type, because it is not correlated with a fossorial type of fore limb. It would appear that these great fore claws, in which the phalanges were sharply flexed, were used in pulling down the branches of trees and also as powerful weapons of defense." The illustrations give a better idea of the animal than can readily be obtained by simple description.

## TAPIRIDAE

The present day tapirs, like the horse, are the descendants of a very ancient family. Unlike the horse, however, specialization in the tapir has not advanced to a high degree, and so far as foot structure is concerned, and to a considerable extent tooth structure also, the modern representatives of the tapir are in much the same condition as the early ancestral horses. They are very similar to the Lophiodonts just mentioned. Indeed, these animals and the ancestral tapirs show so many characteristics of such decided similarity or of such a vague nature as to render their separation and classification a matter of difficulty and some uncertainty.

Fossil remians of the Tapiridae are comparatively rare. They, however, have had a wide geographical distribution and are known to be present in rocks of nearly every period since earliest Tertiary time. Three species, described from the Big Badlands, all belonging to the genus Protapirus, are believed to be in the direct line of ancestry from the modern tapirs. (Plate 14). All of the specimens secured have come from within or near the Big Badlands. The material is not abundant and consists chiefly of skulls, lower jaws, and certain limb bones.

Prof. Scott suggests that the scarcity of the remains is probably because tapirs have always been forest-haunting animals, hence their habits must have kept them in places remote from areas where the accumulation of sediments was in progress and thus only occasional stragglers were buried and preserved.

## EQUIDAE

Of all the fossils of the White River badlands perhaps none have elicited more genuine interest than those of the Equidae, or horse family. The ancestry of the horse is in full harmony with the proud position he holds among present day animals. No other mammal displays such a lengthy, well connected lineage, nor discloses a more beautiful handiwork in the well-ordered development of structure and habits. For perhaps three million years or more, members of the family have roamed the hills and dales of the earth, molding their nature to an ever changing environment, discarding many things inherited from their evident Cretaceous five-toed progenitors, and taking on new features leading to the exquisite relation of organs and actions in the finely-built horse of today.

The earliest known members of the family is the little Hyracotherium, or Eohippus of the Eocene, less than one foot in height, with four well developed toes on each front foot, and three on each hind foot. Splint bones indicate the earlier presence of five toes on the front foot and four on the hind foot, and there is good reason for believing that at some still earlier stage the pentadactyl nature was complete. In connection with the progressive enlargement of the middle toe, profound alteration also took place in other parts of the anatomy, particularly the lengthening of the jaws, increasing complexity of the teeth, pronounced elongation of the lower part of the limbs, and the degeneration of the ulna and fibula.

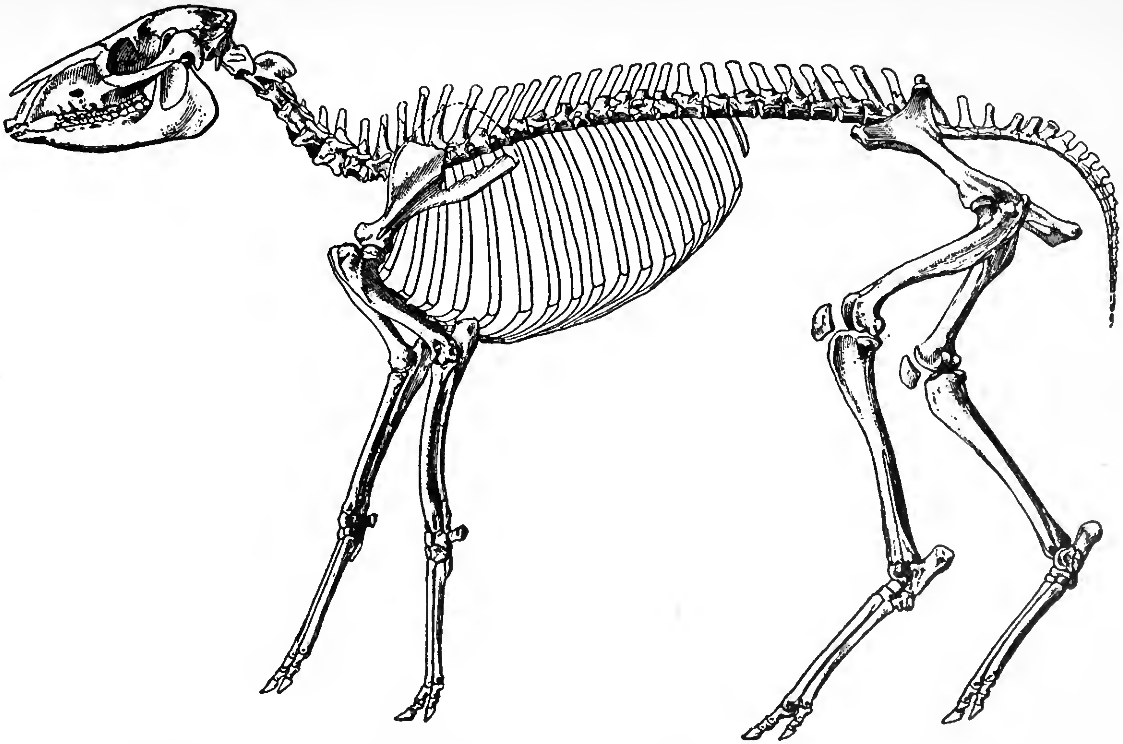

Figure 40—Skeleton of the three-toed Oligocene horse. *Mesohippus bairdi.* Farr, 1896.

The phylogeny of the horse was first suggested by the great French paleontologist, Cuvier. The earliest attempt at its expreession was made by Kowalevsky, the Russian. He was followed in succesive order by Huxley of England, Marsh, Cope, Wortman and Scott of America, and Schlosser of Germany, and more recently by Osborn and others. Interpretation by the earlier men showed inconsistencies and omissions, but with increasing collections of well-preserved material it has been possible to eliminate aberrant forms and to add needful material, until now the genealogical series is fairly complete. In the unraveling of the relationships the monophyletic origin theory has seemed to lose much of its earlier supposed significance as supported by Marsh. Later paleontologists, particularly those following the work of Osborn in his study of the Titanotheres and Rhinoceroses and Osborn and Gidley in their study of the Equidae inclined to the polyphyletic theory, that is, that the representatives of a family instead of being necessarily derived from a single Eocene ancestor may be representative of several contemporaneous phyla represented by as many distinct types of the Eocene. For a diagrammatic representation of the more important evolutionary changes see Figure 48.

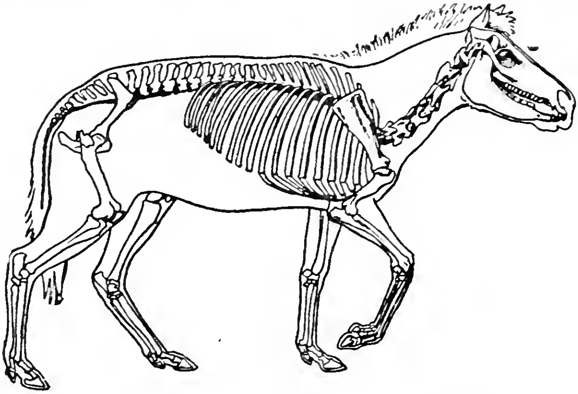

**Figure 41**—Skeleton of the beautifully preserved Upper Miocene three-toed horse. *Neohipparion whitneyi.* Original now in the American Museum of Natural History. W. B. Scott, A History of Land Mammals in the Western Hemisphere, 1913. Published by The Macmillan Company. Reprinted by permission.

Fortunately the fossils representing the extinct horses are abundant and often well preserved. For some years the Peabody Museum of Yale University excelled all others in the extent and importance of its collections, but more recently the American Museum of Natural History has surpassed it. Gidley stated in 1907 that the latter collection then contained several thousand specimens—Eocene to Pleistocene, inclusive. Granger, 1908, says that the Hyracotheres (Eocene) alone were represented by several hundred specimens. Matthew and Cook, 1909, add the information that in their recent work in the Pliocene of northwestern Nebraska, they collected some hundreds of incomplete jaws and about ten thousand separate teeth, besides great numbers of limbs and foot bones. While it should be borne in mind that the above collections represent to a large extent fragmentary material, Osborn states, that in all the museums of the world there were in 1904 only eight complete mounted skeletons of fossil horses, but that of these, five were in the American Museum.

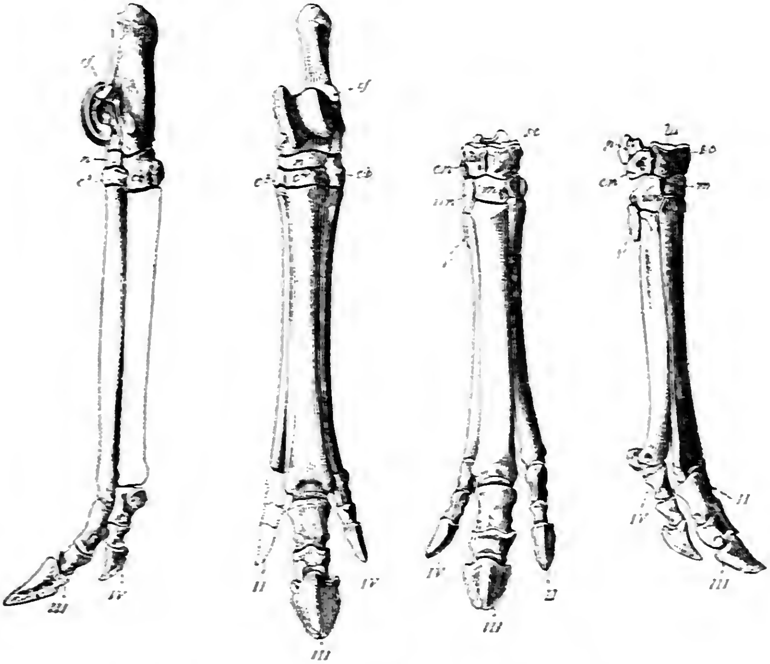

Figure 42—Right hind foot and left fore foot of the three-toed horse, *Mesohippus intermedius*, front and side views. Osborn and Wortman, 1895.

The abundance of the fossil remains and their widespread distribution geologically and geographically, clearly indicate that for ages members of the horse family ranged over the country in countless numbers. They were numerous in both North America and South America. Beginning, as they evidently did, in the earliest Tertiary or late Cretaceous in some generalized form of small height, probably no greater, according to Marsh, than a rabbit, they continued in increasing size to individuals larger than the largest draft horses of the present day. The earliest and the latest known members of the family do not occur in the deposits described in this paper, but intermediate forms are found in considerable numbers. These intermediate forms merit our chief attention.

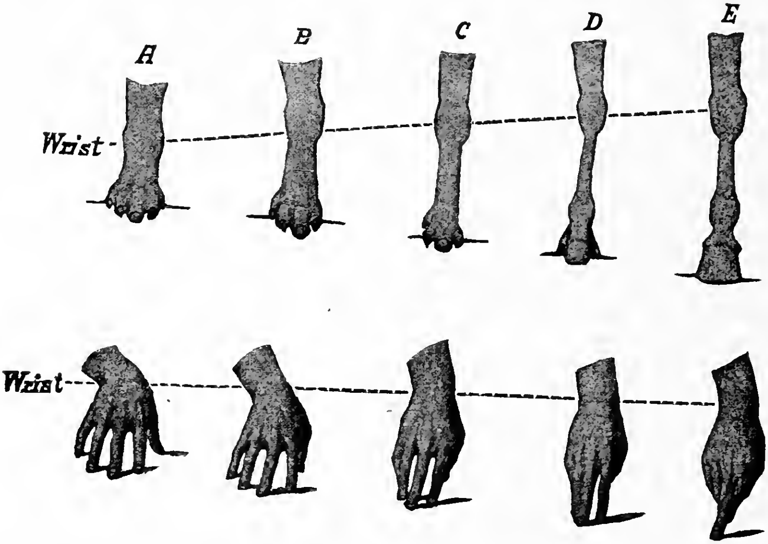

Figure 43—Illustration to show evolution of the fore foot in the Horse family. Osborn.

With one exception all horses of the White River badlands had three toes on each foot. Those of the older formations, particularly of the Oligocene, stand approximately midway in the genealogical line and show characters of absorbing interest.

It may be noted here that Eocene horses are four toed, with short crowned teeth; Oligocene horses are three toed with short crowned teeth; Miocene horses are three toed with progressively long-crowned teeth; Pliocene horses are sometimes three toed and sometimes one toed, with long crowned teeth; and Pleistocene horses are one toed with very long crowned teeth.

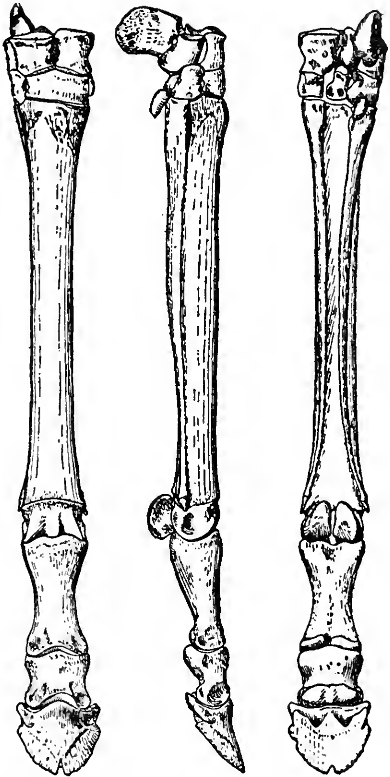

Figure 44—Right fore foot of the earliest known one-toed horse, *Pliohippus lullianus*. Front, side and back views. Troxell, 1916.

The earliest one toed horse of which we have knowledge is *Pliohippus lullianus* Troxell, a ten months old colt, a considerable part of the skeleton of which was found in the summer of 1916 in the valley of Little White river near the town of Mission in the eastern part of the Rosebud Indian Reservation. Remains of another monodactyl species *Pliohippus pernix* found somewhere on the Niobrara river was described in 1874 by Marsh.

Of the many species discovered, the commonest and most noted one is *Mesohippus Bairdi* of the Middle Oliocene. (Plates 16 and 33). In consequence of the fact that all of the earlier skeletons found were much broken and poorly preserved, and only the best bones saved, for forty years little was known of this animal except what could be learned from the foot bones and the head. Since 1890 several well preserved, nearly complete sketletons have been found and some of these have been dscribed in much detail. The adult animal averaged about eighteen inches in height, approximately the height of the coyote. It was a slender-limbed creature, very well adapted for speed. The hind limbs were much longer than the fore limbs, more so proportionately than in the present day horse, and the spines of the lumbar vertebrae were nearly if not quite as high as those of the dorsal region, so that, according to Farr, the rump must have been much elevated above the withers if the different parts of the limbs were not very much more

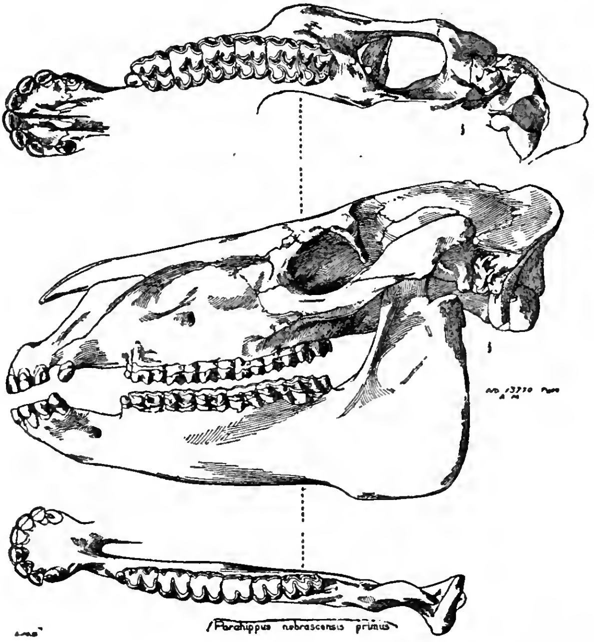

Figure 45—Skull of the browsing three-toed horse *Parahippus nebrascensis*. Osborn 1918. (Lower Miocene.)

flexed on each other than would seem justifiable, judging from recent animals. Scott states that the obliquity of the faces of the dorsal and lumbar vertebrae show that the back was decidedly arched.

The skull was about seven inches in length. The brain was large and apparently well convoluted. It weighed about one-third as much as the brain of the average present day horse. The number of teeth was forty-four, the arrangement on each side, above and below, as follows: Incisors, three;

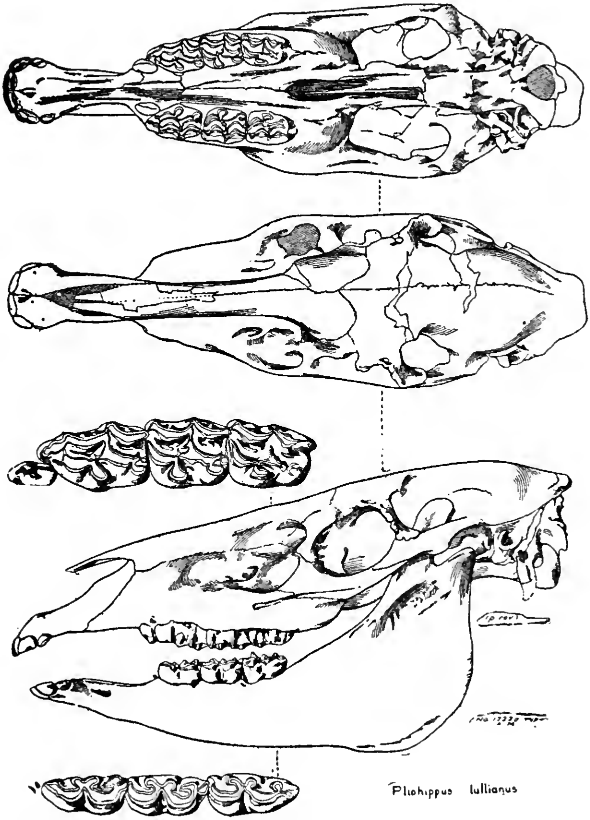

Figure 46—Skull of the earliest known one-toed horse *Pliohippus lullianus*. (A colt ten months old.) Named by Troxell and found near Mission, on the Rosebud Indian Reservation, South Dakota in beds of probably Lower Pliocene age. Osborn, 1918.

canines, one; pre-molars, four; molars, three. They were of the crested or lophiodont type and show the intermediate stage in the conversion of the short, round-knobbed and enamel covered crown, into the long, sharp-crested crown of cement, dentine, and enamel, as in the present day horse, so arranged that the unequal density of these tissues produces a hard, uneven grinding surface at all stages of wear.

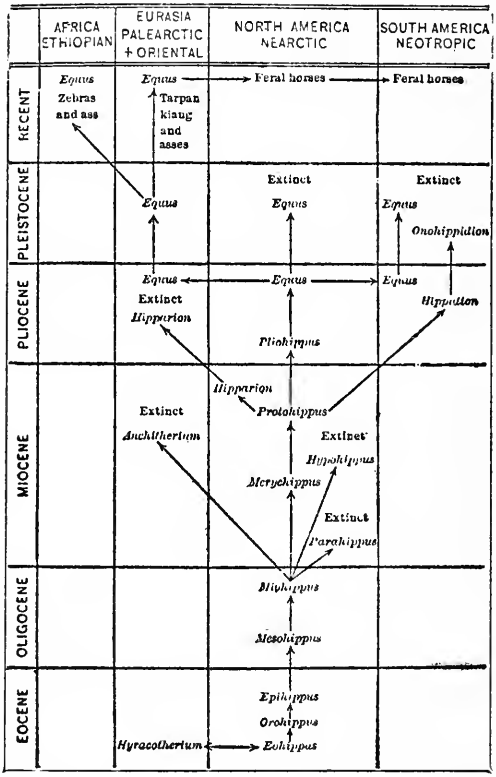

Figure 47—Phylogeny of the Horses. R. S. Lull Organic Evolution, 1917. Published by The Macmillan Company. Reprinted by permission.

The animal, unlike its present day representative evidently had to limit its food to soft vegetable tissue. Indeed it is of interest that the magnificent tooth battery of the horse developed pretty much in unison with the incoming of the hard grasses.

The most striking feature is the tridactyl nature of the feet. There were three well-developed toes on each foot, fore

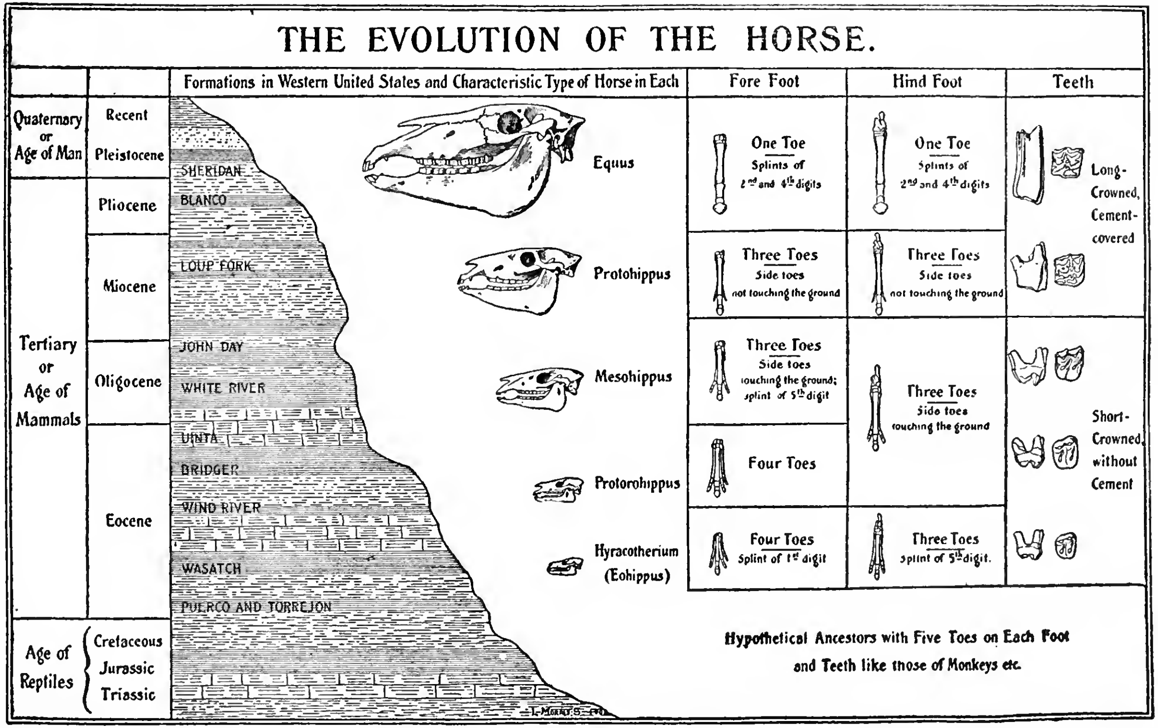

Figure 48—The successive changes in the development of the Horse, arrayed stratigraphically. Matthew, 1905.

and hind. These represent the second, third and fourth toes of five-toed animals. In addition to these, a splint bone on each fore foot represents the fifth toe, and a small nodule of bone is recognized as being the last lingering remnant of the first toe. The middle or third toe is longer and larger than the lateral ones and terminates in an enlarged, somewhat triangular bone, corresponding to the hoof bone of the present horse.

Among the later horses from the badland formations, *Neohipparion whitneyi* of the Upper Miocene is noteworthy. The type specimen found on Little White river by Mr. H. F. Wells of the American Museum expedition in 1902, and described by Mr. Gidley in 1903, is the most perfect fossil horse skeleton ever discovered. (Plates 24 and 34) The preservation of the skeleton is extraordinary, even the rib cartilages being found in place as well as the tip of the tail. The skeleton, approximately forty inches high, was that of a mare, and was found in association with the incomplete skeletons of five colts. It was proportioned like the Virginia deer, "delicate and extremely fleet-footed, surpassing the most highly bred modern race-horse in its speed mechanism, and with a frame fashioned to outstrip any type of modern hunting horse, if not thoroughbred."

Notwithstanding the highly developed nature of its skeleton Neohipparion represents a side branch of the horse family and for some reason, like Hypohippus, the "forest horse" and Parahippus, became extinct. Protohippus, an animal of about the same size as Neohipparion, survived and established for itself, as did the earlier Mesohippus, a definite place in the genealogical line leading to Equus of today.

## TITANOTHERIDAE

The Titanotheres are the largest animals found in the White River badlands. With the exception of turtles and Oreodons they are also the most abundant. The family was a comparatively short-lived one but it has proven to be one of the most interesting known to vertebrate paleontology.

Dr. Hiram A. Prout of St. Louis, in 1846 and 1847, described briefly in the American Journal of Science a portion of the lower jaw of one of these animals, the first specimen ever obtained from the White River badlands, and called

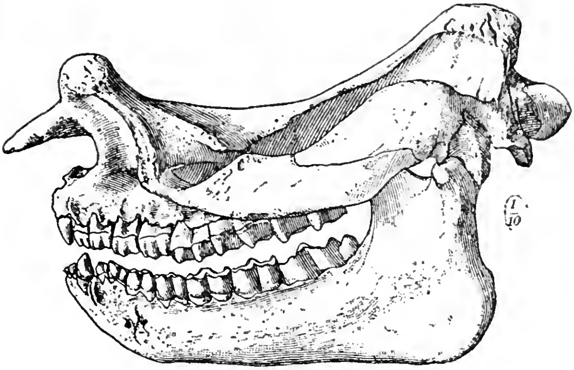

**Figure 49—Skull of the Titanothere** ***Megacerops marshi.*** **Osborn, 1902.**

it a Paleotherium. Later the true character of the specimen was recognized, a new name was necessitated, and Titanotherium (Titanbeast) suggested by Dr. Leidy in 1852, came into use. Since the finding of the earliest specimen many species have been described. The following White River phyla are now recognized: Menodus, Allops, Brontops, Megacerops, Brontotherium. They are distinguished from one another by differences in tooth and horn structure, the shape of the head, and the relative length and massiveness of the limbs. They are all included under the general term Titanotheres. Of these the Brontotheres were the latest and the largest.

**Figure 50—Skull of the Titanothere** ***Brontotherium platyceras.*** **Osborn, 1896.**

Mr. Hatcher in 1886, while searching for Titanothere remains in South Dakota and northwestern Nebraska, discovered that certain forms of the skulls of the Titanotheres are charactertistic of certain horizons in the beds, and this indicated to him the importance of keeping an exact record of the horizon from which each skull or skeleton was taken. Continued search showed that a regular and systematic development took place in these animals from the base to the top of the beds. The most notable change was a gradual and pronounced increase in size. Hatcher says: "This increase in size from the base to the summit of the beds was attended by a very marked development in certain portions of the skeleton, noticeable among which are the following: A variation in shape and an increase in the size and length of the horncores as compared with the size of the skulls was attended, near the summit of the beds at least, by a decided shortening of the nasals. There were also changes taking place in the dentition of these animals, especially in the number of incisors and in the structure of the last, upper, true molar. The number of incisors, though probably never constant, even in the same species, shows a tendency to decrease in skulls found near the summit of the beds.

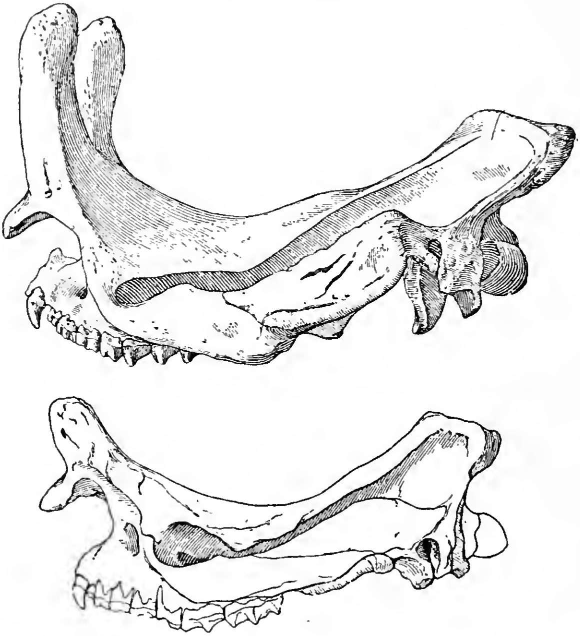

Figure 51—Skulls of *Titanotherium elatum*. Upper skull, male; lower skull, female. Osborn, 1896.

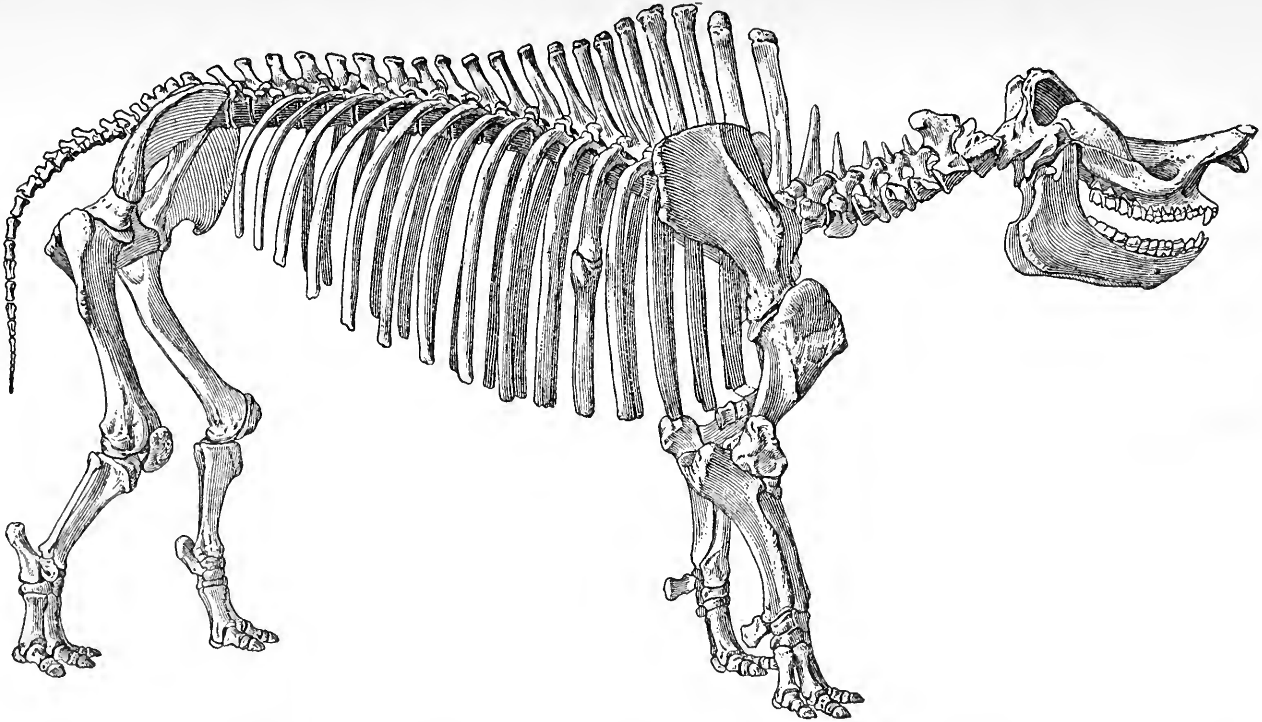

Figure 52—Skeleton of the large Lower Oligocene Titanothere, *Megacerops robustus* from Corral Canyon, approximately one twenty-fifth natural size. Original in the American Museum of Natural History. Osborn and Wortman. 1895.

At the base of the beds the number of incisors is from one to three on a side, while at the top there are never more than two on a side, often only one, sometimes none. In skulls from the very lowest beds the incisors have already become so rudimentary as to be no longer functional. As would be expected, the number of incisors decreased after they became of no functional value. In the matter of incisors the Titanotheridae at the time of their extermination, were in a fair way to accomplish just what the somewhat related, but more persistent, Rhinocerotidae have nearly succeeded in doing, namely: the elimination of the incisor dentition. In view of this weak frontal dentition it would seem that for the securing of its food, the animal must have been provided with a long tongue and a prehensile lip.

The Titanothers had their origin in early Eocene time, were of considerable importance throughout the Bridger and Uinta periods, reached their culmination during Lower Oligocene time, and became wholly extinct at the close of the latter period. (See Fig. 53). They present one of the most interesting illustrations known of rapid evolution in size and special characters followed by quick extinction. They developed slowly at first, and although they may be traced for perhaps half a million years, they seem to have left absolutely no descendants. Outside of North America the Titanotheres have been recognized only in Hungary and Bulgaria, these latter localities have but one representative each.

During the time of their greatest development the Titanotheres were the largest of all the mammals in the localities where they lived. They were well prepared by size and offensive weapons for combating the attacks of predaceous animals and they were possessors of perhaps the most efficient dental equipment ever developed for masticating coarse vegetable food, such as evidently flourished in abundance in the region at that time. Their size was comparable to that of the present day elephant, averaging slightly smaller. One of the best known skeletons, that of *Megacerops robustus* found in Corral Canyon and restored in 1895 by Osborn and Wortman of the American Museum of Natural History measures thirteen feet, eight inches in length, seven feet, seven inches in height, and breadth across the pelvis three feet, ten

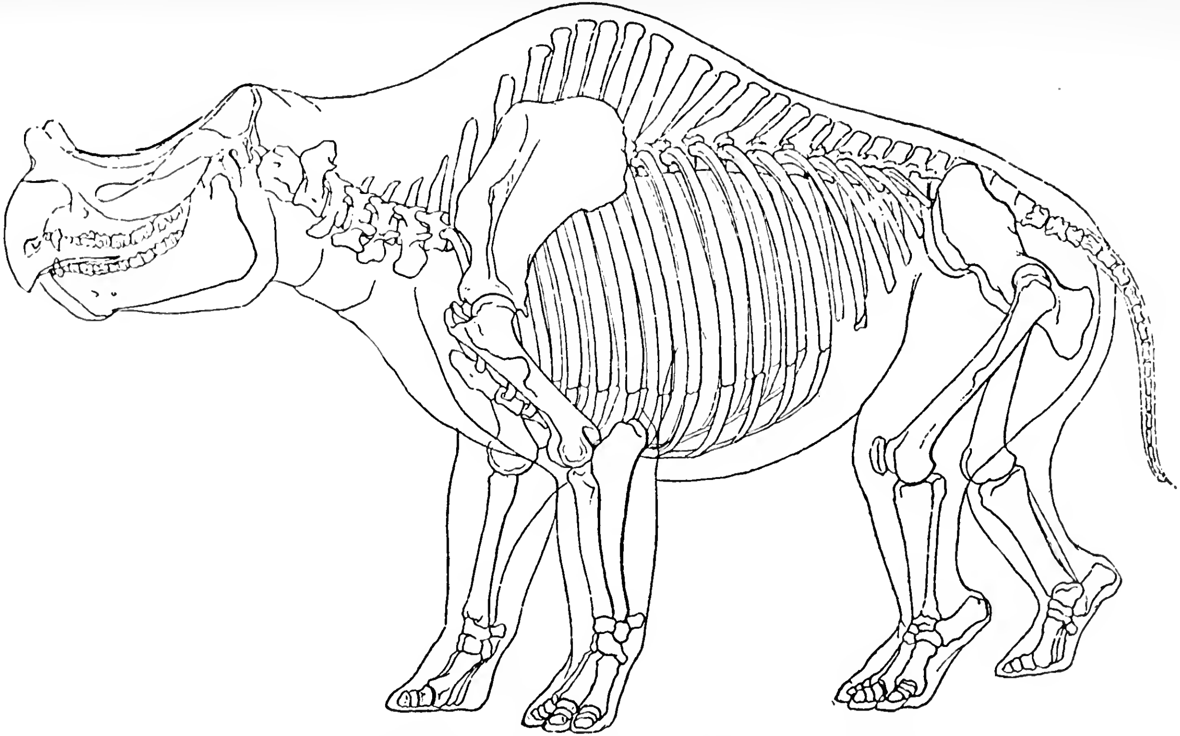

Figure 53—Skeleton of *Titanotherium prouti* of the Lower Oligocene. Scott and Osborn, 1887. Later modified, 1895 by Osborn and Wortman.

inches. This would indicate an animal fourteen feet or more in length and fully eight feet high.

In general appearance the Titanothere showed some resemblance to the rhinoceros, particularly as to the head. The limbs are stouter than in the rhinoceros, the fore limbs especially so. The limbs have some likeness to those of an elephant, but are shorter and apparently more supple. There are four short thick hoofed toes on the front foot corresponding to the second, third, fourth and fifth of five toed animals. (Plate 18). On the hind foot only the second, third, and fourth are present. The body of the animal is short, as in the elephant, and the shoulder is conspicuously high, much as in the bison. (Plates 35 and 36). This is caused by the great elongation of the spinous process of the anterior dorsal vertebrae. The projecting parts have well roughened extremities and doubtless served to support in great measure the stout muscles required to manipulate the powerful head in feeding and to give opportunity for its aggressive use.

The skull is particularly grotesque and noteworthy. It is a long, low, saddle-shaped affair, with remarkable nasal prominences at the extreme end, bearing in most species, (Plate 20) especially the later ones, powerful bony protuberances. These protuberances are commonly spoken of as horns or horn cores, but there is much doubt as to their ever having been sheathed in horn. The skull varies much in the different genera and species, considerably in the different sexes, and individual variation is not uncommon. Its full length in some of the larger species reaches as much as three feet or even more. The width is generally less than two feet, although in occasional skulls, especially of Brontotherium, it may reach more than thirty inches. (Plate 36).

The horn-cores are more or less cellular at the base and are placed transversely and project upward and outward. Their size, shape and position, like other parts of the skull, vary much with species and sex. The ears are placed far to the rear, while the eyes are surprisingly near the front. The brain, like the brain of nearly all early mammalian types, was very small. It was scarcely as large as a man's fist, and the living animal was evidently a very stupid creature. The teeth, usually thirty-eight, were large. This is particularly true of the grinders in the upper jaw. (Plate 19). Not infrequently in the larger species the well-fanged, nearly square upper molars measured more than four inches in diameter. The neck was short and stout and the head in ordinary position was evidently held declined. The Titanothere was a perissodactyl and a pachyderm. The nature of its thick skin is not positively known, but relying on skeletal characters common to thick-skinned animals, the restorations that have been made are believed upon considerable evidence to be within reasonable limits of accuracy. (Plates 35, 36).

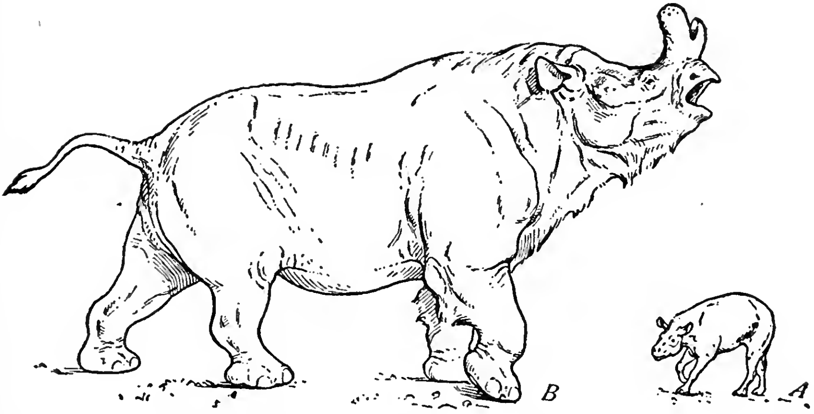

**Figure 54—First and last known stages in the evolution of the Titanotheres. (a) *Eotitanops.* (b) *Brontops robustus.* Believed to be the most accurately restored Titanotheres published. Osborn, 1914.**

Titanothere remains are abundant and several hundred heads have been found but complete skeletons are rare. Hatcher in 1902, gives the total number in the whole country as four, as follows: One in the Carnegie Museum, from War Bonnet creek, northwestern Nebraska one at Yale University, from near Chadron; one in the American Museum of Natural History, from the Big Badlands; and one in Princeton Museum from the Big Badlands. Of these the Carnegie Museum skeleton is from the Lower Titanotherium beds, the other three from the Upper Titanotherium beds.

## ARTIODACTYLS

As previously indicated the artiodactyls include those herbivores in which the axis of the foot is between the third and fourth digits. They nearly always have an even number of toes on each foot, either two or four. None have less than two. Occasionally three or five are present but this is distinctly exceptional.

Artiodactyls have a long time constituted the dominant ungulate order. They include a great assemblage of creatures of many types but with marked unity of structure, the size varying from the little chevrotain to the huge hippopotamus. They have always been most abundant in the old world, nevertheless they have had from near their beginning a good representation in North America and the White River badlands have disclosed a remarkably interesting series. Practically all of these White River forms are described in the following pages.

## ELOTHERIDAE AND DICOTYLIDAE

Few fossil animals of the White River badlands have afforded more real puzzling features than the ancestral swine (giant pigs). Several genera and a number of species have been identified, including several classed as ancestral peccaries, but usually the material is fragmentary and confined mostly to the head and lower jaws. Elotherium is the best known genus, its skeleton being represented by considerable material. It was evidently a very grotesque animal.

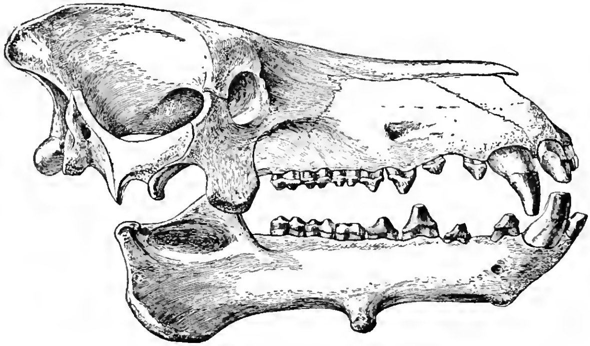

Figure 55—Skull and lower jaws of *Dinohyus hollandi.* Peterson, 1906.

Considered as indirectly ancestral to present day swine, it nevertheless showed few of the distinct suilline characters. In not a few respects it resembled the hippopotamus. Its size varied considerably, ranging in some species to near the size of the present day rhinoceros, the head alone reaching sometimes more than three feet in length. *Dinohyus hollandi*, a nearly related genus, had a skull whose length, according to Peterson, reached more than thirty-five inches. (Plates 37 and 39). The Elothere skull is remarkable in many ways. The muzzle is long and slender, the eyes

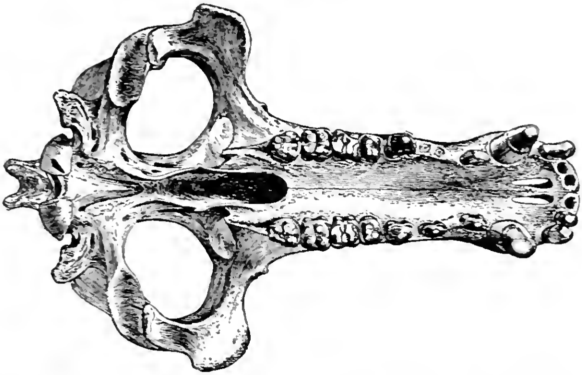

Figure 56—Palatal view of skull of *Dinohyus hollandi.* Peterson, 1906.

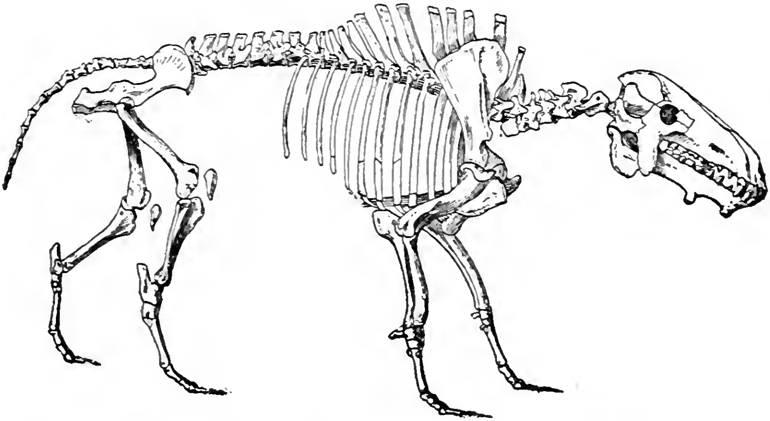

Figure 57—Skeleton of the giant Oligocene pig *Elotherium* (*Entelodon*) *ingens.* Peterson, 1909.

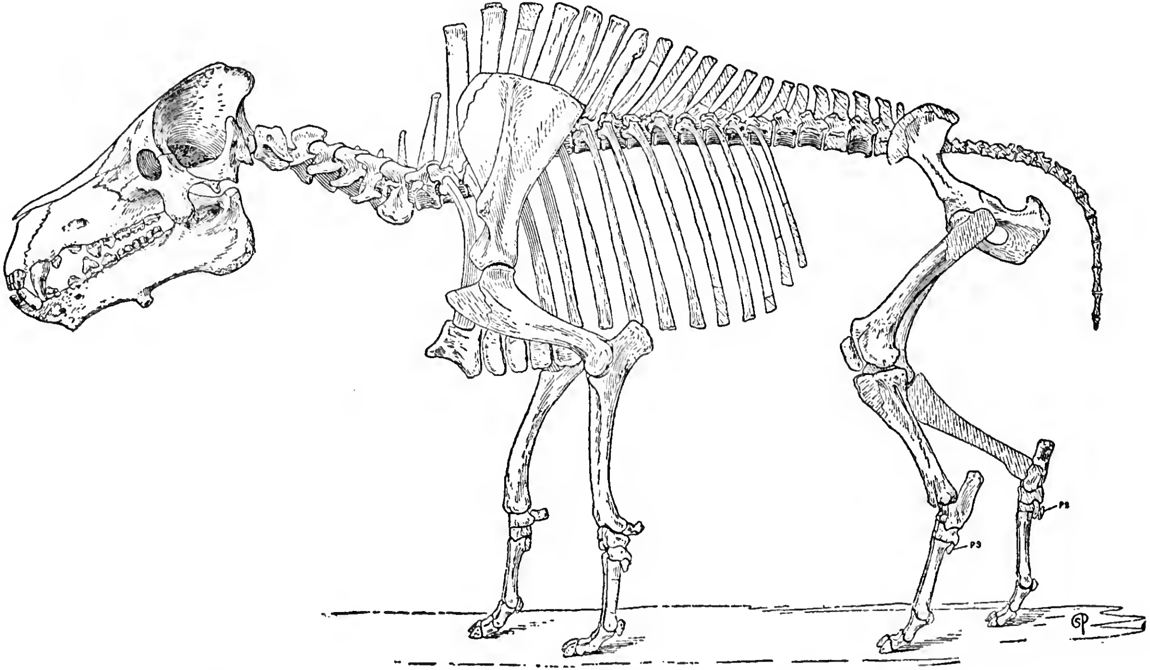

Figure 58—Skeleton of the Lower Miocene pig *Dinohyus hollandi.* Peterson, 1909.

shifted far back, the cranium short, brain cavity absurdly small, the sagittal crest high and thin and the zygomatic arches enormously developed. Other odd features are the pendant compressed plates given off from the ventral surface of the jugals and two pairs of knob-like processes on the ventral borders of the lower jaw. In young individuals the knob-like processes are only rough elevations, in some adults, especially the smaller species, they are little more than rounded knobs, but in the larger forms they become greatly elongated and club-shaped. Their use seems to be wholly unknown. The dentition above and below on each side is as follows: Incisors, three; canines, one; pre-molars, four; molars, three; total, fourty-four. The canines both above and below are large and powerful. They do not appear to be of any sexual significance as the females developed them as fully as the males. Their use seems to have been that of digging up roots, in view of the fact that certain well preserved specimens show deep grooves on the posterior side of the lower teeth near the gums, grooves that could not have been caused by the attrition of the other teeth. The neck is short and massive and well arranged for the attachment of strong muscles necessitated by the great length and weight of the head. The limbs are long, par-

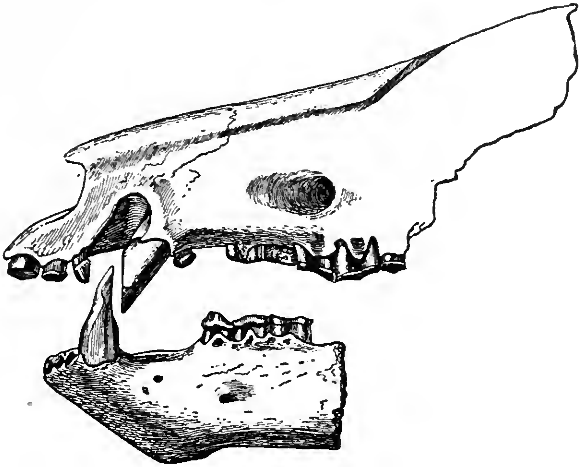

**Figure 59**—Anterior portions of the upper and lower jaws of the ancestral peccary. *Desmathyus* (*Thinohyus*) *Siouxensis*. Peterson, 1905.

ticularly the fore limb, and this in connection with the high shoulder prominence, gives to the animal a peculiar stilted appearance. The foot, fore and hind, has two functional toes corresponding to the third and fourth of five toed animals. The second and fifth are present, but only in rudimentary form. Much that has been said in regard to the structural features of the Elotheres applies also in a general way to the Dicotylidae, but the latter represent a later development and tend more definitely toward the modern peccaries.

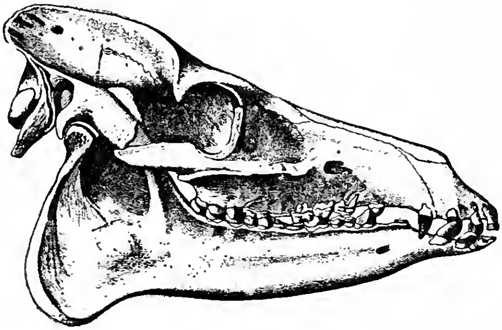

**Figure 60**—Skull of *Hyopotamus* (*Ancodus*) *brachyrhynchus*. Scott, 1895.

Concerning all of the forms, it may be said that they with the Suidae were apparently derived from a common Eocene ancestry. According to Matthew and Gidley the peccaries originated in the new world and have always remained here, while the true pigs (suinae) originated in the old world and never of their own accord reached the new world, their presence here now of the latter being due solely to introduction by man since the discovery of America by Columbus.

## ANTHRACOTHERIDAE

The Anthracotheridae include species of an extinct family of stoutly built, generalized, primitive animals, evidently resembling to some extent the present day pig but having some characters possessed by the hippopotamus. Their nearest important relatives of White River time were apparently the Oreodontidae. These they resembled very closely. Scott states that the likeness as shown in the skull, teeth, vertebrae, limbs, and feet, is fundamental and indicates a common pentadactyl ancestry of perhaps middle Eocene time.

Fossils representing various species of the family are widely distributed over the earth, more particularly in the old world. The name Anthracotherium (Coal-beast) arises from the fact that their remains were first discovered in coal deposits,—the brown-coal deposits of Savoy. A few nearly complete skeletons of Bothriodon the commonest Oligocene form have been obtained from the channel sandstones of the Big badlands.

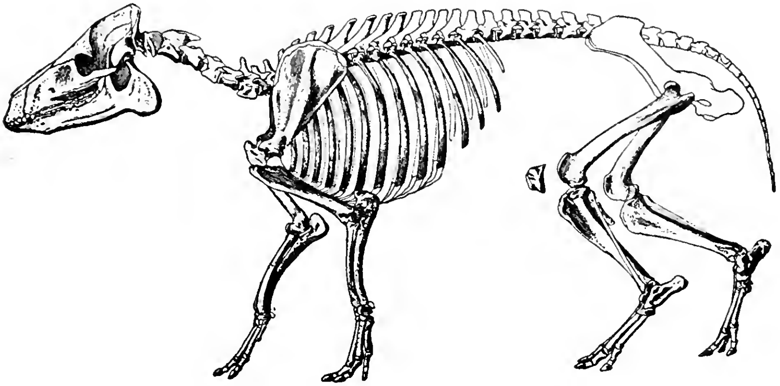

**Figure 61—Skeleton of the Oligocene Anthracothere, *Hyopotamus* (*Ancodus*) *brachyrhynchus*. Scott, 1895.**

## OREODONTIDAE

The Oreodontidae include the commonest fossil mammals of the White River badlands. Representatives of the family are found only in North America. They originated in the Eocene, ranged through the Oligocene and Miocene and became extinct in Lower Pliocene. They are distinguished by many primitive characters and according to Cope they constitute one of the best marked types of Mammalia the world has seen. They occupy a position somewhat intermediate between the ruminants (cud-chewing animals) and the suilline pachyderms (pig-like thick-skinned animals).

The skull has to some extent the form of the present day peccary. The cranial portion is much like that of the camel. The skeleton as a whole more nearly resembles that of the pig, but the number, general proportions, relative position and plan of construction of the teeth are more nearly those of the ruminants and it is this relationship to the ruminants that has governed the classification of the family. Leidy in his description of the Oreodon suggested that it might very appropriately be called a "ruminating hog." One remarkable feature is the highly developed canine teeth in both jaws. These teeth or tusks are three sided with round borders, the upper pair curving forward, downward and slightly outward, the lower pair nearly or quite straight and pointing upward, forward and outward. They give to the jaws something of the appearance of the wolf's jaws but it is only a resemblance and does not indicate any close relationship. (Plates 21 and 22). As in the pigs the eyes were small, the neck and legs short. With the exception of the older forms all of the Oreodontidae had four toes on each foot. These represent the second, third, fourth, and fifth of five toed animals. Agriochoerus and the far commoner Oreodon had five on the front feet. The tail was long and slender. The animals varied considerably in size but the common forms were about the size of the peccary. Promerycochoerus, the largest, was about the size of the wild boar.

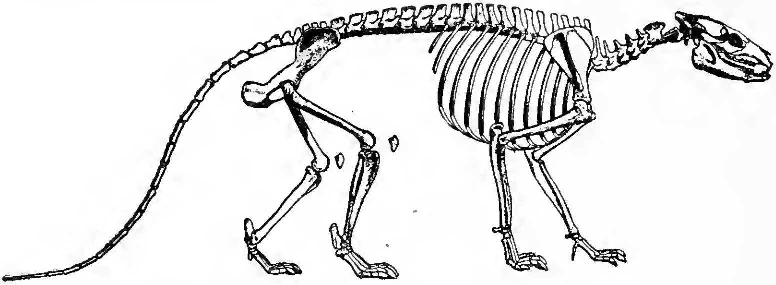

**Figure 62—Skeleton of the Oligocene Oreodont, *Agriochoerus latifrons*. Wortman, 1896.**

Of the several genera, Oreodon, Leptauchena, Agriochoerus, and Promerycochoerus are the best known. Oreodon is by far the most abundant but the others are found in considerable numbers. (Plates 40 and 41). They seem to

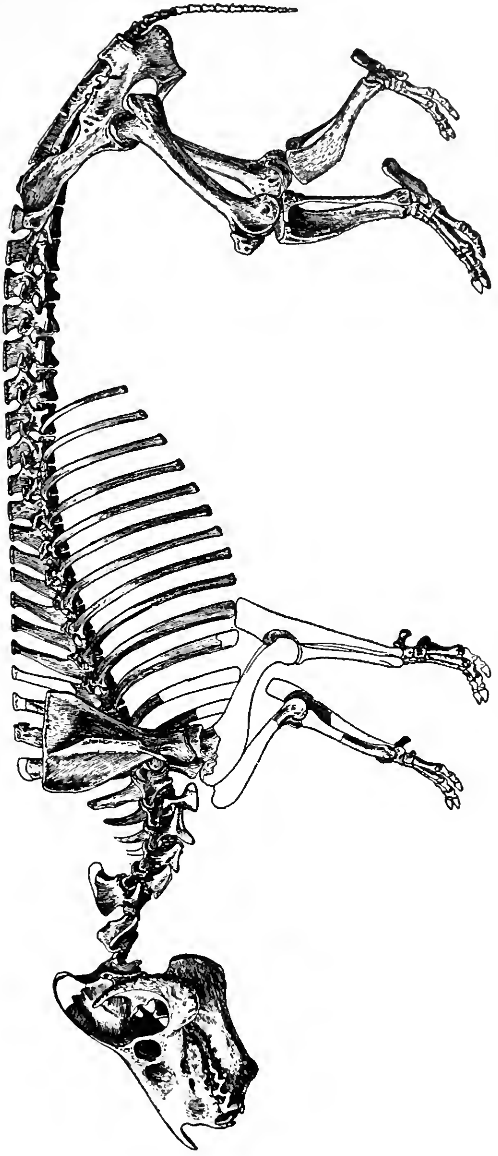

Figure 63—Skeleton of the Lower Miocene Oreodont, *Promerycochoerus carrikeri*. Peterson, 1906.

have ranged in great herds over the Oligocene and Miocene lands of South Dakota, Nebraska, Colorado, Wyoming, Montana and North Dakota. It is interesting in this connection to note that the Oreodontidae, in addition to giving their name to the Oreodon beds of the Middle Oligocene furnished names also for three of the zones above the Middle Oligocene, namely, the Laptauchenia zone, the Promerychocrus zone, and the Merycochoerus zone.

Leptauchenia was founded on fossil remains obtained by Prof. Hayden in 1855 from near Eagle Nest butte. This animal is of interest in that its structure seems to indicate an acquatic habit. (Plate 42). The teeth resemble somewhat those of the llama (Auchenia) hence the name Leptauchenia. Agriochoerus, is remarkable in that its toes were apparently armed with claws instead of hoofs and the first toe (thumb) of the fore foot seems to have been opposable. Aside from its foot structure the animal was much like the Oreodon. (Plate 42). It was approximately three feet long not including the rather long tail. Mesoreodon is likewise remarkable in that the thyroid cartilage of the larynx was ossified much as in the howling monkey and according to Prof. Scott it must have had most unusual powers of voice.

Promerycochoerus, a larger and heavier animal than those of the earlier genera, has been found in considerable numbers in northwestern Nebraska and eastern Wyoming. The restored skeleton of *Promerycochoerus carrikeri* is more than five and one-half feet long and evidently indicates a large bodied slow moving animal, the habits of which as has been suggested were perhaps somewhat the same as those of the hippopotamus. Peterson described the animal briefly as having a massive head, a short, robust neck, dorsal vertebrae, provided with prominent spines, lumbar vertebrae heavy, thoracic cavity capacious, and the feet large. (Plate 38).

The Oreodons are found in the Lower and Middle Oligocene and are particularly common in what is known as the "lower nodular layer" (red layer) of the Middle Oligocene fifteen or twenty feet above the Titanotherium beds. It is on account of the abundance of these fossils and their early discovery in the Middle Oligocene that this division of the badland formations was by Hayden given the name of Oreodon beds. Leidy tells us that as early as 1869 he

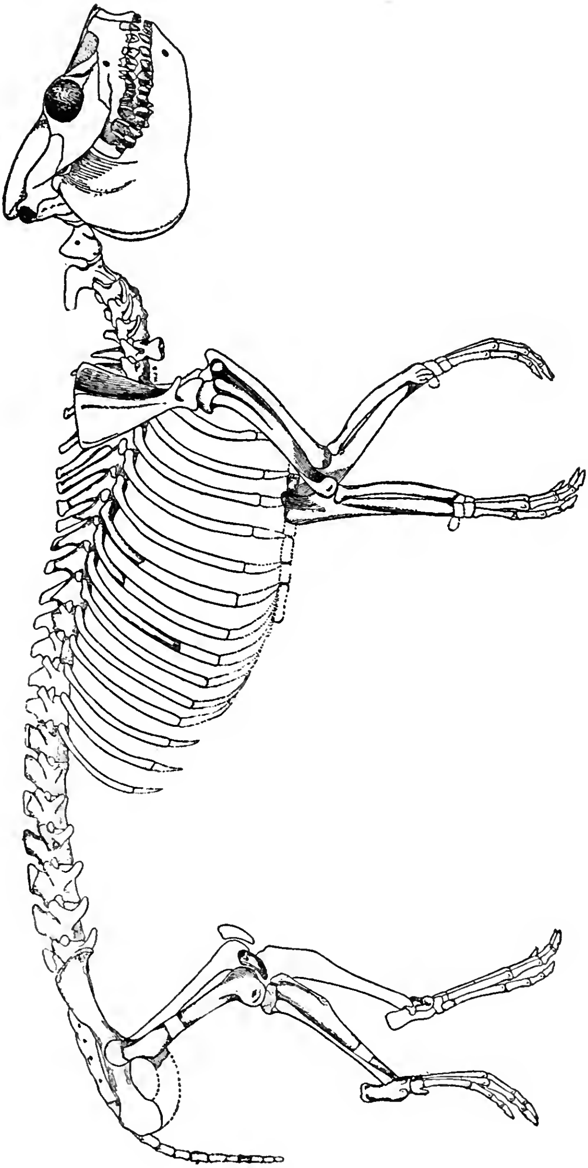

Figure 64—Skeleton of the Lower Miocene Oreodont, *Leptauchenia decora.* Sinclair, 1910.

had observed fossils of approximately five hundred individuals among the collections sent him for study. Few general badland collections fail to show specimens of these interesting creatures, but most of the material is made up of skulls and detached bones. Few complete skeletons have been obtained and until recent years little attempt was made at restoration. The dentition is remarkably complete, the total number of permanent teeth being forty-four arranged in nearly unbroken series in both jaws. Of the Oreodons *Oreodon clubertsoni* is by far the most common. Leidy says that of the five hundred he had observed about four hundred and fifty were of this species. *Oreodon gracilis,* about two-thirds as large as *Oreodon culbertsoni* was perhaps the next in abundance. Its skull was about the size of the red fox and a skeleton mounted by Mr. C. W. Gilmore of the U. S. National Museum measured twenty-seven inches in length and is twelve and one-half inches high at the shoulders. *Eporeodon major,* earlier called *Oreodon major* is still rarer. It is about one-fifth larger than *Oreodon culbertsoni* or nearly twice as large as *Oreodon gracilis.*

## HYPERTRAGULIDAE

The Hypertragulidae include some of the most interesting fossil mammals ever discovered. They are ancient selenodonts (ruminants) resembling in a way the little chevrotain or "deerlet" of India and the musk deer of the Asiatic highlands but they are in reality not closely related to either. They seem to represent an independent offshoot of the primitive ruminant stock but near relatives, either ancestral or descendent are not known.

They are distinguished from all other American ruminants by the combination of functionally tetradactyl front feet with didactyl hind feet. Of the seven genera thus far recognized from the White River region, Protoceras is the most interesting and the best known. (Plate 43). It is found only in the Upper Oligocene and because of its importance the strata containing it are known as the Protoceras beds. Of the other genera Leptomeryx has been most carefully described but with the exception of one find of twenty-six skeletons in one associated group and described by Riggs, Bull. G. S. A., vol. 25, p. 145, the materials available have not been so abundant nor so complete as in the case of Protoceras.

The first Protoceras specimen was obtained by Mr. J. B. Hatcher in 1890. It, like all subsequent material of this kind, was found near the highest part of the Big Badlands, where the Protoceras beds are well exposed. In January, 1891, Prof. Marsh described the animal in the American Journal of Science under the name *Protoceras celer* in allusion to the early appearance of horns in this fleet-footed group of artiodactyls. Before this discovery no horned artiodactyls were known to have lived earlier than Pliocene time. Marsh states it as an important fact that while all existing mammals with horns in pairs are artiodactyls and none of the recent perissodactyls are thus provided, the reverse of this was true among the early forms of these groups.

The head is especially unique. (Plate 23). It displays in many ways the modernized type of structure, and shows sexual differences unparalleled among the ancient artiodactyls. The most obvious characters are the bony protuberances from various parts of the head in the male. In the female these are only faintly indicated. In the male a pair of protuberances project upwards from the rear part of the head in much the same position as the horns of the present day pronghorn antelope. Near the anterior end of the face there is a second pair, laterally compressed and more prominent than the first pair. Over

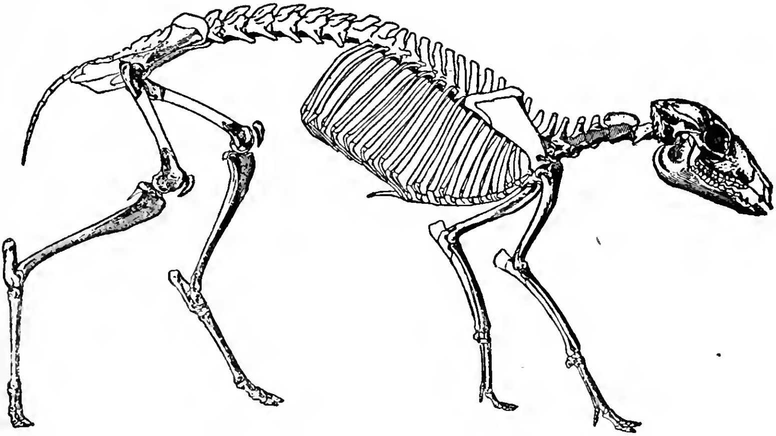

Figure 65—Skeleton of the Oligocene ruminant, *Leptomeryx evansi*. Scott, 1891.

the eyes there is a third pair serving as a sort of protective awning for the eyes. In front of these and slightly nearer the median line of the face there is a fourth pair. These are much less prominent than the others mentioned but their presence is clearly indicated. Finally a fifth pair, slightly more prominent than the last, but less prominent and especially less horn-like than the others, is placed at the side of the face nearly above the anterior molar tooth.

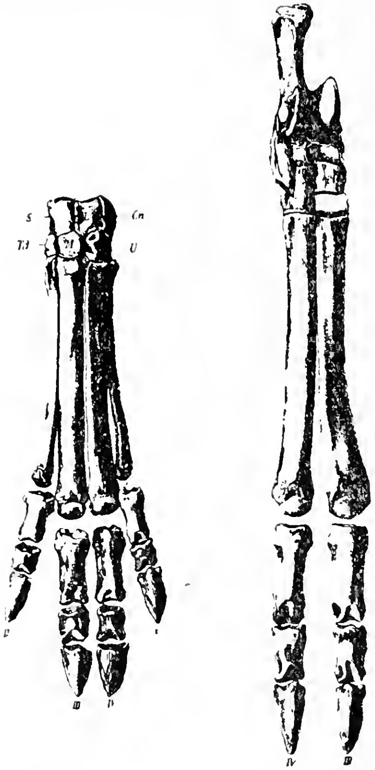

Figure 66—Fore and hind foot of Protoceras, the six-horned ruminant of the Upper Oligocene, Scott, 1895.

The head is long and narrow, tapering rapidly toward the anterior end, where the muzzle becomes extremely slender. The cranium is capacious and well formed. The brain case is of good size and indicates a brain fairly well convoluted, in fact the brain development of Protoceras seems to have been more advanced than any other animals of the time. The nasals are remarkable in that they indicate a long flexible nose if not a true proboscis. Among recent ruminants such a proboscidiform muzzle is found only in the saiga antelope and to a less extent in the moose.

The four toes of the front foot are functional and correspond to the second, third, fourth, and fifth, of five-toed animals. The hind foot shows only two toes, the third and fourth. Small short splint-like processes disclose, however, the rudimentary second and fifth. The hind limb compared with the fore limb, is large and long. The tail is larger and better developed than in the present day deer.

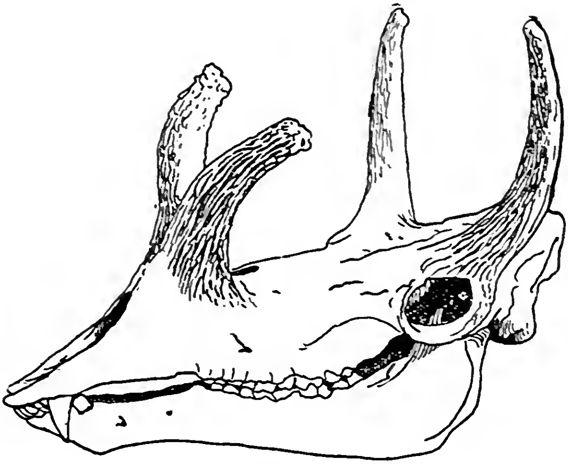

**Figure 67—Skull of the ruminant *Syndyoceras cooki* of the Lower Miocene. Barbour, 1905.**

The size of Protoceras is practically that of the sheep, but the general build seems to have corresponded more nearly to that of the pronghorn antelope. (Plate 44). The animal is, however, not very closely related to either. Syndyoceras had a head that in the male was as fantastic as that of Protoceras. There were two pairs of horns or horn-like outgrowths,—one pair situated above the eyes and curving toward each other, like those of the present day cow and one pair arising anteriorily nearly midway between the eyes and nostrils and curving outward away from each other. (Plate 45.

## CAMELIDAE

The camel originated in North America. The earliest and most primitive ancestors are found here and the evidence shows that the family had traveled far on its road toward modern camels before conditions became favorable for their migation to other continents.

At present the family consists of but two phyla, Camelus and Llama. Of the camels proper there are but two species, *Camelus dromedarius* or Arabian (one-humped) camel, and *Camelus bactrianus* or Bactrian (two-humped) camel. They inhabit the desert regions of Northern Africa, Arabia, and Central Asia. The llamas, including alpacas, guanacos, and vicunas, live only in the arid highlands of South America.

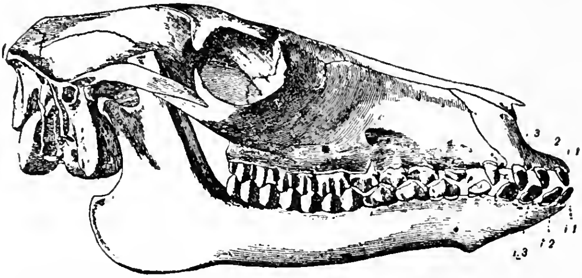

**Figure 68**—Skull of the Oligocene camel, *Poebrotherium wilsoni*. Wortman, 1898.

The camels are among the earliest domesticated animals of which we have knowledge and since the dawn of human history they seem not to have been known in the truly wild state. We lose ourselves in meditation as we think of the position these stupid ungainly creatures have made for themselves in the history of old world transportation but let us not fail to reflect that their earliest ancestral history lies at our own door-way. Ages before Joseph was sold by his brethren to the Ishmaelitic caravan from Gilead the forerunners of these useful beasts of burden were roaming in great numbers the wilds of what we now know as South Dakota and neighboring states seeking the comforts of a primitive living and looking forward in some mysterious way to the convenience of elastic pads for their feet, fleshy humps for their backs and water pockets for their stomachs. Concerning their distribution Scott says:

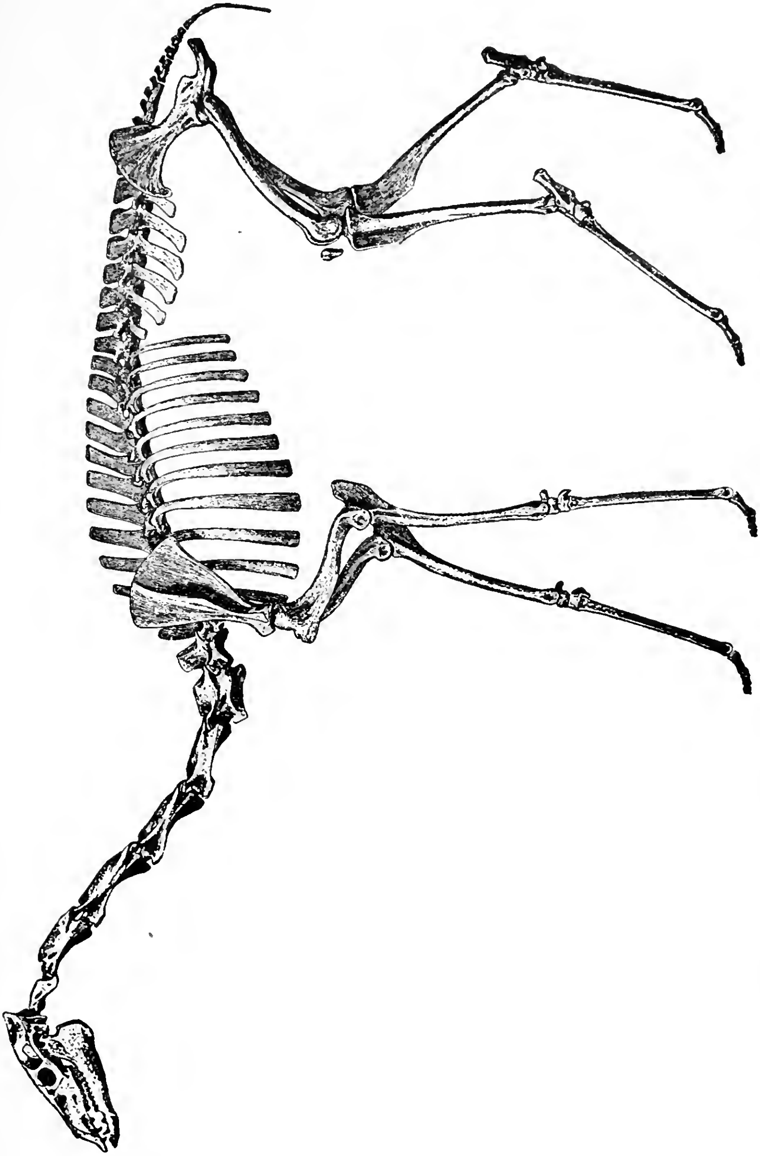

Figure 69—Skeleton of the Lower Miocene camel, *Oxydactylus longipes.* Peterson, 1904.

"Under modern conditions, no mammals could seem more completely foreign to North America than those of the camel family, which, now restricted to two well-defined genera, inhabit central Asia and the colder parts of South America. Yet, as a matter of fact, this family passed through nearly the whole of its development in North America and did not emigrate to the other continents before the late Miocene or early Pliocene, and it is this North American origin of the family which explains its otherwise inexplicable distribution at the present time. To all appearances, the whole family had completely disappeared from this continent in the later Pleistocene, but in the middle and earlier portions of that epoch both true camels and large llama-like animals were very abundant. * * *

"The most ancient known camels of the Old World are found in the Pliocene of India, and the first llamas recorded in South America are also Pliocene. Since both camels and llamas existed together in North America, it may be reasonably asked why only one phylum migrated to Asia and only the other to South America. Why did not each continent receive migrants of both kinds? Without knowing more than we are ever likely to learn about the details of these migrations, it will not be possible to answer these questions, though plausible solutions of the problem suggest themselves. It is to be noted, in the first place, that a migration from the central portion of North America to Asia was by way of the far north and thus involved very different climatic conditions from those which must have been encountered in passing through the tropics to South America. It is perfectly possible that animals which lived together in temperate North America should have had very different powers of adaptation to heat and cold respectively, and the northern route may have been impassable to one and the southern route to the other. To this it might perhaps be objected that llamas are cold-country animals, but this is true only of the existing species, for fossil forms are found abundantly in the Pleistocene of Ecuador, Brazil and Argentina. Another possibility is that both phyla did actually migrate to both continents and that only the camels succeeded in permanently establishing themselves in Asia and only the llamas in South America, though for this solution the fossils afford no evidence."

Within the area described in this book, a number of ancestral species have been identified, some from the Oligocene and some from the Miocene. These are preceded elsewhere by still older forms, the oldest of all so far as yet known being *Protylopus petersoni* a little four toed creature scarcely larger than a jackrabbit, found a few years ago in the Upper Eocene beds of the Washaki basin, Wyoming, and described by Mr. W. B. Matthew of the American Museum of Natural History.

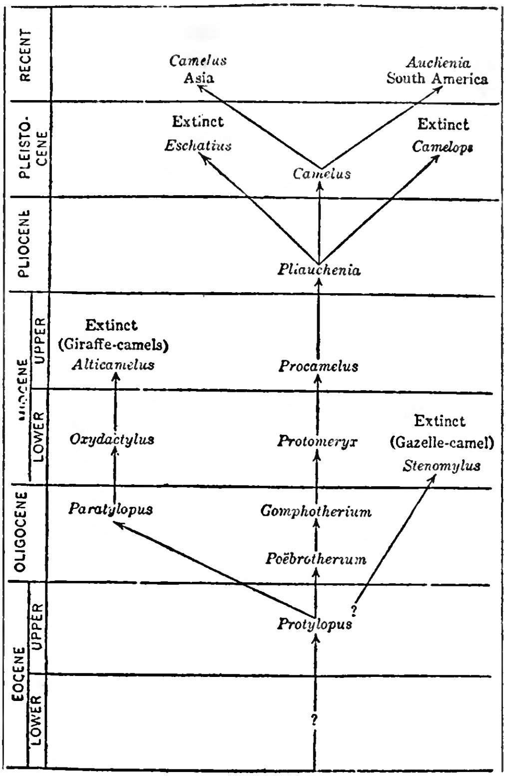

Figure 70—Phylogeny of the Camels. R. S. Lull; Organic Evolution, 1917. Published by the Macmillan Company. Reprinted by permission.

The best known South Dakota species, the one first discovered, and the one that has received the most merited recognition is *Poebrotherium wilsoni*. (Plate 46). The collection of Big Badland material given by Mr. Alexander Culbertson in 1847 to the Academy of Natural Sciences of Philadelphia contained a broken skull of this animal and Dr. Leidy in describing the specimen, the first of the many South Dakota badland fossible vertebrates studied by him, gave it the name it bears. (See Figure 2). He first regarded the animal as allied to the musk deer but later indicated its cameloid nature. Since the description of this earliest Poebrotherium skull abundant other remains have been found but generally they have not been complete. In 1890 the Princeton expedition was fortunate in securing a very excellent skeleton of *Poebrotherium wilsoni* almost entire and Prof. Scott has described this in a most careful manner. It is not possible, nor would it be profitable to go into the details of this description here. Briefly it may be said that the animal was a lightly built, graceful creature with apparently some external likeness to the llama but of about the size and build of the existing gazelle. It shows its relationship in many features of its skeleton but as in many extinct animals the bones show a primitive or generalized nature, and its connection with the llamas is perhaps as close as with the true camels. The eyes are farther back than in the present day camel, the ribs are more slender, and the foot, armed with small pointed hoofs was apparently without a pad. Like the existing camel the foot has only two toes, the third and fourth, but traces of the second and fifth remain as evidenced by the metapodial nodules. The metatarsal bones are separate but pressed closely together and plainly anticipate the definite union into a "cannon bone" during the subsequent Miocene. The animals varied considerably in size, the larger individuals reaching a height of twenty-four inches.

Among the Miocene forms Procamelus has long been known. This genus is of interest in that the camels and llamas of today seem to have descended directly from it. The gazelle camel, Stenomylus, and the giraffe camel, Oxydactylus, were discovered later but they have received full description. Their remains have been found in particular abundance in northwestern Nebraska. Several dozen skeletons of Stenomylus, were obtained from one excavation near Agate Springs. Peterson says it is seldom that the complete knowledge of the osteology of a genus has been acquired so rapidly after its discovery as that of Stenomylus and that

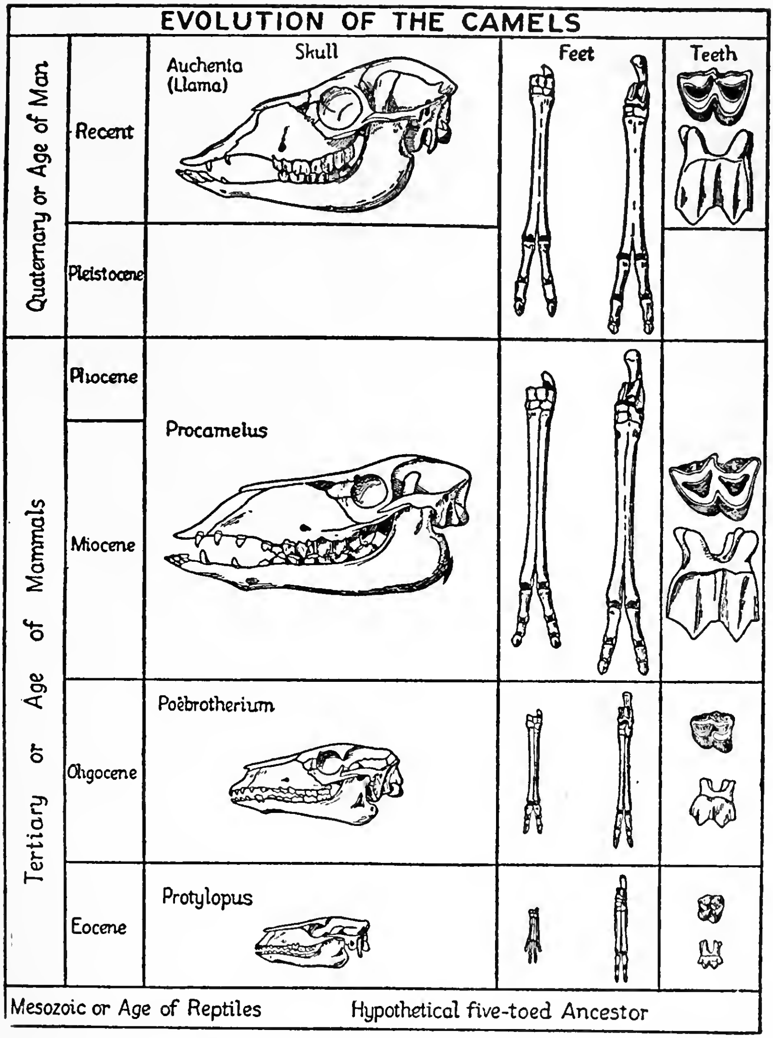

Figure 71—The evolution of the camel as indicated by the skull, feet and teeth. (Modified from Scott) R. S. Lull: Organic Evolution, 1817. Published by The Macmillan Company. Reprinted by permission.

more complete remains of this genus have been found than that of any other Miocene camel. The accompanying sketch by Peterson, page 71, shows a number of the skeletons as they were found in the quarry. These graceful llama-like little camels lived apparently in herds in an upland country where hard grasses constituted their chief food. In general it may be said that the Miocene forms became increasingly more cameloid in that they are larger, the side toes disappear, the metatarsal bones become more fully united and rugosities of the hoof bones indicate the presence of a small foot pad.

With the close of the Miocene important geographical changes came about including the raising of the isthmus of Panama above sea level and the forming of a land connection across Behring Strait. In this way widespread migration became possible. The camels during and immediately subsequent to the development of these land bridges were especially abundant and diversified throughout North America, hence readily took advantage of the opportunity to enter South America in the one direction and Asia and thence to Europe and Africa in the other. Later during Pleistocene time by reason of unfavorable climate or other conditions the North American branches of the family all died out while some at least of the more favorably situated foreign members lived on. Thus in the light of their ancestral history the wide separation of such nearly related animals as the camel and the llama, so long a perplexing question, is readily understood.

## CERVIDAE

Until 1904 nothing was known of the ancestral deer within the region of the White River badlands. In that year Mr. Matthew described a fragmentary jaw, *Blastomeryx wellsi* from the Upper Miocene. Since then several other species have been noted.

The earliest material obtained gave little information as to the definite relation of Blastomeryx to present ruminants but in the study of the later collections Mr. Matthew discovered it to be a primitive deer approximately ancestral to the American Cervidae and derivable in its turn from the Oligocene genus Leptomeryx whose relation to the Cervidae had not before been suspected. Its nearest relative structurally among the present day Cervidae is the musk deer. The general proportion of the skull is much as in the musk deer and like that animal it has no trace of horns or antlers such as gradually developed in later times and the upper canines are in the form of long, slender, recurved tusks. The skeleton as a whole has many primitive characters but the various species all show the general cervid affinities. The animal in life stood from one to one and a half feet high at the shoulders.

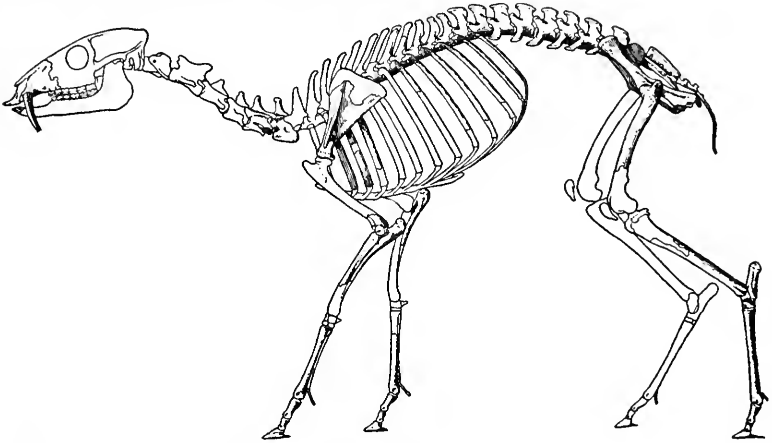

**Figure 72—Skeleton of the primitive Lower Miocene deer, *Blastomeryx advena.* Matthew, 1908.**

## REMAINS OF ANIMALS OTHER THAN MAMMALS

As indicated elsewhere fossil remains of backboned animals other than mammals in the Badlands are in general of little numerical consequence. Only in the case of turtles is there a decided exception. Occasional fragmentary remains of lizards and crocodiles are found and a few petrified birds eggs have been picked up but these are all that are worthy of mention. Shelled animals lived in the region but their remains are generally rare and of little consequence except from the standpoint of refined science. The beautiful and well known invertebrate shells from southwestern South Dakota so often seen in museums are from older geological formations. Coming chiefly from the Cheyenne river and its tributaries they are erroneously supposed by many to be of the same age as the mammal-bearing beds of the Tertiary.

Interest naturally attaches to the turtles, crocodiles and birds eggs, the first because of their size and abundance, and the second because of their having lived in this latitude and the third because of the general rarity of fossil eggs. These may be briefly described.

## TURTLES

Few Badland fossils are more abundant or more widely distributed or better preserved than the turtles. The size of the individuals varies from a few inches in length to more than two feet. Specimens three feet long are occasionally observed. These large sized Tertiary forms should not be confused with the far larger Cretaceous turtles found in the black Pierre shales near the Big Badlands. These Cretaceous turtles became veritable monsters and reached a greater size than any others yet found anywhere in the world, either living or fossil. The type specimen, found near Railroad Buttes, southeast of the Black Hills and described by Mr. Wieland in 1896, had a total length of approximately eleven feet, and fragmentary portions of a still larger individual showed a length of forty inches for the head alone.

From the various Badland formations in the White River region ten species of turtles have been described. Of all these only *Stylemys nebrascensis* occurs in abundance. (Plate 48). So far as I have learned each of the other species is known by only one or two specimens. Published reference to these latter is meagre and confined in the main to brief scientific description.

*Stylemys nebrascensis,* the common form, was first described in 1851 by Dr. Joseph Leidy, and is the earliest discovered fossil turtle in America. The first specimens were obtained by Dr. John Evans of the Owen Geological Survey in 1849 and since then hundreds of specimens have found their way into the museums of the world. The visitor in the Badlands can scarcely fail to find them if he walks along the outcrops of the containing strata and in favorable localities he may see them with surprising frequency. I myself have observed many dozens of them in a few hours walk in Indian draw and there are other places where they seem to be as abundant. They are found particularly in the Oreodon beds but occur in the Protoceras beds also. As yet none have been found in the Titanotherium beds.

The shell body is often preserved with remarkable perfection but owing to the fact that weathering readily separates the bones, specimens exposed on the surface are usually more or less disintegrated. The head and feet are rarely found. Dr. Leidy, who first described the species stated that he had seen hundreds of shells but no skull. Even today there is record of only two skulls. One of these in the Carnegie Museum of Pittsburg is accompanied by the shell. The other is in the Princeton Museum but the body to which it belonged was not found. The general absence of the head is due perhaps to the fact that Stylemys was a dry land tortoise and any freshet that might be able to carry or roll the heavy decaying body into water where deposition was taking place would wrench the head away. This, separate from the body, would be inconspicuous and hence fail of ready detection.

Several fossil turtle eggs have been found in the Badlands and they are regarded as belonging to the common species just described. Hay states that they are slightly elongated but he indicates that this is perhaps due to deformation by pressure from an original globular form. They

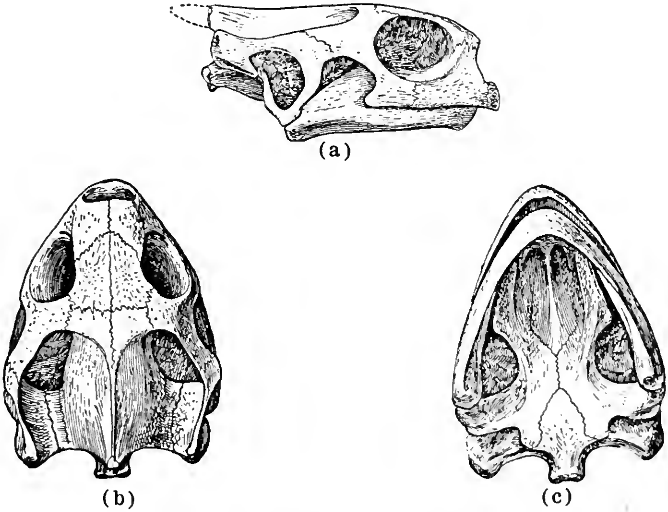

Figure 73—Head of the abundant Oligocene dryland tortoise, *Stylemys nebrascensis*. Natural size, (a) view of right side; (b) view from above; (c) view from below. Hay, 1906.

are a little less than two inches in diameter. They were formerly in the James Hall collection but are now in the American Museum of Natural History.

## CROCODILES

Two species of crocodiles have been described from the White River badlands. These were found near Sheep mountain. Fragments of others have been obtained from the Finney breaks near Folsom. All of the specimens are from the Titanotherium beds. Besides other parts each species is represented by a considerable portion of the head.

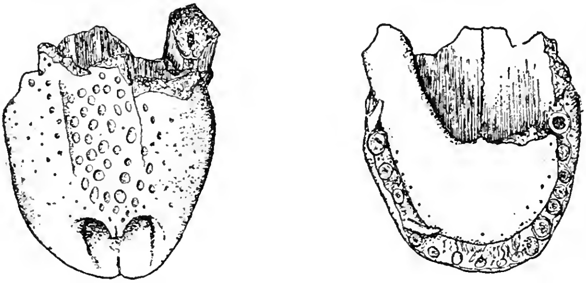

Figure 74—Anterior portion of head of the Oligocene crocodile, *Crocodilus prenasalis* found in Indian draw, (a) view from above; (b) view from below. Loomis, 1904.

The author found the first of these, *Crocodilus prenasalis,* in 1899. (Plate 47). In this the nasal opening is placed forward hence the specific name. The part of the head that is preserved is broad and short and contains the root portions of eighteen teeth, two of which retain the nearly complete crowns. These are conical and slightly recurved and the longest is approximately one half inch in length. The portion of the head preserved shows a width of

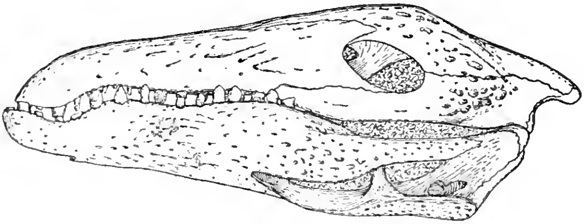

Figure 75—Head of the Oligocene crocodile *Caimanoides visheri.* Mehl, 1916.

two and five-eights inches within two inches of the nasal end. The animal in life was perhaps six feet long. The second species, *Caimanoidea visheri*, found in 1911, shows characters tending toward the alligators. Its length in life was about five and one half feet.

These fossils are of interest in showing in striking manner the Floridian character of the climate in the White River region during early Oligocene time and they add to other evidence that the country was then a land of inundation.

## BIRDS EGGS

Several fossil birds eggs have been found in or near the Big Badlands. Unlike eggs found elsewhere as fossils the badland birds eggs are distinctly petrified, that is they show a practically complete replacement of the original matter by mineral material. Soft animal tissues quickly decay and only exceptional conditions allow for their preservation or petrefaction. Turtle eggs are occasionally found filled with hardened mud and eggs of certain extinct birds have been preserved by reason of the thickness of their shells but the Badland birds eggs show not only the thickness of the original shell but apparently also the position of the white and the yolk of the egg.

One of the Badland eggs found by Mr. Kelly Robinson in 1896 has been carefully described by Dr. O. C. Farrington of the Field Museum. The shell portion is made up of dark colored chalcedony, the color being due to organic matter. The portion representing the white of the egg is gray translucent chalcedony with occasional black blotches the exact nature of which was not determined. The yolk is replaced by opal in two portions of about equal size but with different texture. The egg measures 2.03 inches by 1.49 inches, long and short diameters, conforming in size and general shape to that of the present day Florida duck (*Anas fulvigula*). Plate 48.)

Since the publication of the paper by Mr. Farrington other birds eggs from the Badlands, perfect in outline and similar in size and shape to the one described have been found. One of these is now in the geological museum of the South Dakota State School of Mines.

## THE BADLAND LIFE OF TODAY

Conditions for present day animal and plant life in the Badlands are fairly favorable. The average annual rainfall is approximately seventeen inches. Of this amount about thirteen inches comes during the five crop growing months, April, May, June, July and August. The average annual temperature is about 44 deg. Fahrenheit.

The soil varies considerably. Much of the flatter country is covered by a silty or sandy loam which nourishes rich, native grasses and it has proven under cultivation to be favorable for the growing of vegetables and grains.

The native plants incline toward the hardy semi-arid types. Annuals are conspicuous in many places especially where moisture lingers longest. Pubescent-leaved perennials with their well-anchored roots are widely distributed. There is a surprising abundance of flowers and they appear in tenaceous succession through the summer. Grasses are the predominant plants over much of the country. Chief among the many species are buffalo grass, grama grass, wheat grass, needle or spear grass, blue stem and wire grass. Of these the buffalo grass and grama grass have been of the greatest value in making of the region a great cattle range. Cacti and yuccas among the gorgeously blooming plants and sage brush among the woody shrubs are abundant and conspicuous but they are by no means uniformly distributed. The chief wild fruits are plums, chokecherries, sandcherries, buffalo berries, gooseberries, currants, wild grapes, raspberries and service berries.

Trees are abundant in places but well wooded areas are greatly restricted. Cottonwoods are common along some of the alluvial flats and red cedar and the western yellow pine form considerable of a forest growth among the higher breaks. Pine Ridge, a prominent irregularly etched escarpment and an integral part of the area under discussion owes much of its picturesque nature to the presence of the pines and cedars scattered so promiscuously among its otherwise nearly bare slopes and precipices. In addition to these there are in much less abundance the box elder, ash, elm, hackberry, stunted oak, and willow.

There are or were until recently more than forty native mammals frequenting the Badlands. Approximately three hundred species of birds have also been found visiting or making their homes in the region· The commonest of the birds are the cliff swallow, the rock wren, the meadow lark and the chikadee but others may be found in considerable numbers. Mammals once occupying the country in an important manner but now nearly or wholly dispersed are the bison, elk, deer, bear, antelope, mountain sheep and puma. Among those that are yet to be found in abundance or in considerable numbers are the following: Coyote, gray wolf, gopher, jack rabbit, cottontail rabbit, prairie dog, badger, skunk, porcupine, raccoon, bobcat, kitfox, weasel, mice and shrews.

## RECENT HISTORY

The history of the White River Badlands in so far as it relates to man before the advent of the white settler has to do chiefly with the Teton Indians. When white men first penetrated the region they found Indians frequenting the country and calling it a part of their possessions. In the earliest days the Crows, (Absarokas) controlled the country and later the Cheyennes but sometime before the close of the eighteenth century the lands passed into the possession of the Tetons of the Dakota Sioux. The claims of the several Teton tribes shifted from time to time, the Brules and the Minneconjous for a while occupying much of the country but later the Oglalas assumed a large control. (Plate 49).

The earliest white men to see the Badlands were traders and trappers in search of furs. Their coming led in due course to military and exploratory expeditions. Conflicts of diverse kinds occurred between the Indians and the newcomers and for a number of years an irritating warfare prevailed. However, most of the actual fighting took place outside the region under consideration. The severest conflict in the Badlands proper occurred during the Messiah Craze of 1890. This is commonly known as the Wounded Knee affair. It was an unfortunate clash between federal troops and the Indians in which 200 Indians, men, women, and children, and sixty soldiers were killed.

During the last quarter of a century, with the growing preponderance of white people the Indians have progressed toward civilization and many of their homes show semblance of comfort, stability and wealth. The traveller finds them today kind and considerate and many a white settler has reason to rejoice in their friendship. The fathers and mothers, notwithstanding their disadvantages, have generally a fair knowledge of English and most of the children are receiving training in good elementary and industrial schools. The expansive reservations established years ago have nearly disappeared. In opening up these reservations the Indians first receive liberal individual allotments of land, then that which remains is available for settlement by the whites. Opportunity for good financial returns from a large part of the Badlands, notwithstanding their detractive name, has been abundantly proven and with better understanding of conditions, the wealth of the region will greatly increase.

## HOW TO SEE THE BADLANDS

The White River Badlands are readily accessible. Many of their features may be observed with pleasure and satisfaction from a Pullman window. Well-travelled wagon roads connect the better known passes and these give opportunity through much of the year for delightful automobile drives. Off-the-road places may be reached by saddle or in pedestrian boots.

Railroads cross the country in several places and give abundant opportunity to visit almost any desired locality. The Pierre, Rapid City and Northwestern railroad now merged with the Chicago and Northwestern system, going up Bad River valley and thence over into the Cheyenne valley crosses a narrow northerly projecting arm at the town of Wall, South Dakota. The Chicago and Northwestern railroad from Omaha crosses Pine Ridge from southeast to northwest at Chadron, Nebraska. The connecting Chadron-Lander line, following up the head of White River cuts Pine Ridge from northeast to southwest near Crawford and again farther west in a nearly east-west direction in Converse county (now Converse and Albany counties) Wyoming. The Chicago, Burlington and Quincy railroad from Lincoln traverses the Crawford locality from southeast to northwest, it being nearly at right angles to the Chadron-Lander connection of the Chicago and Northwestern.

The Chicago, Milwaukee and St. Paul railroad gives to the car window sightseer the best and most abundant opportunity to view the general ruggedness of the Badlands and affords also a very good opportunity to study close at hand, though in hasty manner, many things of interest. For many miles this railroad winds its way up White River valley along the southern face of the Great Wall, then plunges into the very heart of the picturesque Big Badlands the culminating feature of all the area included under the name, White River Badlands. From near Kadoka to Scenic there is a never ceasing array of those topographic peculiarities that make the region famous and, in the Big Badlands, they are placed together in most fantastic manner. Sheep Mountain (Cedar Point), the most famous locality of all this wonderful country lies a few miles south of Scenic. It may be seen from the car window but its strange grandeur can be understood only by a special visit and its chief feature—School of Mines canyon—should be traversed only with proper equipment and guide. Those wishing to study the Great Wall will find it accessible from any of the nearby railway towns. Interior is the largest and in some respects the most convenient place from which to drive or walk but there are facilities at every station and at some of them they are nearly or quite as good as at Interior.

Those desiring to visit remote areas either in southwestern South Dakota, northwestern Nebraska or southeastern Wyoming will have little difficulty in obtaining direction and suggestion. The people generally will be found accommodating to the point of urgent hospitality. One needs of course to bear in mind that much of the country is still sparsely settled and that as in any other place annoying weather conditions may at times prevail but the real lover of the great out-of-doors, man or woman, will usually find little of real hardship. He who has opportunity to ramble over this strange country in the bright mornings of early summer when the short grasses are brilliant green or who in the on-coming autumn can camp near some good spring and enjoy the beauty of the prairie evening and the stillness of the arid night is blest with a golden privilege.

The Badlands are strange, and inspirational and good. For many years only those technically trained in nature's ways could appreciate them but now in these days of wider opportunity with railway facilities, good roads, numerous settlers and the omnipresent automobile every one can cultivate a growing comprehension of their meaning. Even the name is rapidly losing its forbidding aspect. Until recently the country was to the causal visitor but a grotesque quarry for dry bones. It should be to all men a living storehouse of wonderful works.

# A List of the Fossil Mammals Found in the White River Badlands*

## LOWER OLIGOCENE (TITANOTHERIUM ZONE.)

- Carnivora (Fissipedia).
  - Canidae.
    - Daphoenus dodgei Scott. Am. Phil. Soc., Trans., vol. 19, 1898, p. 362. Nw. Neb.
  - Felidae.
    - Dinicitis fortis Adams.
- Perissodactyla.
  - Rhinocerotidae.
    - Trigonias obsborni Lucas. U. S. Nat. Mus., Proc., vol. 23, 1900, pp. 221-223. So. Dak.
    - Leptaceratherium trigondum Osborn and Wortman. Am. Mus. Nat. His., Bull., vol. 6, 1894, pp. 201-203, (Aceratherium). So. Dak.
    - Caenopus cf. platycephalus Osborn and Wortman. Am. Mus. Nat. Hist., Bull., vol. 6, 1894, p. 206, (Aceratherium). So. Dak.
    - Caenopus mitis Cope.
  - Lophiodontidae.
    - Colodon (Mesotapirus) occidentalis Leidy.
  - Equidae.
    - Mesohippus proteulophus Osborn.
    - Mesohippus hypostylus.
    - Mesohippus celer Marsh. Am. Jour. Sci., vol. 7, 1874, p. 251, (Anchitherium). Nw. Neb.
  - Titanotheridae (Brontotheridae).
    - Titanotherium prouti Leidy.
    - Titanotherium helocerus (Cope).
    - Titanotherium trigonoceras (Cope).
    - Megacerops dispar (Marsh). Am. Jour. Sci., vol. 34, 1887, p. 328, (Brontops). So. Dak.

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*Fossil forms too poorly preserved to admit of careful description and naming have been omitted from this list. In compiling the list I have made extensive use of Matthew's Faunal Lists of the Tertiary Mammalia of the West as given in U. S. Geological Survey Bulletin No. 361, 1909. I have made no effort on my own part to indicate the relative value of synonyms where synonyms exist, but have endeavored to follow closely the nomenclature as given by Matthew and by later authors. For additional convenient helpful literature the reader is referred to Hay's Bibliography and Catalogue of the Fossil Vertebrata of North America, U. S. Geological Survey Bulletin No. 179, 1902, and to Palmer's Index Generum Mammalium; a list of the Genera and Families of Mammals, U. S. Department of Agriculture, Division of Biological Survey, 1904.

Effort has been made to indicate the scientific paper in which each form was first described and named, its year of publication, also the approximate locality within the area covered by the accompanying map of the Black Hills region where the earliest or type specimen was found. Such reference is omitted in a few instances where I have not had opportunity to examine the original publication. In a few instances fossils found south of the Niobrara-Platte river divide and fossils found near and to the east of Ft. Niobrara are included but generally such forms are not considered as coming within the scope of this paper. So. Dak. means in all cases the southwestern part of the state. Mauv. Terres where used corresponds fairly well to the Big Badlands, hence refers generally to fossils from South Dakota.

Megacerops tichoceras Scott and Osborn. Mus. Comp. Zool., Bull., vol. 13, 1887, pp. 159-160, (Menodus). So. Dak.
Megacerops robustus (Marsh). Am. Jour. Sci., vol. 34, 1887, pp. 326-327, (Brontops). Nw. Neb.
Megacerops brachycephalus Osborn. Am. Mus. Nat. Hist., Bull., vol. 16, 1902, pp. 97-98. So. Dak.?
Megacerops bicornutus Osborn. Am. Mus. Nat. Hist., Bull., vol. 16, 1902, p. 99. So. Dak.?
Megacerops marshi Osborn. Am. Mus. Nat. Hist., Bull., vol. 16, 1902, pp. 100-101. So. Dak.?
Allops serotinus Marsh. Am. Jour. Sci., vol. 34, 1887, p. 331. So. Dak.
Allops crassicornis Marsh. Am. Jour. Sci., vol. 42, 1891, pp. 268-269. So. Dak.
Allops amplus (Marsh). Am. Jour. Sci., vol. 39, 1890, pp. 523-524, (Diploclonus). So. Dak.
Symborodon montanus (Marsh). Am. Jour. Sci., vol. 9, 1875, p. 246, (Anisacodon). Nw. Neb.
Symborodon copei Osborn, Am. Mus. Nat. Hist., vol. 24, 1908, pp. 616-617. So. Dak.
Brontotherium ramosum (Osborn).
Brontotherium dolichoceras (Scott and Osborn). Mus. Comp. Zool., Bull., vol. 13, 1887, pp. 160-161, (Menodus). So. Dak.
Brontotherium leidyi Osborn. Am. Mus. Nat. Hist., Bull., vol. 16, 1902, pp. 105-106. So. Dak.
Brontotherium hatcheri Osborn. Am. Mus. Nat. Hist., Bull., vol. 24, 1908, pp. 615-616. So. Dak.

Artiodactyla.
Elotheridae (Entelodontidae).
Elotherium (Entelodon) crassum Marsh. Am. Jour. Sci., vol. 5, 1873, pp. 487-488.
Anthracotheridae.
Hyopotamus (Ancodon) americanus Leidy. Acad. Nat. Sci., Phila., Proc., vol. 8, 1856, p. 59. So. Dak.
Oreodontidae (Agriochoeridae).
Oreodon (Merycoidodon) hybridus Leidy. Ext. Mam. of Dak. and Neb., 1869, pp. 105-106. Mauv. Terres.
Oreodon (Merycoidodon) affinis Leidy. Ext. Mam. of Dak. and Neb., 1869, p. 105. Mauv. Terres.
Oreodon (Merycoidodon) bullatus Leidy. Ext. Mam. of Dak. and Neb., 1869, p. 106. Mauv. Terres.
Hypertragulidae.
Heteromeryx dispar Matthew.

## MIDDLE OLIGOCENE (OREODON ZONE.)

Carnivora (Creodonta).
Hyaenodontidae.
Hyaenodon horridus Leidy. Acad. Nat. Sci., Phila., Proc., vol. 6, 1853, pp. 392-393. Mauv. Terres.
Hyaenodon cruentus Leidy. Acad. Nat. Sci., Phila., Proc., vol. 6, 1853, p. 393. Mauv. Terres.
Hyaenodon crucians Leidy. Acad. Nat. Sci., Phila., Proc. vol. 6, 1853, p. 393. Mauv. Terres.
Hyaenodon paucidens Osborn and Wortman. Am. Mus. Nat Hist., Bull., vol. 6, 1894, pp. 223-224. So. Dak.

Hyaenodon leptocephalus Scott and Osborn. Mus. Comp. Zool., Bull., vol. 13, 1887, p. 152.
Hyaenodon mustelinus Scott. Acad. Nat. Sci., Phila., Jour., vol. 9, 1894, pp. 499-500. So. Dak.

Carnivora (Fissipedia).
Canidae.
Daphoenus vetus Leidy. Acad. Nat. Sci., Phila., Proc., vol. 6, 1853, p. 393, Mauv. Terres.
Daphoenus hartshornianus (Cope).
Daphoenus felinus Scott. Am. Philos. Soc., Trans., vol. 19, 1898, pp. 361-362. Nw. Neb.
Daphoenus nebrascensis (Hatcher). Carnegie Mus., Mem., vol. 1, 1902, pp. 95-99, (Proamphicyon). Nw. Neb.
Daphoenus inflatus (Hatcher). Carnegie Mus., Mem., vol. 1, 1902, pp. 99-104, (Protemnocyon). Nw. Neb.
Cynodictis gregarius (Cope).
Cynodictis lippincottianus (Cope).

Felidae.
Dinictis felina Leidy. Acad. Nat. Sci., Phila., Proc., vol. 8, 1856, p. 91, Mauv. Terres.
Dinictis squalidens (Cope).
Dinictis paucidens Riggs.
Hoplophoneus primaevus (Leidy).
Hoplophoneus occidentalis (Leidy). Acad. Nat. Sci., Phila., Jour., vol. 7, 1869, pp. 63-64, (Depranodon). Mauv. Terres.
Hoplophoneus oreodontis Cope.
Hoplophoneus marshi Thorpe. Am. Jour. Sci., vol. 50, 1920, pp. 211-214. Nw. Neb.
Hoplophoneus molossus Thorpe. Am. Jour. Sci., vol. 50, 1920, pp. 220-224. Nw. Neb.

Insectivora.
Erinaceidae.
Proterix loomisi Matthew.
Leptictidae.
Leptictis haydeni Leidy.
Ictops dakotensis Leidy.
Ictops bullatus Matthew. Am. Mus. Nat. Hist., Bull., vol. 12, 1899, p. 55. So. Dak.
Ictops porcinus (Leidy).
Soricidae.
Protosorex crassus Scott. Acad. Nat. Sci., Phila., Proc., 1894, pp. 446-448. So. Dak.

Rodentia.
Castoridae.
Eutypomys thomsoni Matthew.
Ischyromyidae.
Ischyromys typus Leidy. Acad. Nat. Sci., Phila., Proc., vol. 8, 1856, p. 89, Mauv. Terres.
Muridae.
Eumys elegans Leidy. Acad. Nat. Sci., Phila., Proc., vol. 8, 1856, p. 90, Mauv. Terres.
Leporidae.
Palaeolagus haydeni Leidy. Acad. Nat. Sci., Phila., Proc., vol. 8, 1856, pp. 89-90, Mauv. Terres.
Palaeolagus turgidus Cope.

Perissodactyla.
  Hyracodontidae.
    Hyracodon nebrascensis Leidy.
    Hyracodon major Scott and Osborn. Mus. Comp. Zool., Bull., vol. 13, 1887, p. 170. So. Dak.?
  Amynodontidae.
    Metamynodon planifrons Scott and Osborn. Mus. Comp. Zool., Bull., vol. 13, 1887, pp. 165-169. So. Dak.

Rhinocerotidae.
    Caenopus (Subhyracodon) occidentalis Leidy.
    Caenopus (Subhyracodon) copei Osborn. Am. Mus. Nat. Hist., Mem., vol. 1, 1898, pp. 146-150, (Aceratherium). So. Dak.
    Caenopus (Subhyracodon) simplicidens Cope.
    Leptaceratherium trigonodum (Osborn and Wortman).
    "Hyracodon" planiceps Scott and Osborn. Mus. Comp. Zool., Bull., vol. 13, 1887, pp. 170-171. So. Dak.
  Lophiodontidae.
    Colodon (Mesotapirus) procuspidatus Osborn and Wortman. Am. Mus. Nat. Hist., Bull., vol. 7, 1895, pp. 362-364. So. Dak.
    Colodon (Mesotapirus) dakotensis Osborn and Wortman. Am. Mus. Nat. Hist., Bull., vol. 7, 1895, pp. 362-364. So. Dak.
    Colodon (Mesotapirus) longipes Osborn and Wortman. Am. Mus. Nat. Hist., Bull., vol. 7, 1895, p. 366. So. Dak.
  Tapiridae.
    Protapirus simplex Wortman and Earle. Am. Mus. Nat. Hist., Bull., vol. 5, 1893, pp. 168-169. So. Dak.
  Equidae.
    Mesohippus bairdi Leidy.
    Mesohippus obliquidens Osborn. Am. Mus. Nat. Hist., Bull., vol. 20, 1904, p. 173. So. Dak.
    Mesohippus trigonostylus Osborn. Am. Mus. Nat. Hist., Mem., vol. 2, pt. 1, (new series) 1918, pp. 47-48. So. Dak.

Artiodactyla.
  Elotheridae (Entelodontidae).
    Elotherium (Enteloden) mortoni Leidy.
    Elotherium (Entelodon) ingens Leidy. Acad. Nat. Sci., Phila., Proc., vol. 8, 1856, pp. 164-165. Mauv. Terres.
  Dicotylidae (Tagassuidae).
    Perchoerus probus Leidy. Acad. Nat. Sci., Phila., Proc., vol. 8, 1856, p. 165. Mauv. Terres.
    Perchoerus nanus (Marsh). Am. Jour. Sci., vol. 48, 1894, p. 271, (Thinohyus). So. Dak.
  Anthracotheridae.
    Anthracotherium curtum (Marsh). Am. Jour. Sci., vol. 47, 1894, p. 409, Heptacodon. So. Dak.
    Hyopotamus (Ancodon) rostratus Scott. Acad. Nat. Sci., Phila., Jour., vol. 9, 1894, Appendix, p. 536. So. Dak.
  Leptochoeridae.
    Leptochoerus spectabilis Leidy. Acad. Nat. Sci., Phila., Proc., vol. 8, 1856, p. 88. Mauv. Terres.
    Lepthochoerus gracilis Marsh. Am. Jour. Sci., vol. 48, 1894, pp. 271-273. So. Dak.

Stibarus quadricuspis (Hatcher). Carnegie Mus., Ann., vol. 1, 1901, pp. 131-134, (Leptochoerus).

Oreodontidae (Agriochoeridae).

Agriochoerus antiquus Leidy.

Agriochoerus latifrons Leidy. Ext. Mam. of Dak. and Neb., 1869, pp. 135-141. Mauv. Terres.

Oreodon (Merycoidodon) culbertsoni (Leidy).

Oreodon (Merycoidodon) gracilis Leidy.

Oreodon (Merycoidodon) sp. cf. bullatus Leidy.

Hypertragulidae.

Hypertragulus calcaratus Cope.

Leptomeryx evansi Leidy. Acad. Nat. Sci., Phila., Proc., vol. 6, 1853, p. 394. Mauv. Terres.

Hypisodus minimus Cope.

Hypisodus alacer Troxell. Am. Jour. Sci., vol. 49, 1920, pp. 393-396.

Camelidae.

Poebrotherium wilsoni Leidy. Acad. Nat. Sci., Phila., Proc., vol. 3, 1847, pp. 322-326. Mauv. Terres.

Poebrotherium labiatum Cope.

Poebrotherium eximium Hay. U. S. Geol. Surv., Bull. No. 179, 1902, p. 67. This was first described by Wortman as Poebrotherium wilsoni Leidy. See Am. Mus. Nat. Hist., Bull., vol. 10, 1898, pp. 111-112. So. Dak.

Poebrotherium andersoni Troxell. Am. Jour. Sci., vol. 43, 1917, pp. 381-389.

Paratylopus primaevus Matthew. Am. Mus. Nat. Hist., Bull., vol. 20, 1904, pp. 211-213. So. Dak.

## UPPER OLIGOCENE

(Protoceras and Lower Leptauchenia Zones.)

Carnivora (Fissipedia).

Canidae.

Cynodictis temnodon Wortman and Matthew. Am. Mus. Nat. Hist., Bull., vol. 12, 1899, p. 130.

Felidae.

Dinictis bombifrons Adams.

Hoplophoneus insolens Adams. Am. Jour. Sci., vol. 1, 1896, p. 429. So. Dak.

Eusmilus dakotensis Hatcher. Am. Nat., vol. 29, 1895, pp. 1091-1093. So. Dak.

Rodentia.

Castoridae.

Steneofiber nebrascensis (Leidy). Acad. Nat. Sci., Phila., Proc., vol. 8, p. 89. Mauv. Terres.

Perissodactyla.

Rhinocerotidae.

Caenopus tridactylus Osborn. Am. Mus. Nat. Hist., Bull., vol. 5, 1893, pp. 85-89, (Aceratherium). So. Dak.

Caenopus platycephalus Osborn and Wortman.

Tapiridae.

Protapirus obliquidens Wortman and Earle. Am. Mus. Nat. Hist., Bull., vol. 5, 1893, pp. 162-169. So. Dak.

Protapirus validus Hatcher. Am. Jour. Sci., vol. 1, 1896, pp. 162-168. So. Dak.

Equidae.
  Mesohippus intermedius Osborn and Wortman. Am. Mus. Nat. Hist., Bull., vol. 7, 1895, pp. 334-356. So. Dak.
  Mesohippus meteulophus Osborn. Am. Mus. Nat. Hist. Bull., vol. 20, 1904, pp. 174-175. So. Dak.
  Mesohippus brachystylus Osborn. Am. Mus. Nat. Hist., Bull., vol. 20, 1904, pp. 175-176. So. Dak.
  Miohippus validus Osborn. Am. Mus. Nat. Hist., Bull., vol. 20, 1904, p. 177. So. Dak.
  Miohippus gidleyi Osborn. Am. Mus. Nat. Hist., vol. 20, 1904, p. 178. So. Dak.
  Miohippus crassicuspis Osborn. Am. Mus. Nat. Hist., Bul., vol. 20, 1904, pp. 178-179. So. Dak.
  Colodon copei Osborn and Wortman. Am. Mus. Nat. Hist., Bull., vol. 7, pp. 356-358, 1895. So. Dak.
  Parahippus cognatus Leidy. Acd. Nat. Sci., Phila., Jour., vol. 7, p. 314, 1869. Nw. Neb.

Artiodactyla.
Elotheridae (Entelodontidae).
  Elotherium (Entelodon) cf. ingens Leidy.
  Elotherium (Entelodon)? crassus Marsh.
  Elotherium (Entelodon) bathrodon Marsh. Am. Jour. Sci., vol. 7, 1874, p. 534. So. Dak.
Dicotylidae (Tagassuidae).
  Perchoerus robustus (Marsh). Am. Jour. Sci., vol. 48, 1894, p. 94, (Thinohyus).
  Perchoerus platyops (Cope). Hayden Surv., Bull., vol. 6, pp. 174-175, (Palaeochoerus). So. Dak.
Anthracotheridae.
  Anthracotherium karense Osborn and Wortman. Am. Mus. Nat. Hist., Bull., vol. 6, 1894, pp. 222-223. So. Dak.
  Hyopotamus (Ancodon) brachyrhynchus Osborn and Wortman. Am. Mus. Nat. Hist., Bull., vol. 6, 1894, pp. 220-221. So. Dak.

Oreodontidae (Agriochoeridae).
  Agriochoerus major Leidy. Acad. Nat. Sci., Phila., Proc., vol. 8, 1856, p. 164. Mauv. Terres.
  Agriochoerus gaudryi (Osborn and Wortman). Am. Mus. Nat. Hist., Bull., vol. 5, 1893, pp. 5-13, (Artionyx). So. Dak.
  Agriochoerus migrans (Marsh). Am. Jour. Sci., vol. 48, 1894, pp. 270-271, (Agriomeryx). So. Dak.
  Eporeodon (?Eucrotaphus) major (Leidy). Smithson. Contr. to Knowl., vol. 6, p. 55, (Oreodon). So. Dak.
  Eucrotaphus jacksoni Leidy.
Hypertragulidae.
  81-82. So. Dak.
  Protoceras comptus Marsh. Am. Jour. Sci., vol. 48, 1894, pp. 93-94. So. Dak.
  Protoceras nasutus Marsh.
  Calops cristatus Marsh. Am. Jour. Sci., vol. 48, 1894, p. 94. So. Dak.
  Calops consors March.
Camelidae.
  Pseudolabis dakotensis Matthew. Am. Mus. Nat. Hist., Bull., vol. 20, 1904, p. 211. So. Dak.

## LOWER MIOCENE.

Carnivora.

Canidae.

Nothocyon gregorii Matthew. Am. Mus. Nat. Hist., Bull., vol. 23, 1907, p. 183. So. Dak.

Nothocyon vulpinus Matthew. Am. Mus. Nat. Hist., Bull., vol. 23, 1907, pp. 183-184. So. Dak.

Nothocyon annectens Peterson. Carnegie Mus., Ann., vol. 4, 1908, pp. 53-54. Nw. Neb.

Nothocyon? lemur Cope.

Daphoenodon superbus Peterson. Carnegie Mus., Ann. vol. 4, 1908, pp. 51-53. Nw. Neb.

Daphoenodon periculosus Cook. Neb. Geol. Surv., vol. 3, 1909, pp. 268-270. Nw. Neb.

Mesocyon robustus Matthew. Am. Mus. Nat. Hist., Bull., vol. 23, 1907, p. 185. So. Dak.

Enhydrocyon crassidens Matthew. Am. Mus. Nat. Hist., Bull., vol. 23, 1907, pp. 190-193. So. Dak.

Cynodesmus thomsoni Matthew. Am. Mus. Nat. Hist., Bull., vol. 23, 1907, pp. 186-188. So. Dak.

Cynodesmus minor Matthew. Am. Mus. Nat. Hist. Bull., vol. 23, 1907, p. 189. So. Dak.

Temnocyon venator Cook. Neb. Geol. Surv., vol. 3, 1909, pp. 262-266. Nw. Neb.

Temnocyon percussor Cook. Neb. Geol. Surv., vol. 3, 1909, p. 266. Nw. Neb.

Borocyon robustum Peterson. Carnegie Mus., Mem., vol. 4, 1910, pp. 263-267. Nw. Neb.

Paroligobunis simplicidens Peterson. Carnegie Mus., Mem., vol. 4, 1910, pp. 269-278. Nw. Neb.

Mustelidae.

?Brachypsalis simplicidens Peterson. Carnegie Mus., Ann., vol. 4, 1908, pp. 44-46. Nw. Neb.

Oligobunis lepidus Matthew. Am. Mus. Nat. Hist., Bull., vol. 23, 1907, pp. 194-195. So. Dak.

Megalictis ferox Matthew. Am. Mus. Nat. Hist., Bull., vol. 23, 1907, pp. 197-204. So. Dak.

Aelurocyon brevifacies Peterson. Carnegie Mus., Ann., vol. 4, 1908, 68-72. Nw. Neb.

Felidae.

Nimravus sectator Matthew. Am. Mus. Nat. Hist., Bull., vol. 23, 1907, pp. 204-205. So. Dak.

Insectivora.

Chrysochloridae.

Arctoryctes terrenus Matthew.

Rodentia.

Castoridae.

Euhapsis brachyceps Peterson. Carnegie Mus., Mem., vol. 2, 1905, pp. 179-184, (platyceps). Nw. Neb.

Euhapsis gaulodon Matthew. Am. Mus. Nat. Hist., Bull., vol. 23, 1907, pp. 208-210. So. Dak.

Steneofiber? pansus Cope.

Steneofiber fossor Peterson. Carnegie Mus., Mem., vol. 2, 1905, pp. 140-166. Nw. Neb.

Steneofiber barbouri Peterson. Carnegie Mus. Mem., vol. 2, 1905, pp. 166-171. Nw. Neb.

Steneofiber simplicidens Matthew. Am. Mus. Nat. Hist., Bull., vol. 23, 1907, pp. 205-207. So. Dak.
Steneofiber sciuroides Matthew. Am. Mus. Nat. Hist., Bull., vol. 23, 1907, p. 207. So. Dak.
Steneofiber brachyceps Matthew. Am. Mus. Nat. Hist., Bull., vol. 23, 1907, p. 208. So. Dak.
Geomyidae.
Entoptychus formosus Matthew. Am. Mus. Nat. Hist., Bull., vol. 23, 1907, pp. 212-213. So. Dak.
Entoptychus curtus Matthew. Anm. Mus. Nat. Hist., Bull., vol. 23, 1907, pp. 213-214. So. Dak.
Leporidae.
Lepus primigenius Matthew. Am. Mus. Nat. Hist., Bull., vol. 23, 1907, p. 216. So. Dak.
Lepus macrocephalus Matthew. Am. Mus. Nat. Hist., vol. 23, 1907, pp. 214-216. So. Dak.
Perissodactyla.
Rhinocerotidae.
Diceratherium cooki Peterson. Science, vol. 24, 1906, pp. 282-283. Nw. Neb.
Diceratherium niobrarense Peterson. Science, vol. 24, 1906, pp. 281-282. Nw. Neb.
Diceratherium arikarense Barbour.
Diceratherium petersoni Loomis.
Diceratherium schiffi Loomis.
Metacaenopus egregius Cook. Neb. Geol. Surv., vol. 3, pp. 245-247. Nw. Neb.
Metacaenopus stigeri Loomis.
Epaiphelops virgasectus Cook.
1908, pp. 245-247. Nw. Neb.
Chalicotheridae.
Moropus? elatus Marsh. Am. Jour., Sci., vol. 14, 1877, pp. 250-251. So. Dak.
Moropus cooki Barbour. Neb. Geol. Surv., vol. 3, 1908, (Considered by Holland and Peterson as Moropus elatus). Nw. Neb.
Moropus petersoni Holland. Science, vol. 28, 1908, p. 810. Nw. Neb.
Moropus hollandi Peterson. Science, vol. 38, 1913, p. 673. Nw. Neb.
Moropus matthewi Holland and Peterson. Carnegie Mus., Mem., vol. 3, 1914, pp. 230-231. Ne. Colo.
Moropus parvus Barbour.
Equidae.
Miohippus equinanus Osborn. Am. Mus. Nat. Hist., Mem., vol. 2, pt. 1 (new series), 1918, pp. 65-66. So. Dak.
Miohippus gemmarosae Osborn. Am. Mus. Nat. Hist., Mem. vol. 2, pt. 1 (new series), 1918, pp. 66-68. So. Dak.
Parahippus pristinus Osborn. Am. Mus. Nat. Hist., Men. vol. 2, pt. 1 (new series), 1918, pp. 76-77. So. Dak.
Parahippus pawniensis atavus Osborn. Am. Mus. Nat. Hist., Mem. vol. 2, pt. 1 (new series), 1918, pp. 79-80. Nw. Neb.
Parahippus nebrascensis primus Osborn. Am. Mus. Nat. Hist., Mem. vol. 2, pt. 1 (new series), 1918, pp. 80-82. Nw. Neb.
Parahippus aff crenidens Scott.

Parahippus nebrascensis Peterson. Carnegie Mus. Ann., vol. 4, 1908, pp. 57-60. Nw. Neb.

Parahippus tyleri Loomis. Am. Jour. Sci., vol. 26, 1908, pp. 163-164. Nw. Neb.

Kalobatippus agatensis Osborn. Am. Mus. Nat. Hist., Mem. vol. 2, pt. 1 (new series), 1918, pp. 71-73. Nw. Neb.

Proboscidea.

Gomphotherium conodon Cook. Am. Jour. Sci., vol. 28, 1909, pp. 183-184. Nw. Neb.

Artiodactyla.

Elotheridae, (Entelodontidae).

Dinohyus hollandi Peterson. Science, vol. 22, 1905, pp. 211-212.

Dicotylidae (Tagassuidae).

Desmathyus siouxensis (Peterson). Carnegie Mus., Mem., vol. 2, 1906, pp. 308-320, (Thinohyus). Nw. Neb.

Desmathyus pinensis Matthew. Am. Mus. Nat. Hist., Bull., vol. 23, 1907, pp. 217-218.

Anthracotheridae.

Ancondon (?Bothodon) leptodus Matthew. Am. Mus. Nat. Hist., Bull., vol. 26, pp. 1-7. So. Dak.

Oreodontidae, (Agriochoeridae).

Mesoreodon megalodon Peterson. Carnegie Mus. Ann., vol. 4, 1908, pp. 24-26. Nw. Neb.

Promerychochoerus carrikeri Peterson. Carnegie Mus., Ann., vol. 4, 1908, pp. 26-29. Nw. Neb.

Promerychochoerus vantasselensis Peterson. Carnegie Mus. Ann., vol. 4, 1908, pp. 36-37. Nw. Neb.

Phenacocoelus typus Peterson. Carnegie Mus., Ann., vol. 4, 1908, pp. 29-32. Nw. Neb.

"Merychyus elegans Leidy."

"Merychyus" harrisonensis Peterson. Carnegie Mus., Ann., vol. 4, 1908, pp. 37-40. Converse Co., Wyo.

Merychyus minimus Peterson. Carnegie Mus., Ann., vol. 4, 1908, pp. 41-44. Nw. Neb.

Leptauchenia decora Leidy. Acad. Nat. Sci., Phila., Proc., vol. 8, 1856, p. 88. So. Dak.

Leptauchenia major Leidy. Acad. Nat. Sci., Phila., Proc., vol. 8, 1856, pp. 163-164. Mauv. Terres.

Leptauchenia nitida Leidy. Acad. Nat. Sci., Phila., Jour., vol. 7, 1869, pp. 129-131. So. Dak.

Camelidae.

Stenomylus gracilis Peterson. Carnegie Mus., Ann., vol. 4, 1908, pp. 41-44. Nw. Neb.

Stenomylus hitchcocki Loomis. Am. Jour. Sci., vol. 29, 1910, pp. 298-318. Nw. Neb.

Stenomylus crassipes Loomis. Am. Jour. Sci., vol. 29, 1910, pp. 319-323. Nw. Neb.

Protomeryx halli Leidy. Acad. Nat. Sci., Phila., Proc., vol. 8, 1856, p. 164. So. Dak.

Protomeryx leonardi Loomis. Am. Jour. Sci., vol. 31, 1911, pp. 68-70. S. E. Wyo.

Protomeryx?cedrensis Matthew.

Oxydactylus longipes Peterson. Carnegie Mus., Ann., vol. 2, 1904, pp. 434-468. Nw. Neb.

Oxydactylus brachyceps eterson. Carnegie Mus., Ann., vol. 2, 1904, pp. 469-471, (brachyodontus). Nw. Neb.
Oxydactylus longirostris Peterson. Carnegie Mus., Ann., vol. 7, 1911, pp. 260-266. Nw. Neb.
Oxydactylus lulli Loomis. Am. Jour. Sci., vol. 31, 1911, pp. 66-68. S. E. Wyo.
Oxydactylus gibbi Loomis Am. Jour. Sci., vol. 31, 1911, pp. 67-68. S. E. Wyo.
Oxydactylus campestris Cook, Am. Nat., vol. 43, 1909, pp. 188-189.
Oxydactylus brachyodontus Peterson.

Hypertragulidae.
Syndyoceras cooki Barbour. Science, 1905, vol. 33, pp. 797-798.
Hypertragulus "calcaratus Cope."

Cervidae.
Blastomeryx advena Matthew. Am. Mus. Nat. Hist., Bull., vol. 23, 1907, p. 219. So. Dak.
Blastomeryx primus Matthew. Am. Mus. Nat. Hist., Bull., vol. 24, 1908, p. 543. So. Dak.
Blastomeryx olcotti Matthew. Am. Mus. Nat. Hist., Bull., vol. 24, 1908, p. 543. So. Dak.

## UPPER MIOCENE

Carnivora.
Canidae.
Aelurodon saevus (Leidy). Acad. Nat. Sci., Phila., Proc., 1858, p. 21. Nw. Neb.
Aelurodon haydeni (Leidy). Acad. Nat. Sci., Phila., Proc., 1858, p. 21. Nw. Neb.
Ischyrocyon hyaendus Matthew. Am. Mus. Nat. Hist., Bull., vol. 20, 1904, pp. 246-249. So. Dak.

Mustelidae.
Potamotherium lacota Matthew. Am. Mus. Nat. Hist., Bull., vol. 20, 1904, pp. 254-255. So. Dak.
Lutra pristina Matthew. Am. Mus. Nat. Hist., Bull., vol. 20, 1904, pp. 256-257. So. Dak.

Rodentia.
Castoridae.
Eucastor (Dipoides) tortus Leidy. Acad. Nat. Sci., Phila., Proc., 1858, p. 23. Nw. Neb.
Mylagaulidae.
Mylagaulus monodon Cope.

Perissodactyla.
Rhinocerotidae.
?Aphelops brachyodus Osborn. Am. Mus. Nat. Hist., Bull., vol. 20, 1904, p. 322. So. Dak.

Equidae.
Hypohippus affinis Leidy. Acad. Nat. Sci., Phila., Proc., 1858, p. 26. Nw. Neb.
Protohippus perditus Leidy. Acad. Nat. Sci., Phila., Proc., 1858, p. 26. Nw. Neb.
Protohippus placidus Leidy. Acad. Nat. Sci., Phila., Jour., vol. 7, 1869, pp. 277-279. Nw. Neb.

Protohippus supremus Leidy. Acad. Nat. Sci., Phila., Jour., vol. 7, 1869, p. 328. Nw. Neb.
Protohippus pernix (Marsh). Am. Jour. Sci., vol. 7, 1874, pp. 252-253. Nw. Neb.
Protohippus simus Gidley. Am. Mus. Nat. Hist., Bull., vol. 22, 1906, pp. 139-140.
Neohipparion whitneyi Gidley. Am. Mus. Nat. Hist., Bull., vol. 19, 1903, pp. 467-476. So. Dak.
Neohipparion occidentale (Leidy). Acad. Nat. Sci., Phila., Proc., vol. 8, 1856, p. 59, (Hipparion). So. Dak.
Neohipparion dolichops Gidley. Am. Mus. Nat. Hist., Bull., vol. 22, 1906, pp. 148-151. So. Dak.

Artiodactyla.
Dicotylidae (Tagassuidae).
Prosthemnops crassigenis Gidley. Am. Mus. Nat. Hist., Bull., vol. 20, 1904, pp. 265-267. So. Dak.
Camelidae.
Procamelus occidentalis Leidy. Acad. Nat. Sci., Phila., Proc., 1858, pp. 23-24. Nw. Neb.
Procamelus robustus Leidy. Acad. Nat. Sci., Phila., Proc., 1858, p. 89. Nw. Neb.
Cervidae.
Blastomeryx wellsi Matthew. Am. Mus. Nat. Hist., Bull., vol. 20, 1904, pp. 125-126. So. Dak.
Blastomeryx marshi Lull. Am. Jour., Sci., vol. 50. 1920, pp. 125-130. Nw. Neb.
Aletomeryx gracilis Lull. Am. Jour. Sci., vol. 50, 1920. pp. 85-124. Nw. Neb.

## PLIOCENE*

Perissodactyla.
Equidae.
Pliohippus lullianus Troxell. Am. Jour. Sci., vol. 24, 1916, pp. 335-348. So. Dak.
Pliohippus pernix Marsh. Am. Jour. Sci., vol. 7, 1874, pp. 252-253. Nw. Neb.
Pliohippus robustus Marsh. Am. Jour. Sci., vol. 7, 1874, p. 253. Nw. Neb.
Pliohippus leidyanus Osborn. Am. Mus. Nat. Hist., Mem., vol. 2, pt. 1 (new series), 1918, p. 162. Nw. Neb.

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*For a faunal list of beds of this age found in Southern Sioux County, Nebraska, see: Matthew, W. D. and Cook, H. J. A Pliocene Fauna from Western Nebraska. Am. Mus. Nat. Hist., Bull., vol. 26, pp. 361-414, 1909.

# A List of Fossil Vertebrates Other Than Mammals Found in the White River Badlands.

## TURTLES*

### LOWER OLIGOCENE

Graptemys inornata Loomis. Am. Jour. Sci., vol. 18, 1904, p. 429. So. Dak.

Testudo brontops Marsh. Am. Jour. Sci., vol. 40, 1890, p. 179. So. Dak.

Xenochelys formosa Hay. Am. Mus. Nat. Hist., Bull., vol. 22, 1906, p. 29. So. Dak.

### MIDDLE AND UPPER OLIGOCENE

Stylemys nebrascensis Leidy Acad. Nat. Sci., Phila., Proc., vol. 5, 1851, p. 172. So. Dak.

Testudo laticunea Cope.

Testudo thomsoni Hay. Hay's Fossil Turtles of North America, 1908, pp. 400-401. So. Dak.

### LOWER MIOCENE

Testudo arenivaga Hay. Carnegie Mus. Ann., vol. 4, 1906, pp. 16-17, Nw. Neb.

Testudo emiliae Hay. Hay's Fossil Turtles of North America, 1908, pp. 419-420. So. Dak.

### UPPER MIOCENE

Testudo edae Hay. Carnegie Mus., Ann., vol. 4, 1906, p. 19. Nw. Neb.

Testudo hollandi Hay. Carnegie Mus., Ann., vol. 4, 1906, p. 18. Nw. Neb.

Testudo niobrarensis Leidy. Acad. Nat. Sci., Phila., Proc., 1858, p. 29, Nw. Neb.

## LIZARDS

Aciprion formosum Cope.

Rhineura hatcheri Bauer. Am. Nat., vol. 27, 1893, p. 998.

Hyporhina antigua Bauer. Am. Nat., vol. 27, 1893, p. 998.

## CROCODILES

Crocodilus prenasalis Loomis. Am. Jour. Sci., vol. 18, 1904, pp. 427-429. L. Olig. of So. Dak.

Caimanoidea visheri Mehl Jour. Geol., vol. 24, 1916, pp. 47-56. So. Dak.

## BIRDS

Birds egg (Anatidae?) Farrington. Field Mus., Geol. Ser., vol. 1, 1899, pp. 193-200. L. Olig. of So. Dak.

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*The nomenclature here given for the turtles is that of O. P. Hay in his work, The Fossil Turtles of North America, 1908.

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# INDEX*

*The plates are not indexed.

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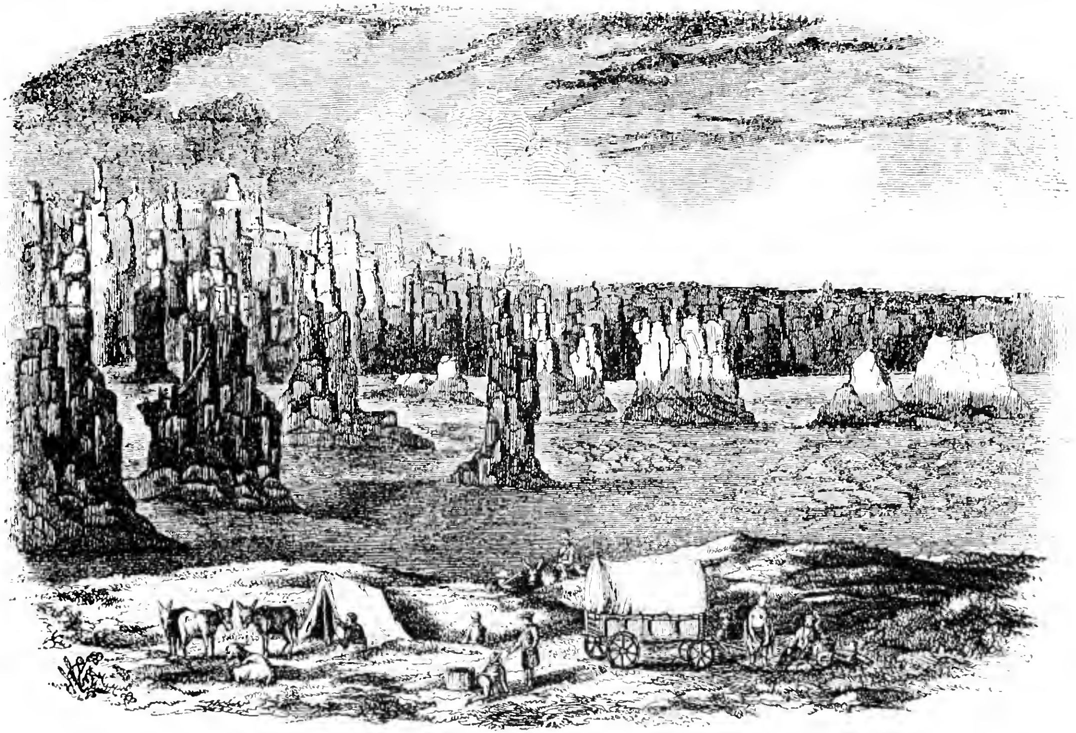
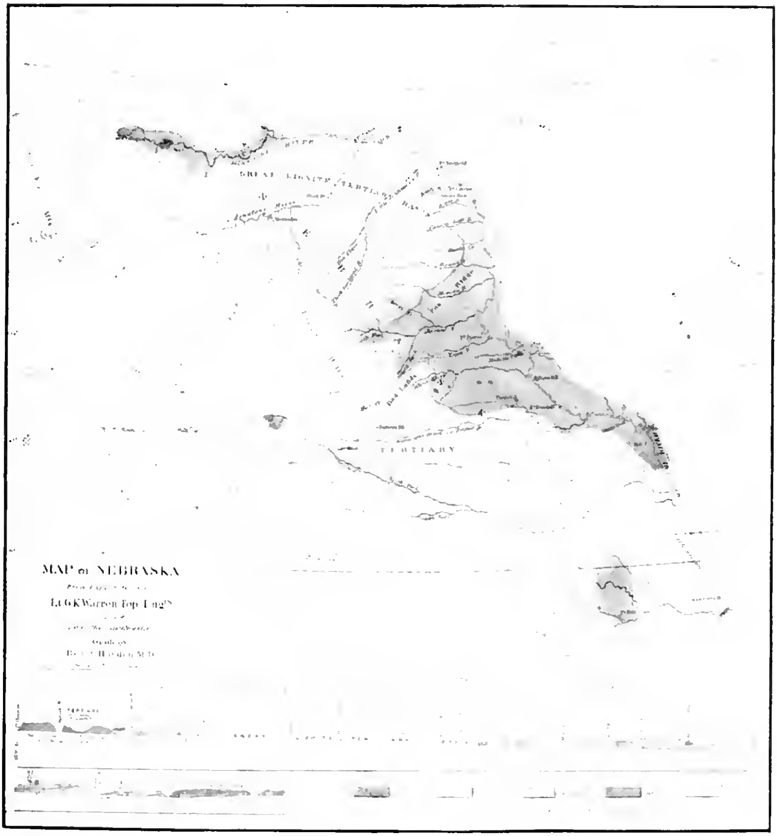
# PLATES

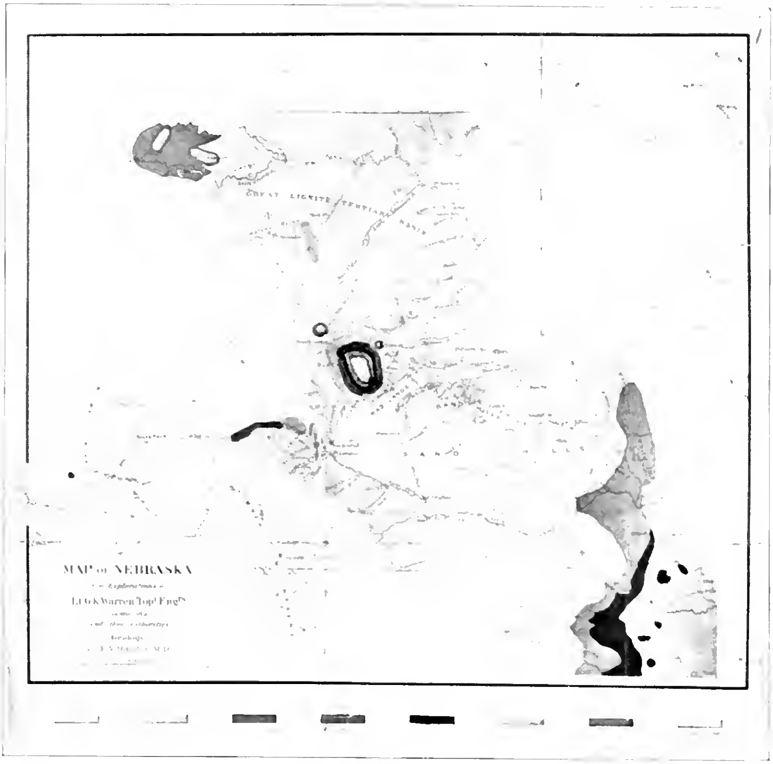


Earliest published view of the White River Badlands, Sketched by Dr. John Evans in the field, 1849. Owen Geolog. Survey, 1852.

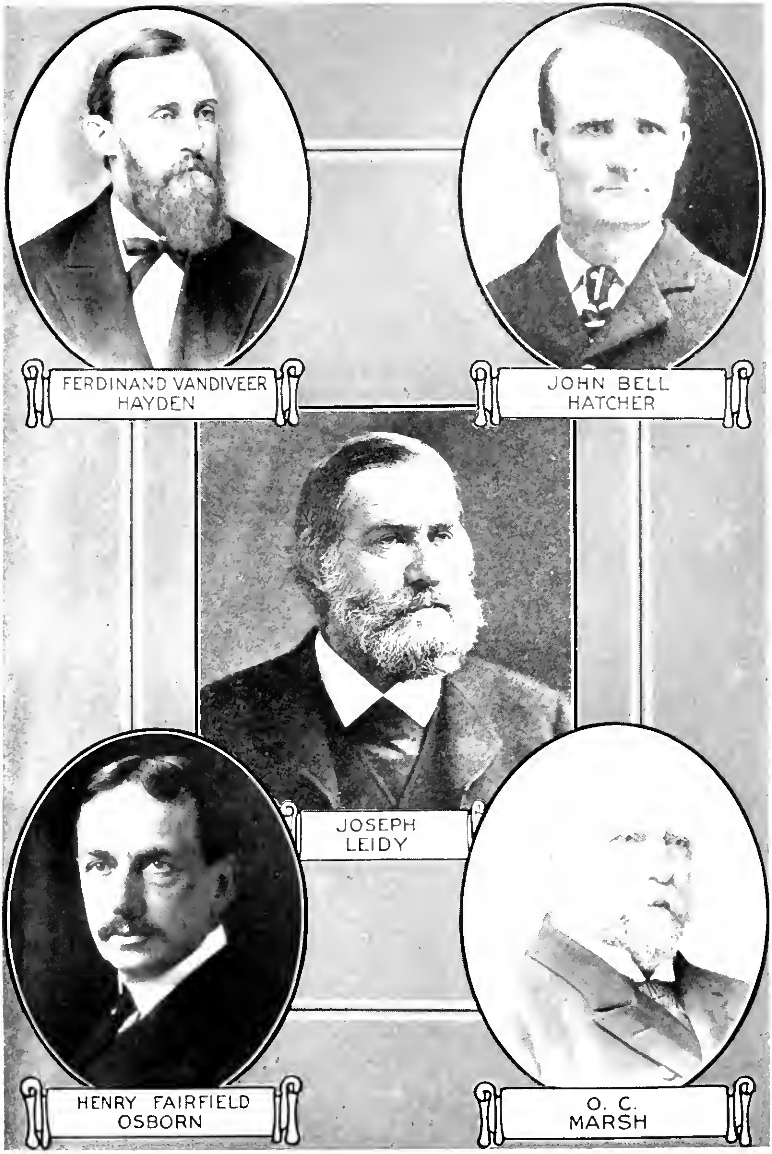
Reproduction of one of the early views of the Big Badlands by Dr. F. V. Hayden, Am. Nat., 1882.



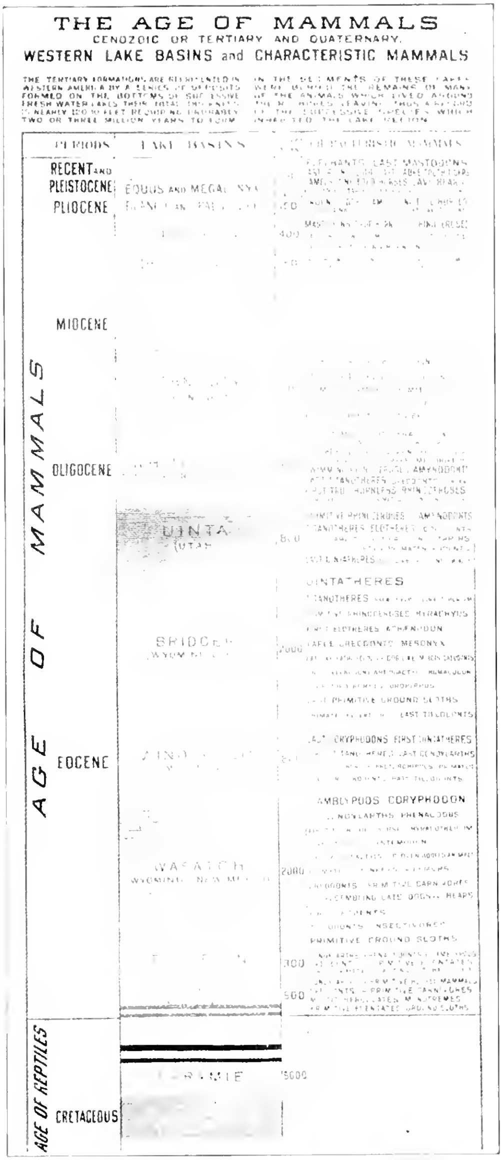
Reproduction of Hayden's Earliest Geological Map of the Upper Missouri country. The original map is colored to show the several rock divisions as then known. Note the erroneous extension of the Black Hills to the Yellowstone river, Hayden, 1857.



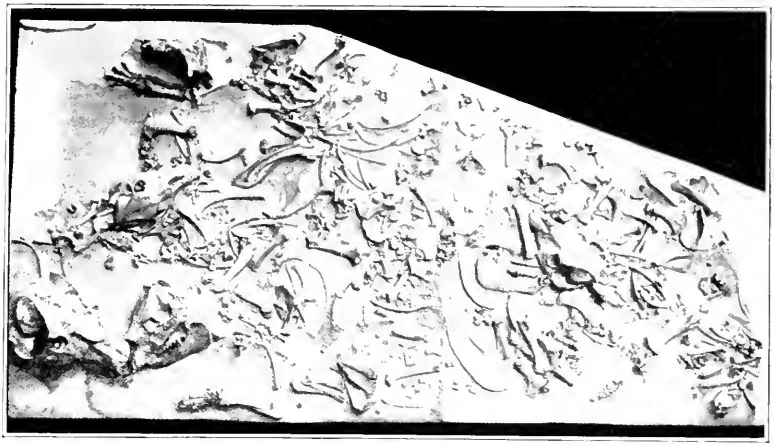
Reproduction of Hayden's second Geological Map of the Upper Missouri country. This map is the first ever published showing any details of the geology of the Black Hills. The geology of the surrounding country, including the Badlands, is more fully indicated than in Hayden's earlier map. Hayden, 1858.



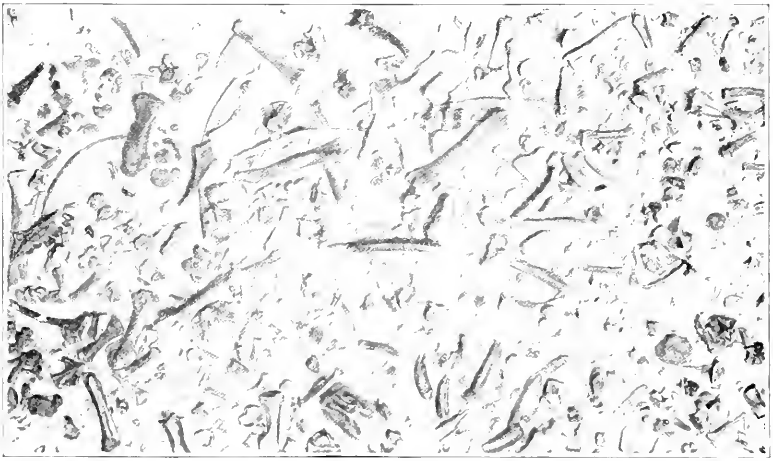
Some of the men who have done noteworthy work in unravelling the history of the White River Badlands. For description of their work see the text pages.



Divisions of the Age of Mammals. Characteristic fossil mammals, and the geological formations in which they are found. Matthew, 1903.

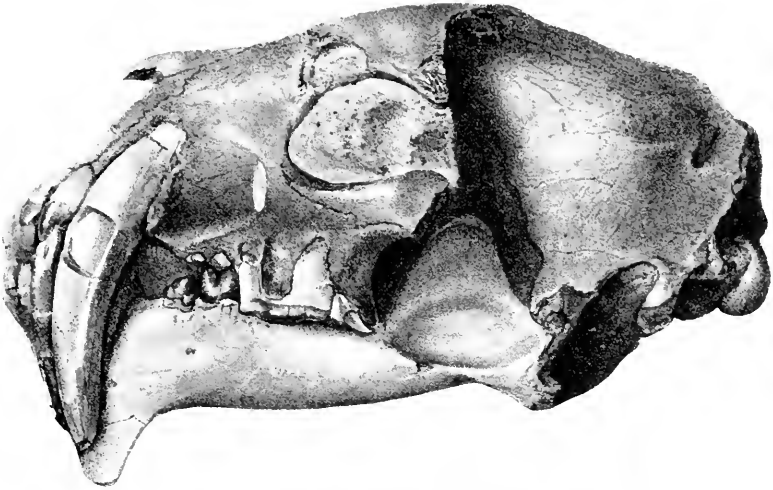


A. Matrix contains skeletons of one adult and four young individuals of *Merycochoerus proprius*. Matthew, 1901.

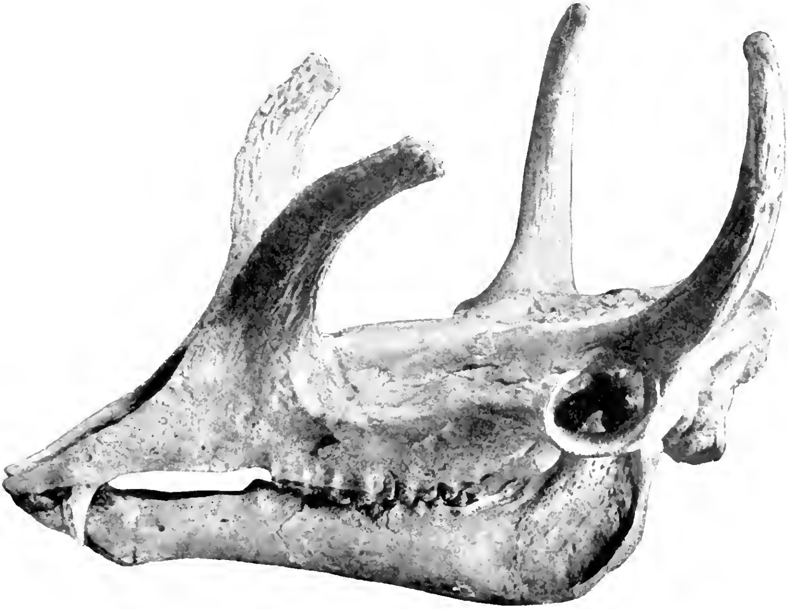


B. Bones are chiefly those of *Diceratherium*, *Moropus*, *Dinohyus*, and *Dinocyon*. Barbour, 1909.

Rock slabs showing abundance and arrangement of fossil bones as found in the quarry and indicating some of the difficulties of restoration.



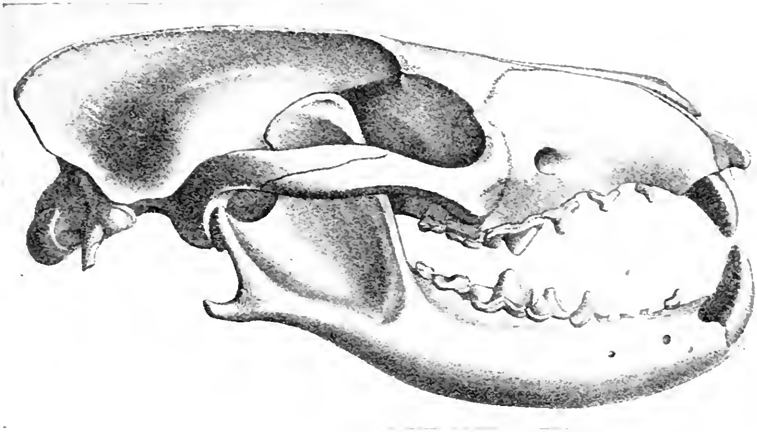
A. Head of *Hoplophoneus primaevus.* Leidy 1869.



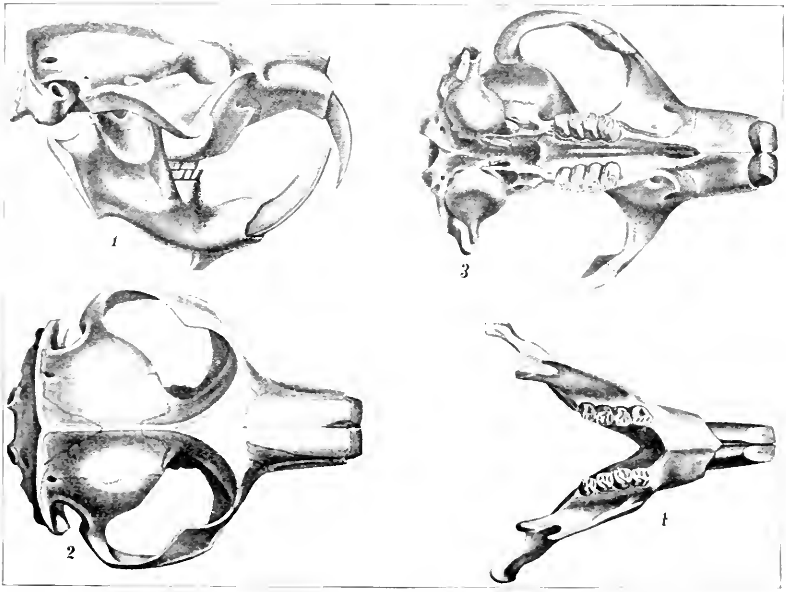
B. Head of *Syndyoceras Cooki.* Barbour. 1905.

A. Restoration of head of the Titanothere Megacerops. Lull, 1905.

B. Outline restoration of head of the Saber-tooth tiger, *Smilodon*, to show the wide open jaw and the opportunity the animal had of using the great canine fangs for stabbing and ripping its prey. Matthew, 1905.

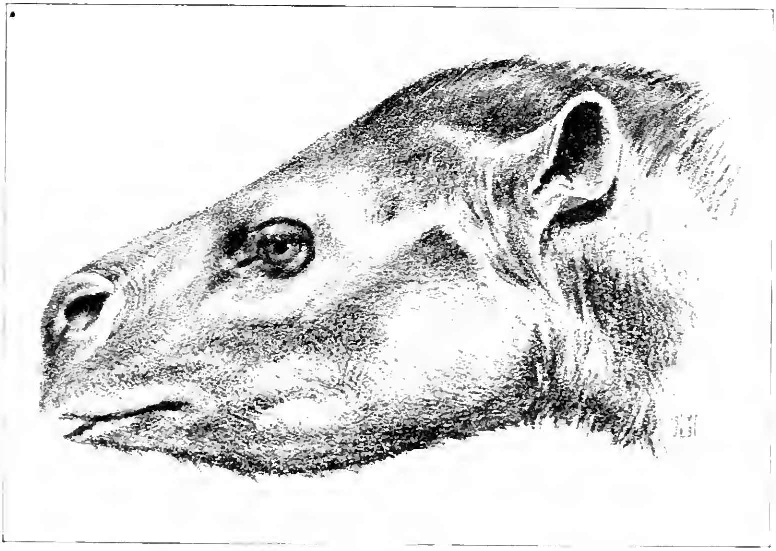


A. Head of *Daphoenus felinus*. Hatcher, 1902.

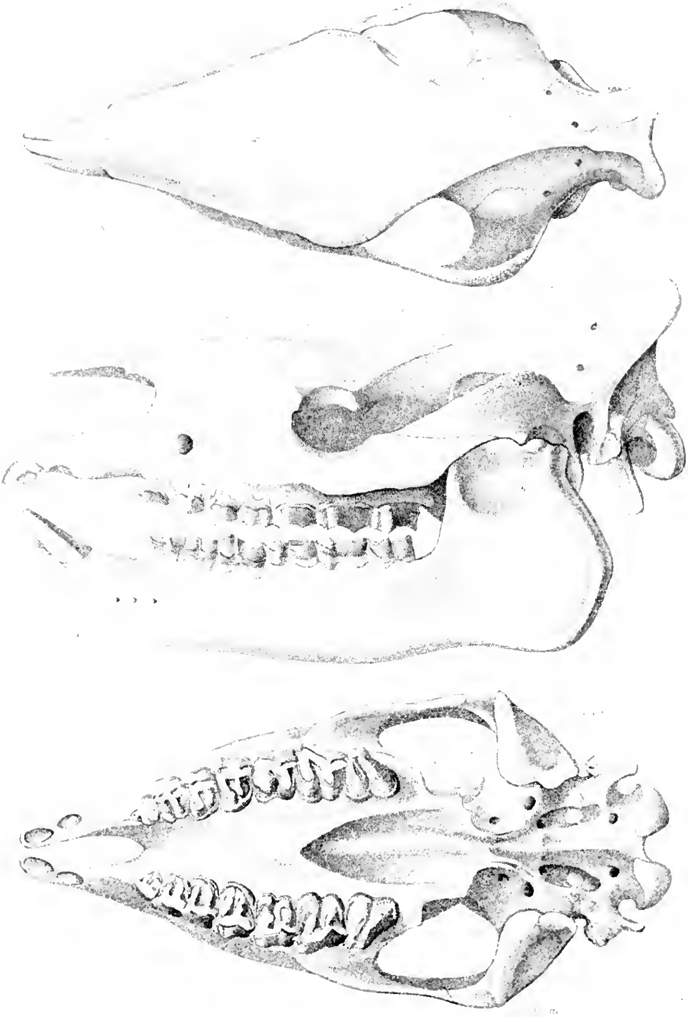


B. Fossil rodents from the Harrison Beds. (Upper Miocene). Peterson, 1905.

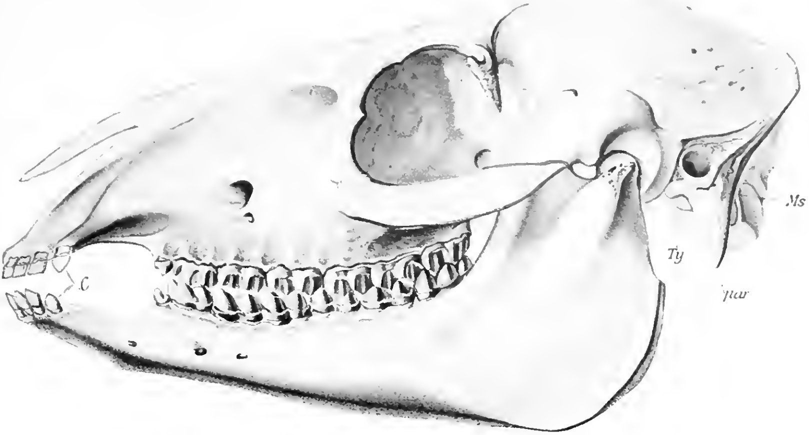
A. Head of *Hyrocodon nebrascensis.* An oligocene rhinoceros. Scott, 1896.



B. Head of the White River tapir, *Protapirus validus.* Restored from a skull in the museum of Princeton University. W. B. Scott, A History of Land Mammals in the Western Hemisphere, 1913. Published by the Macmillan Company. Reprinted by permission.

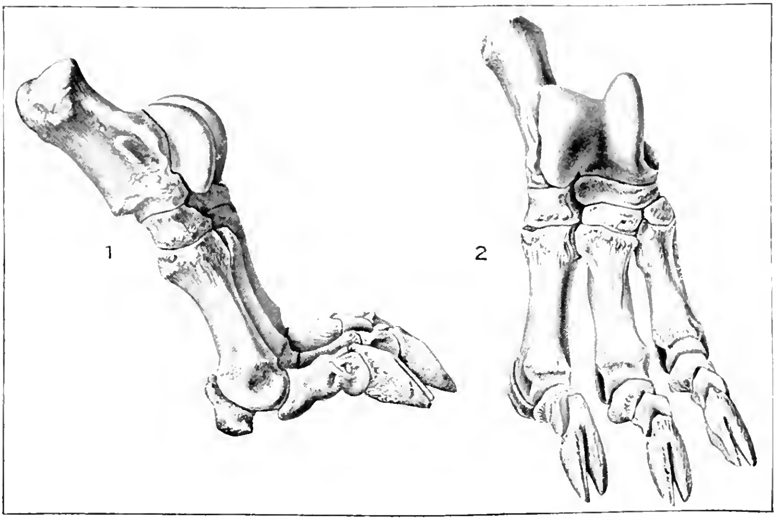


Skull of White River rhinoceros, *Caenopus (Aceratherium) occidentalis.* Upper view, side view, and palatal view. Osborn, 1898.

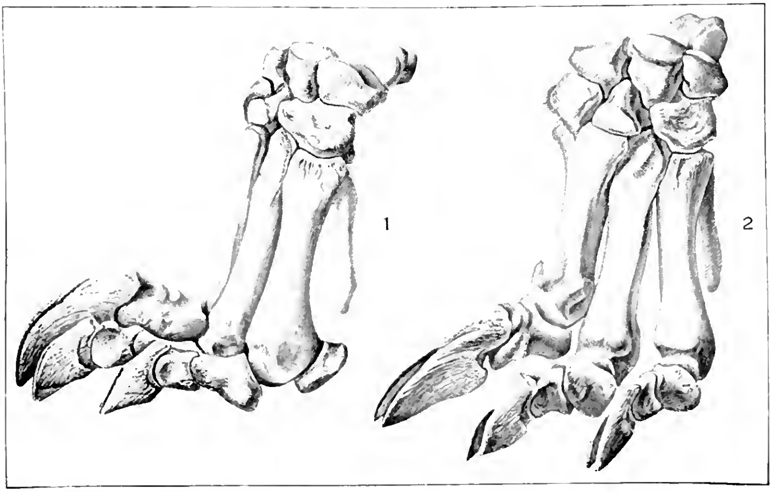


A. Head of *Mesohippus bairdi*. Scott, 1891.

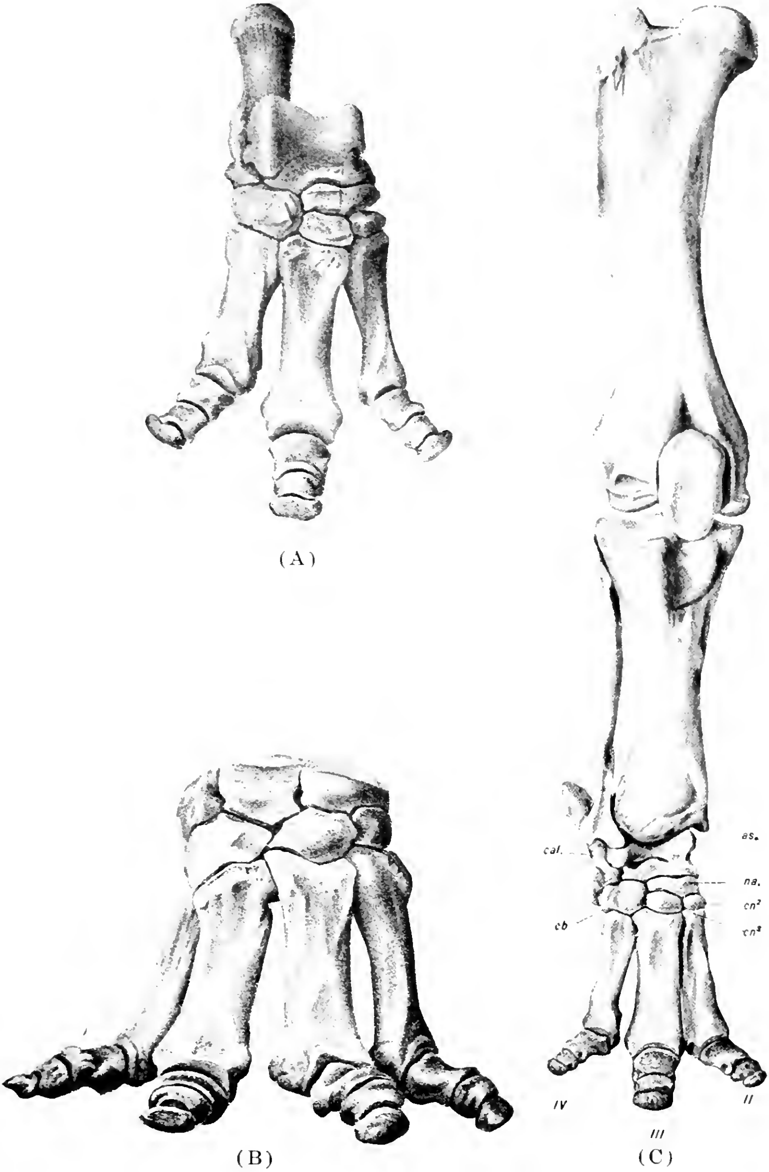
B. Head of the Oligocene three toed horse, *Mesohippus bairdi* compared with that of the present day horse *Equus caballus*.



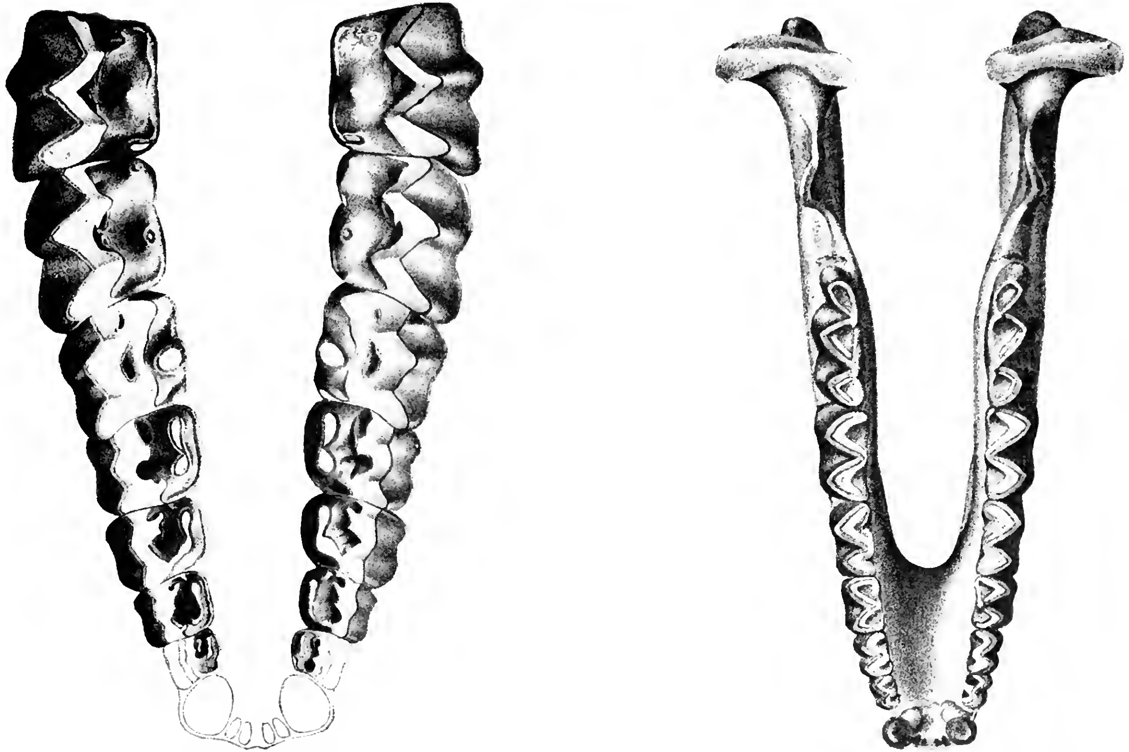
A. Right hind foot of *Moropus elatus* 1. External view. 2. Anterior view. Holland and Peterson, 1914.



B. Fore foot of *Moropus elatus*. 1. Ulnar view. 2. Anterior view. Holland and Peterson, 1914.



A. Right hind foot of Titanothere, Marsh, 1876.
B. Right fore foot of Titanothere, Marsh, 1876.
C. Right hind limb of Titanothere (Megacerops), Lull, 1905.

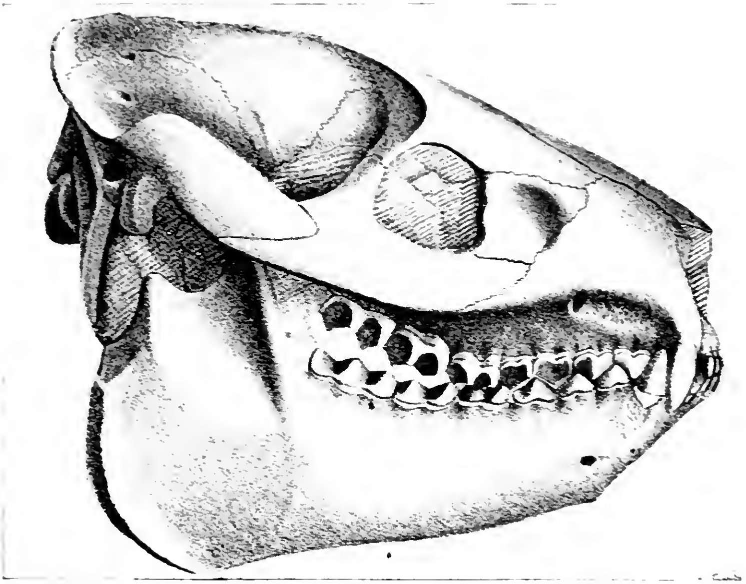


A. Upper teeth of Titanothere. Marsh, 1876.

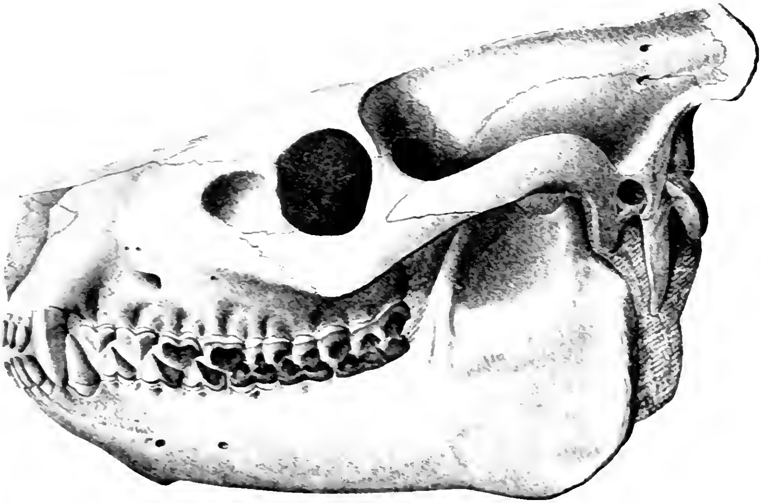
B. Lower jaw of Titanothere. Marsh, 1876

Both figures much reduced. B is reduced more than A.

Skull of *Titanotherium ingens* viewed from above. The anterior end is toward the top of the plate. Marsh, 1874.



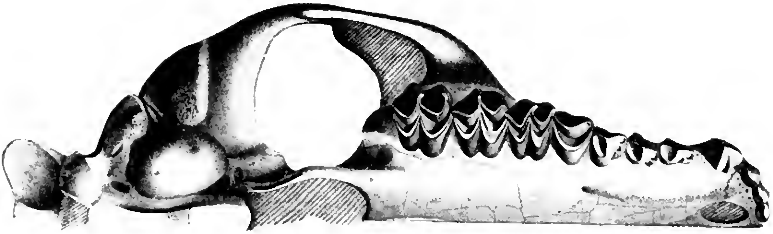
A. Head of *Merycoidodon (Oreodon) gracile.* Leidy. 1869.



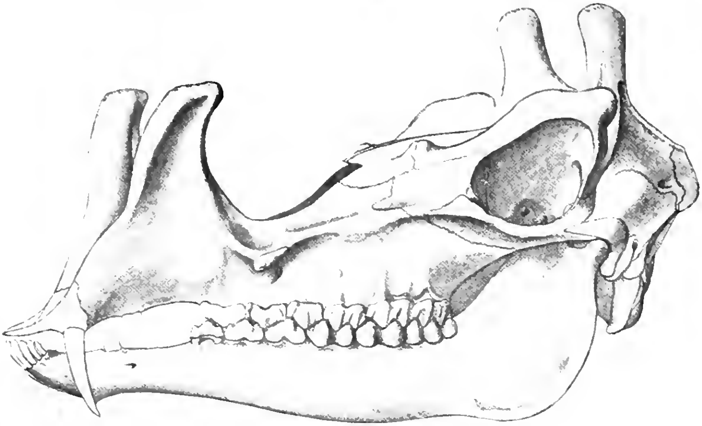
B. Head of *Merycoidodon (Oreodon) culbertsoni.* Leidy. 1869.

A. Skull of *Eporeodon major.* Leidy, 1869.

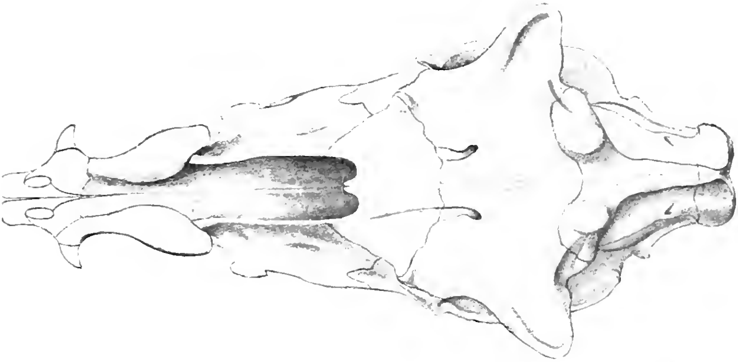
B. Left half of skull of *Eporeodon major*, as seen from above. Leidy, 1869.



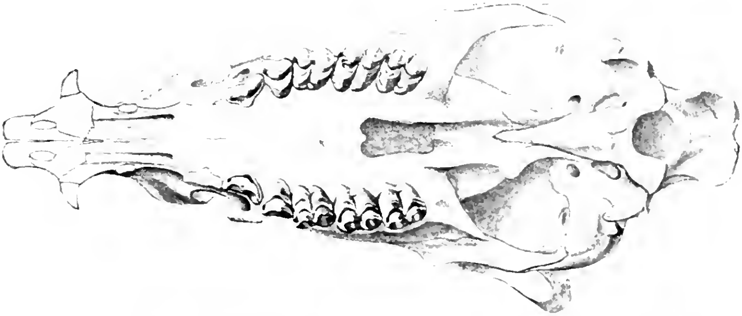
C. Right half of skull of *Eporeodon major*, as seen from below. Leidy, 1869.



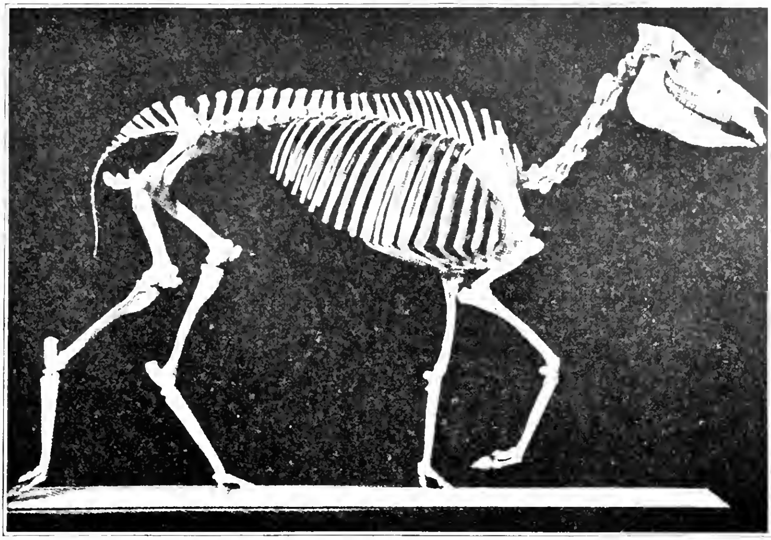
A. Head of *Protoceras celer.* Marsh, 1897.



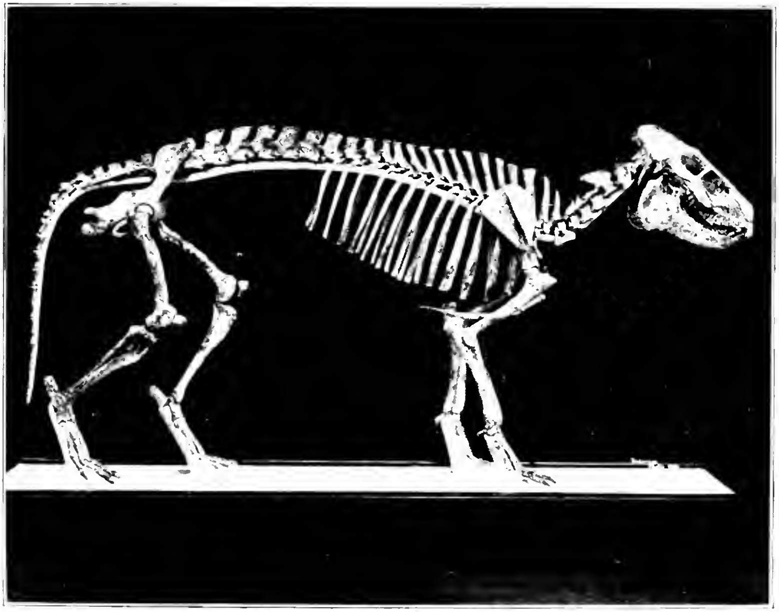
B. Skull of *Protoceras celer* as seen from above. Marsh, 1897.



C. Skull of *Protoceras celer* as seen from below. Marsh, 1897.



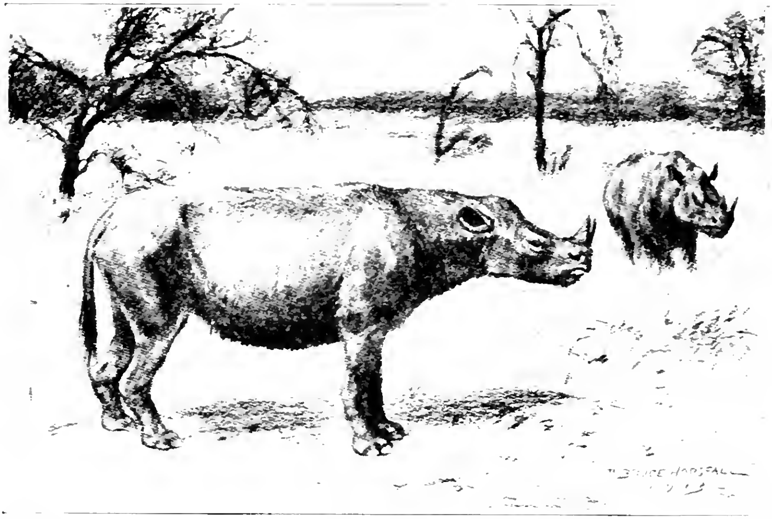
A. Skeleton of the Upper Miocene three toed horse *Neohipparion whitneyi*. Osborn. Copyrighted by the American Museum of Natural History. Reprinted by permission.



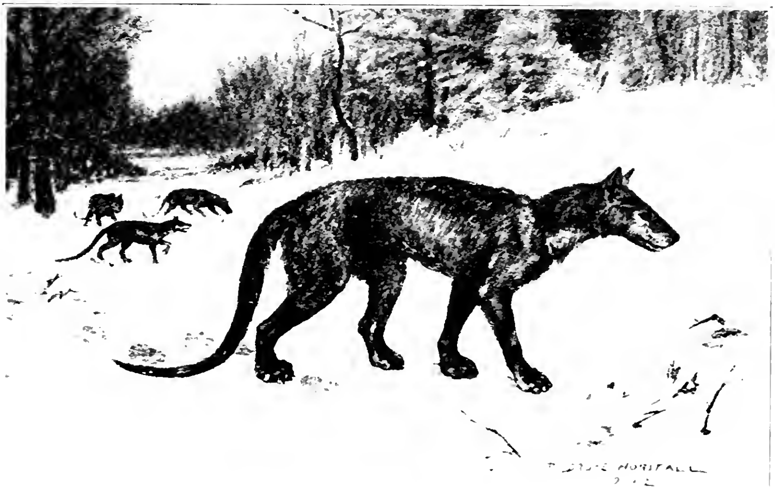
B. Skeleton of the primitive antiodactyl *Merycoidodon (Oreodon) culbertsoni* of the Oligocene. Osborn. Copyrighted by the American Museum of Natural History. Reprinted by permission.

A. Hyaenodon, a Creodont Carnivore of the Oligocene. H. R. Knipe, Nebula to Man, 1905. Published by J. M. Dent and Co., Reprinted by permission.

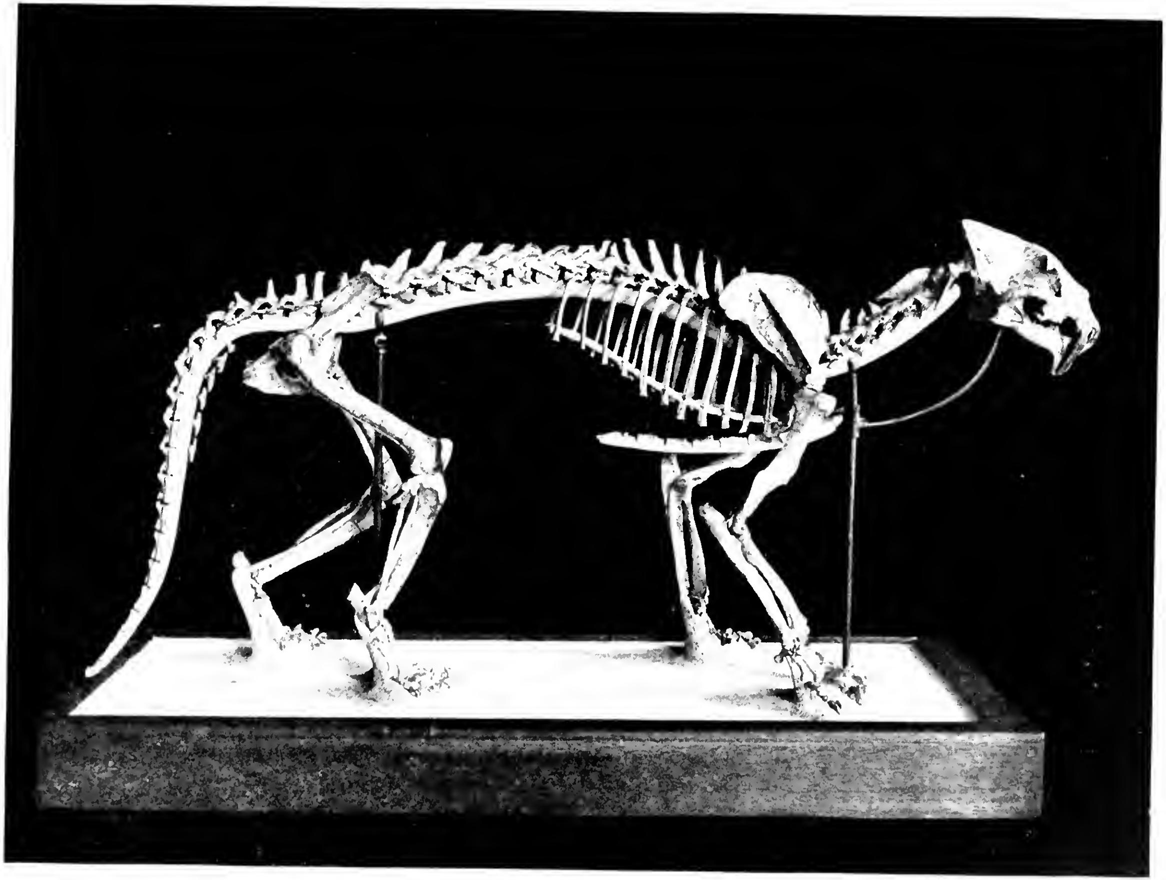
B. Restoration of animals of the Fayum, Egypt, approximately contemporaneous with those of the White River Badlands. Arsinoitherium attacked by the Creodont Pterodon. H. F. Osborn, The Age of Mammals in Europe, Asia and North America, 1910. Published by the Macmillan Company, Reprinted by permission.



A. The small paired-horned rhinoceros, *Diceratherium cooki* of the Lower Miocene. Restored from a skeleton in the Carnegie Museum, Pittsburgh. W. B. Scott. A History of Land Mammals in the Western Hemisphere, 1913. Published by The Macmillan Company. Reprinted by permission.



B. The Lower Miocene bear dog *Daphoenodon superbus*. Restored from a skeleton in the Carnegie Museum, Pittsburgh. W. B. Scott. A History of the Land Mammals in the Western Hemisphere, 1913. Published by The Macmillan Company. Reprinted by permission.



Skeleton of the early saber-tooth tiger *Hoplophoneus primaevus* of the Oligocene. Osborn. Copyrighted by the American Museum of Natural History. Reprinted by permission.

Restoration of the Oligocene saber-tooth tiger. *Hoplophoneus primaevus.* Osborn.
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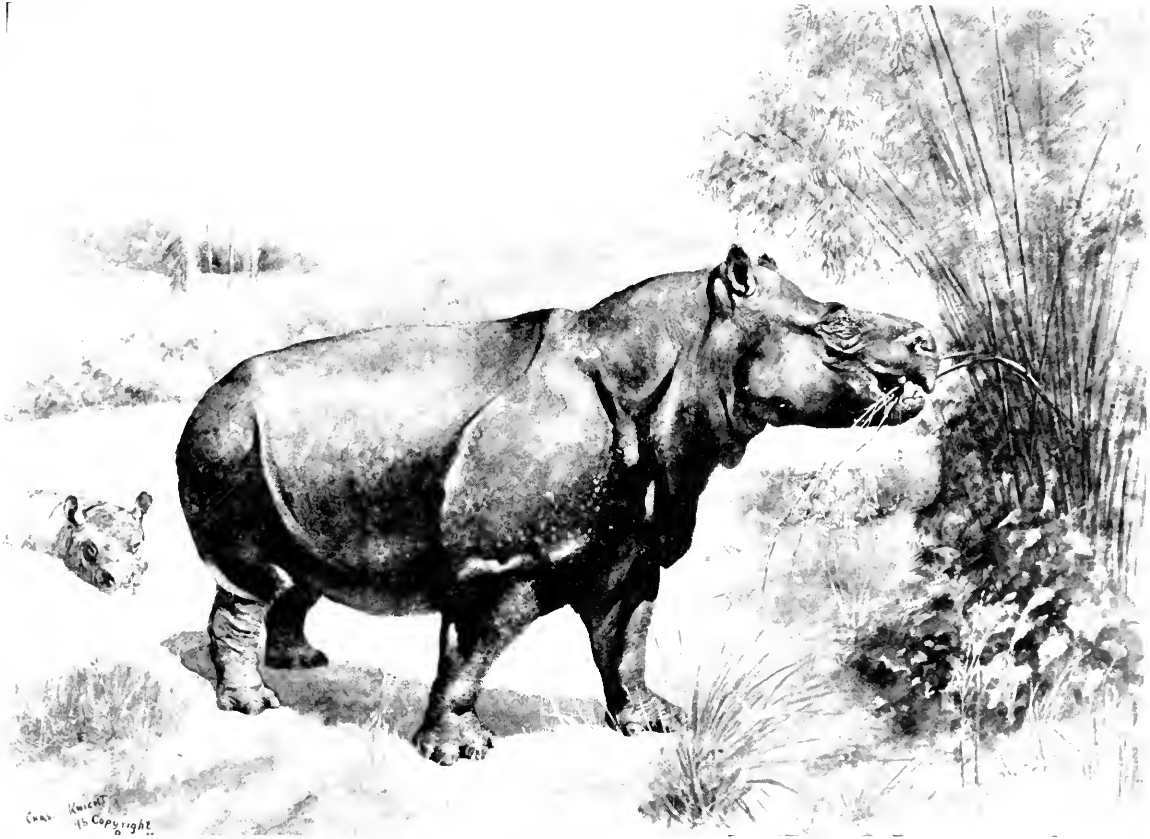

The Oligocene aquatic rhinoceros. *Metamynodon planifrons.* Osborn.
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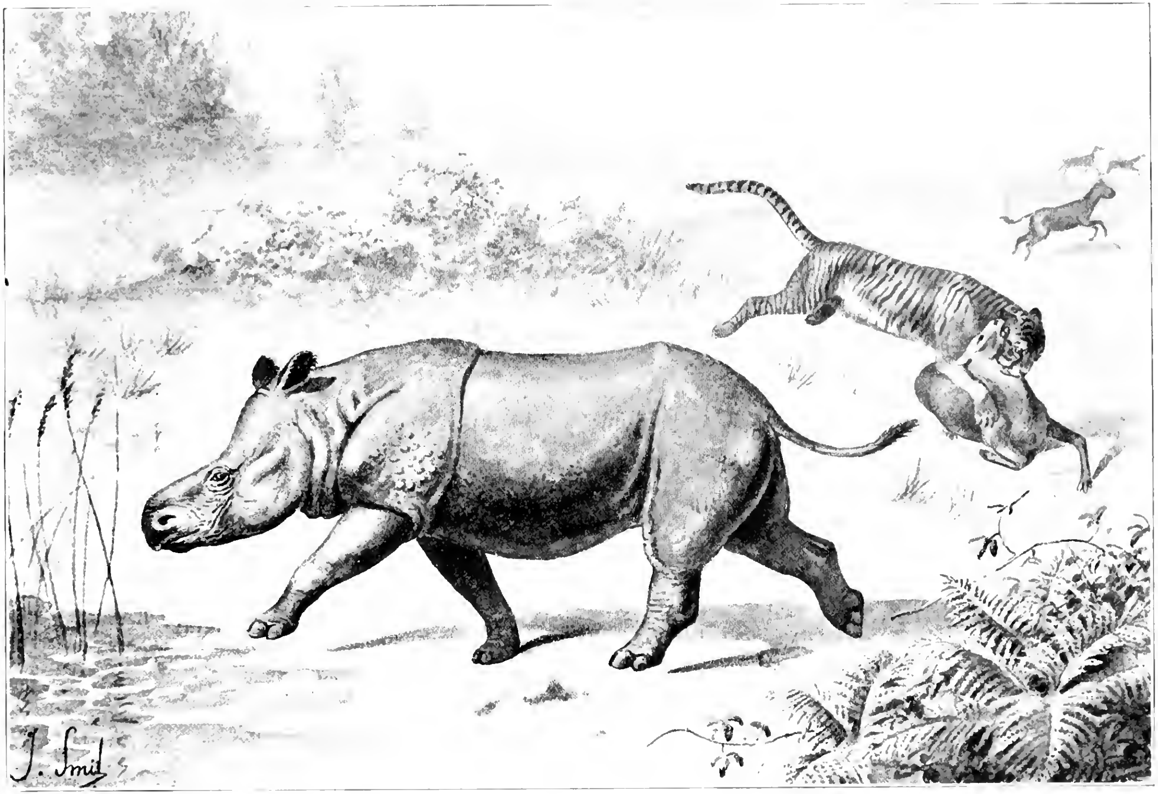
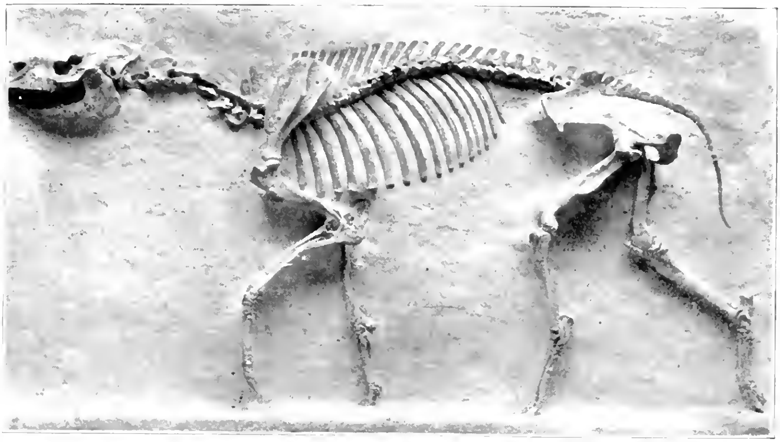
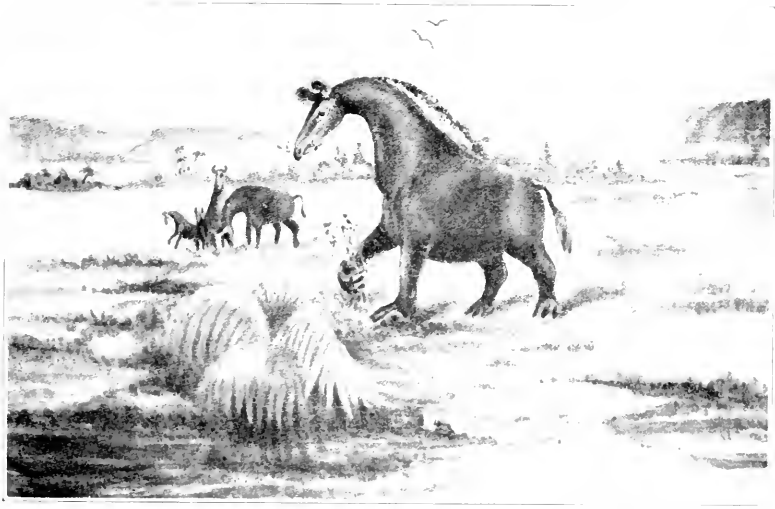


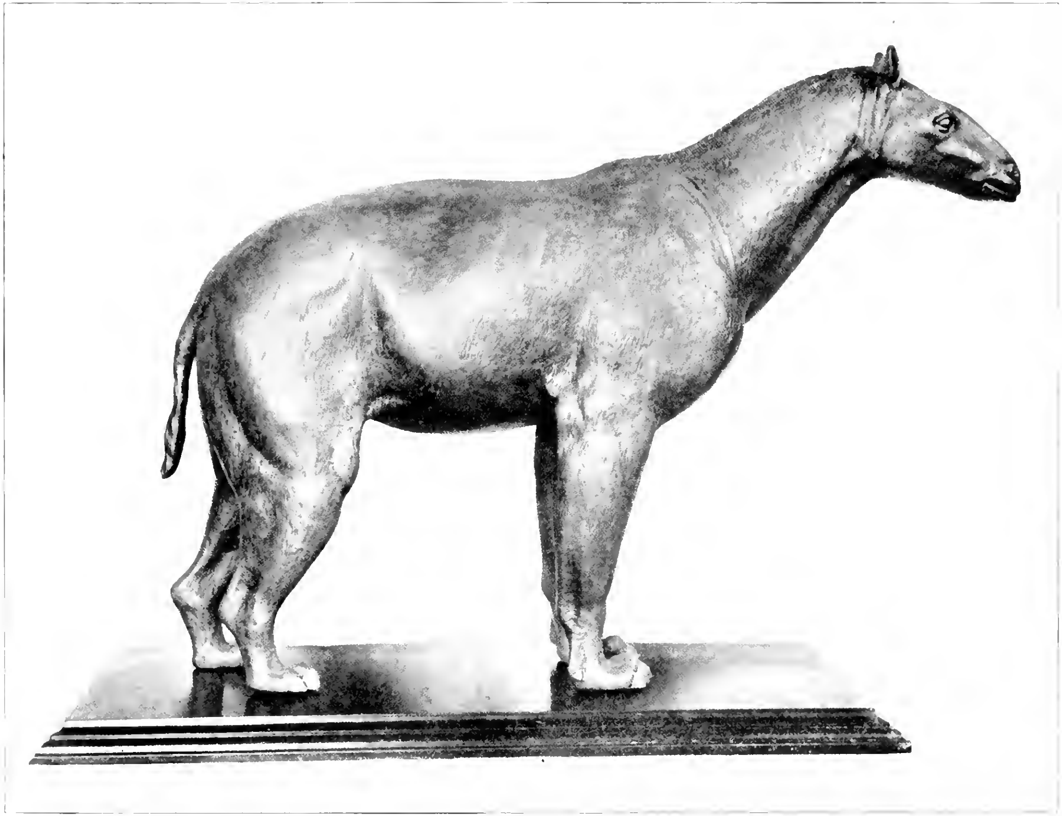
The aquatic rhinoceros, *Metamynodon* the smaller running rhinoceros, *Hyracodon* and the saber-tooth tiger *Dinictis*, all from the Oligocene. H. R. Knipe, Nebula to Man, 1905. Published by J. M. Dent and Co. Reprinted by permission.



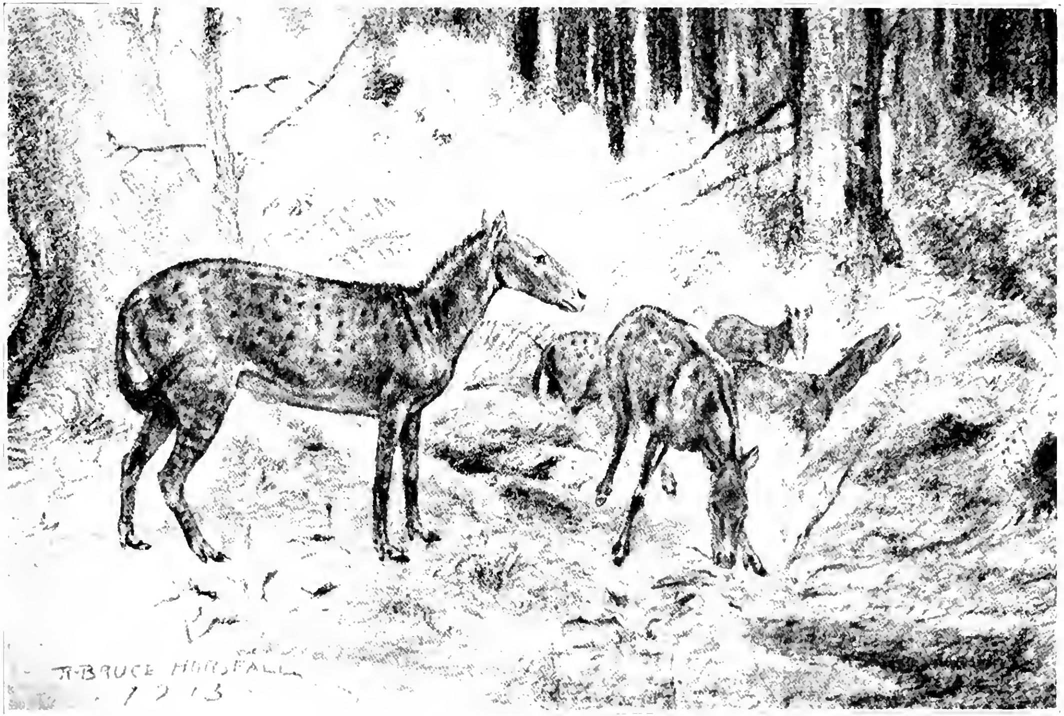
A. Skeleton of *Hyracodon nebrascensis.* Restoration in Museum of Princeton University. Sinclair. Head of same shown enlarged in Plate 14 A.



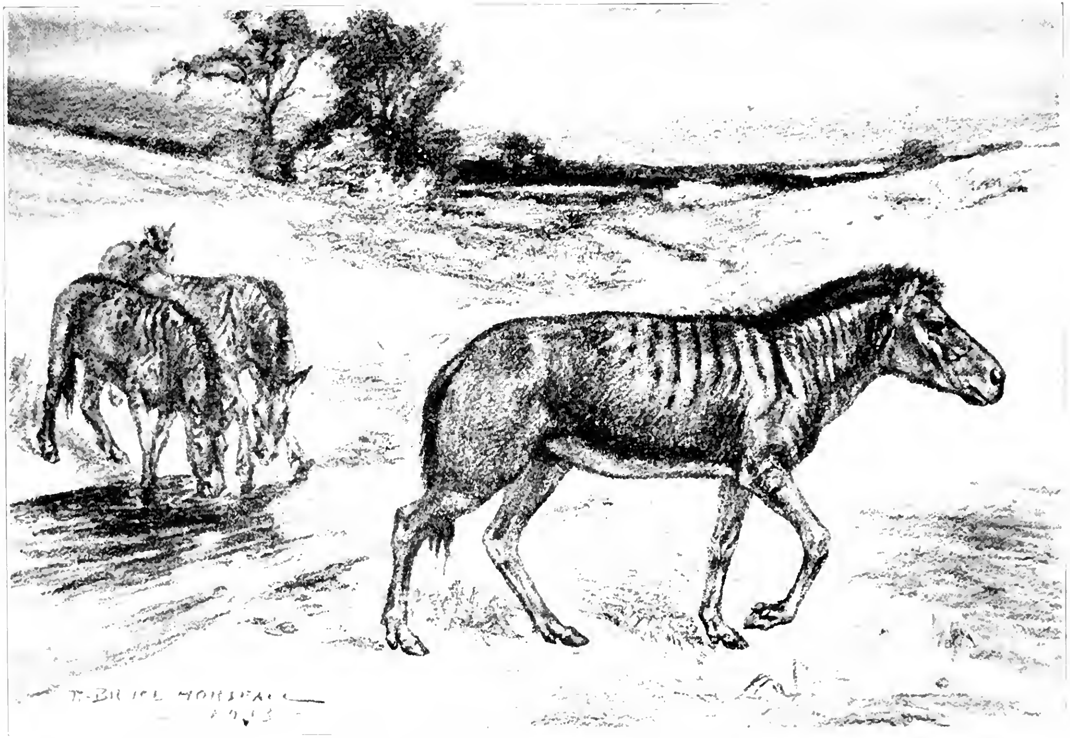
B. *Moropus cooki,* as restored by Barbour, 1909.



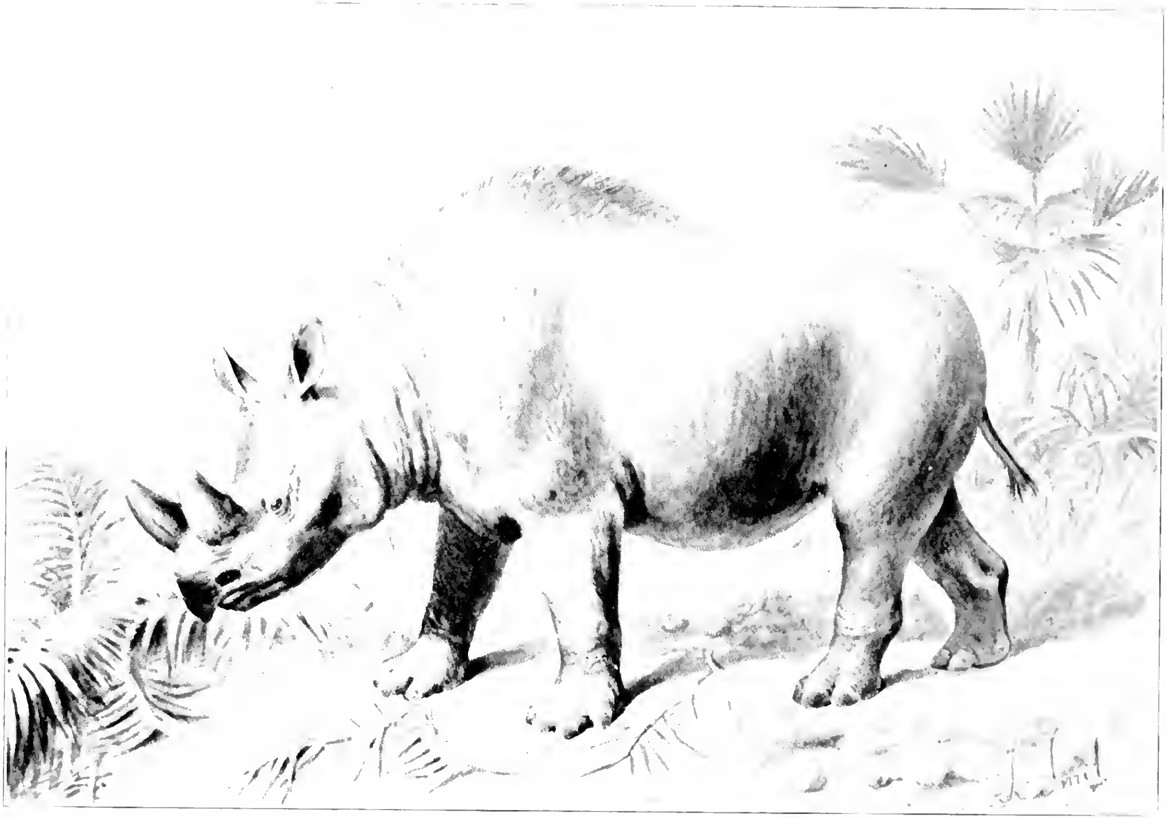
Model of *Moropus Elatus.* Holland and Peterson, 1914.



The small, browsing, three toed, short-necked horse, *Mesohippus bairdi* of the Oligocene. Restored from a skeleton in the American Museum of Natural History. W. B. Scott. A History of Land Mammals in the Western Hemisphere, 1913. Published by the Macmillan Company. Reprinted by permission.



The three-toed, grazing horse, *Neohipparion whitneyi* of the Upper Miocene. Restored from skeleton in the American Museum of Natural History. W. B. Scott. A History of Land Mammals in the Western Hemisphere, 1913. Published by The Macmillan Co. Reprinted by permission.



*Titanotherium* (*Brontops*) from the Oligocene. H. R. Knipe. Nebula to Man. 1905.
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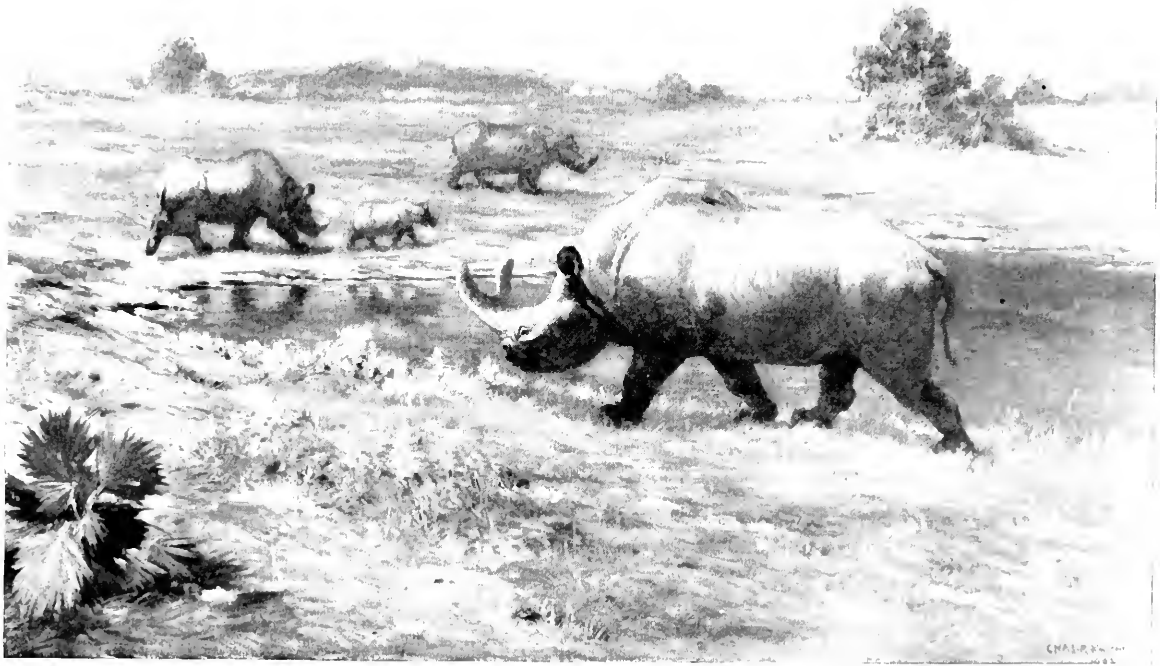
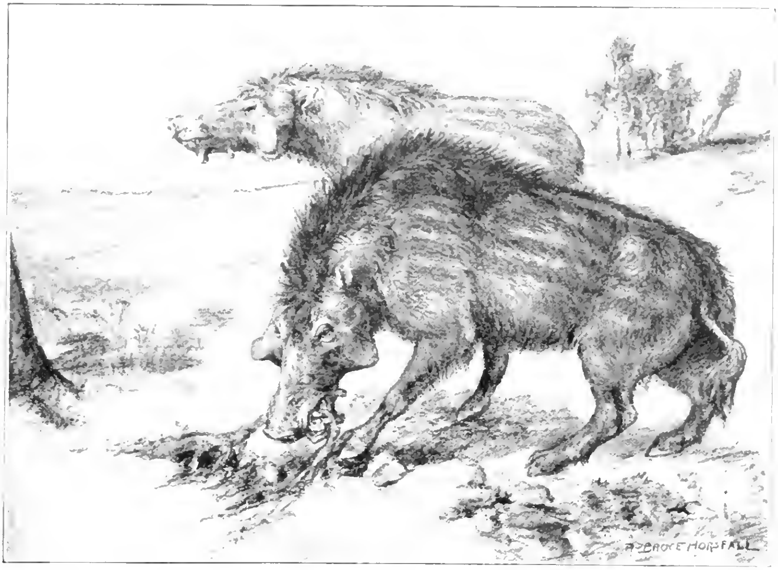
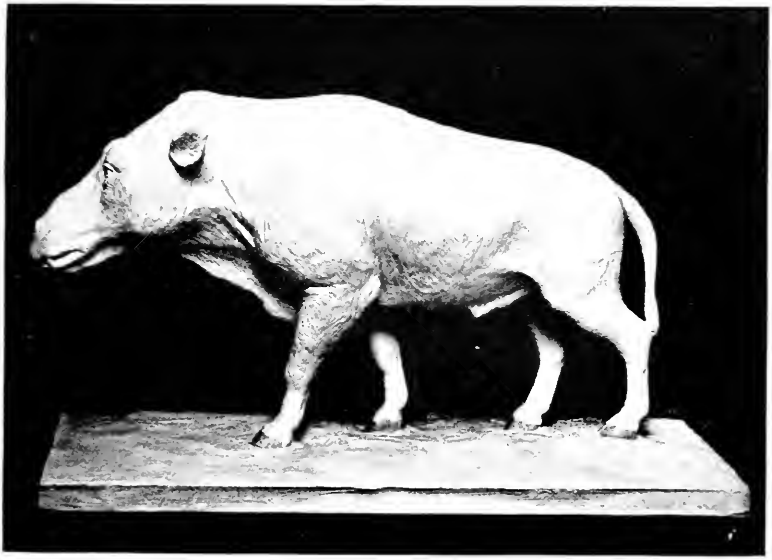


*Brontotherium gigas.* A flat-horned titanothere, the largest animal of the White River Badlands, Osborn. Copyrighted by the American Museum of Natural History. Reprinted by permission.

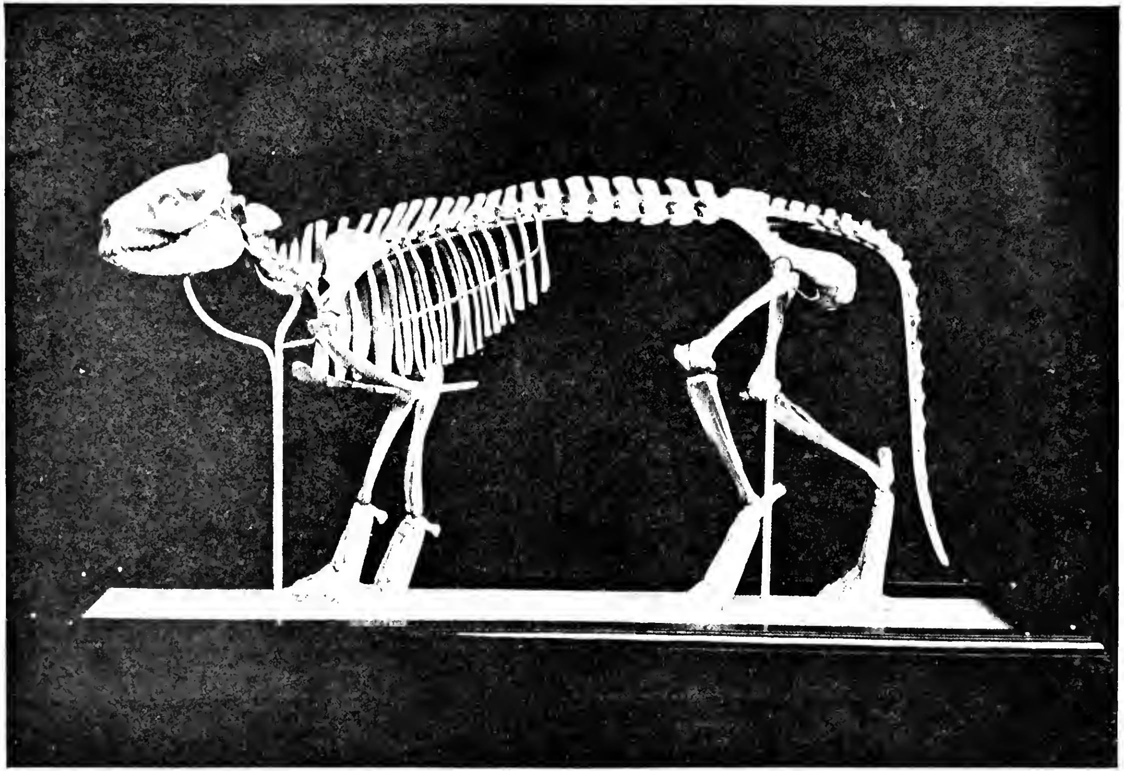


A. The giant pig *Archaeotherium ingens.* Restored from a skeleton in the museum of Princeton University. W. B. Scott. A History of Land Mammals in the Western Hemisphere. 1913. Published by The Macmillan Company. Reprinted by permission.



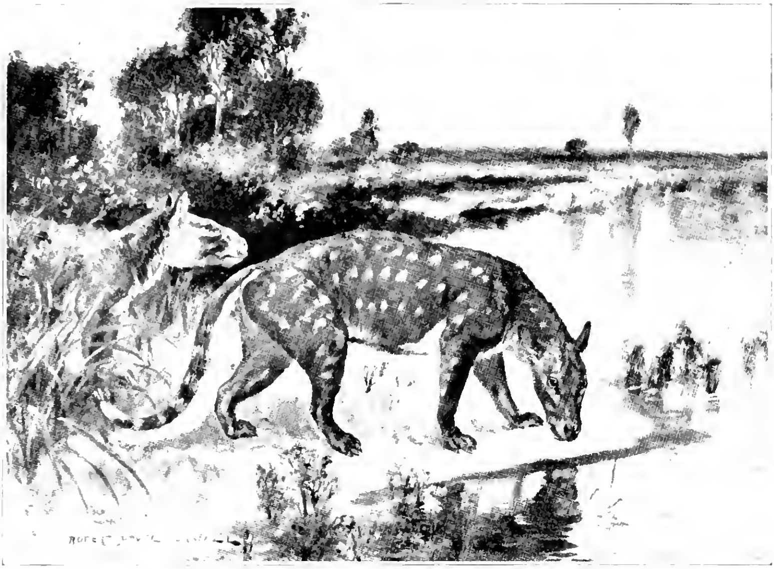
B. Model of the giant entelodont, *Dinohyus hollandi* of the Oligocene. From a skeleton in the Carnegie Museum. Peterson, 1909.

Restoration of the giant pig, *Elotherium* (*Entelodon*) *imperator* of the Upper Oligocene. Osborn. American Museum of Natural History. Reprinted by permission.

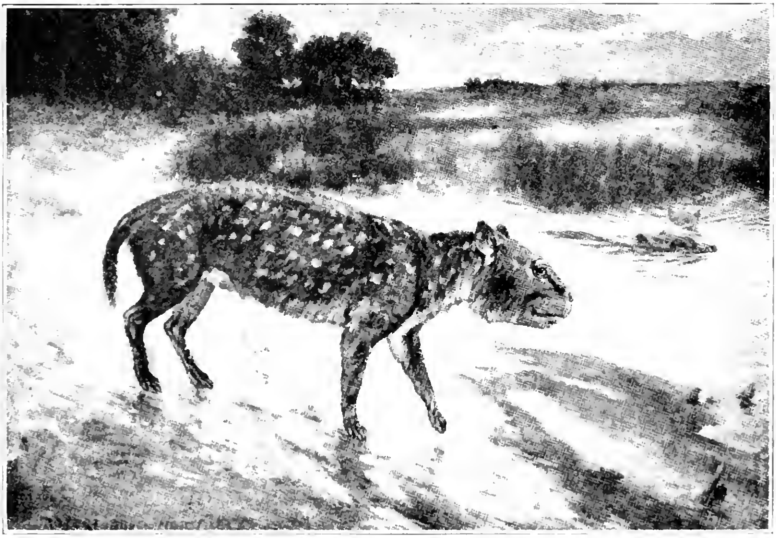


Skeleton of the Oligocene Oreodont, *Merycoidodon (Oreodon) gracilis.* Gilmore. 1906.

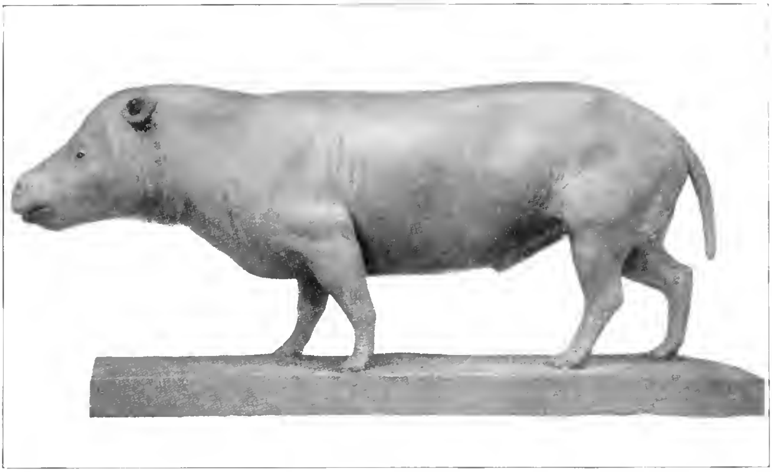
Restoration of the abundant Oreodont, *Merycoidodon (Oreodon) culbertsoni.* From a skeleton in the American Museum of Natural History. W. B. Scott. A History of Land Mammals in the Western Hemisphere. 1913. Published by The Macmillan Company. Reprinted by permission.



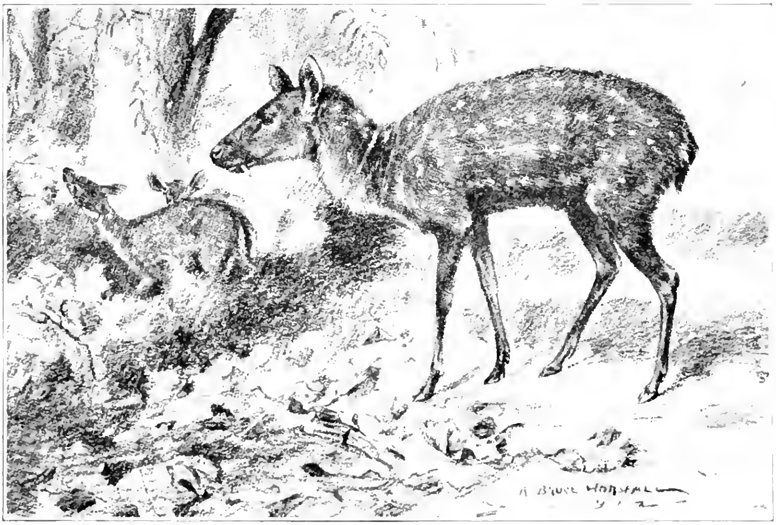
A. *Agriochoerus antiquus.* Restored from a skeleton in the American Museum of Natural History. W. B. Scott. A History of Land Mammals in the Western Hemisphere, 1913. Published by The Macmillan Company. Reprinted by permission.



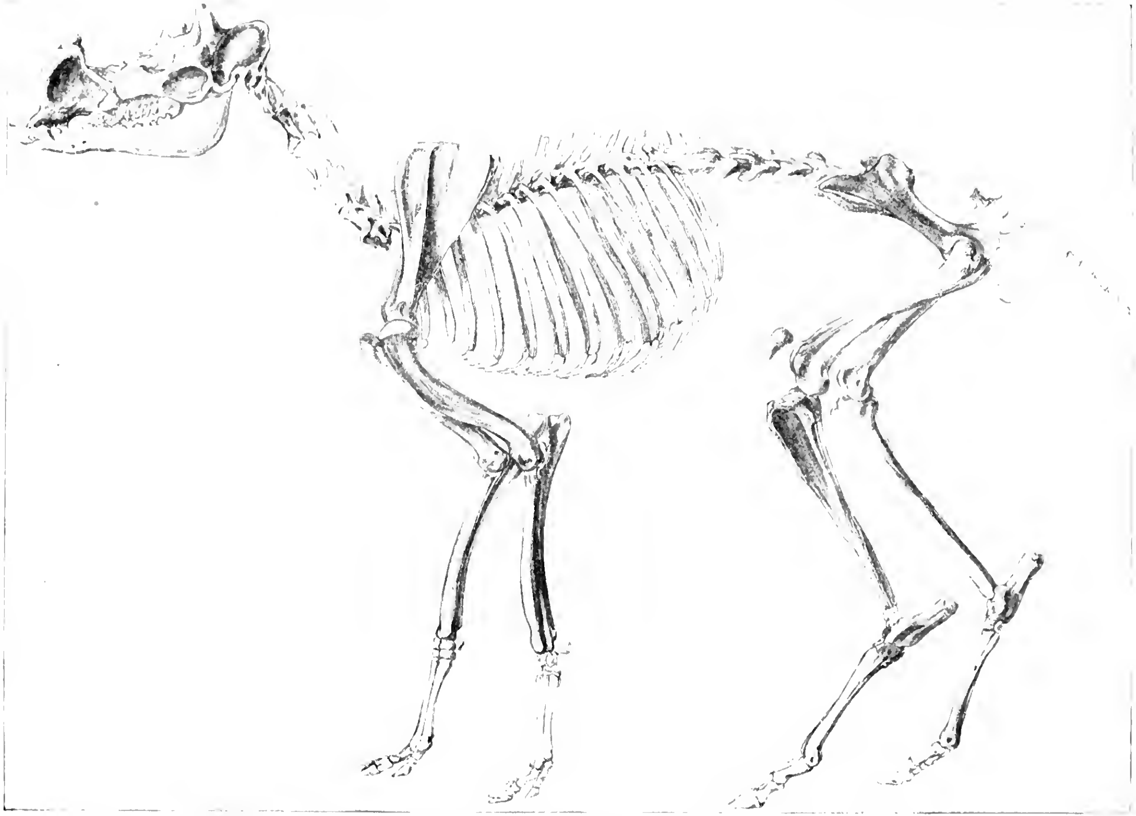
B. *Leptauchenia nitida.* Restored from a skeleton in the American Museum of Natural History. W. B. Scott. A History of Land Mammals in the Western Hemisphere. 1913. Published by The Macmillan Company. Reprinted by permission.



A. Model of *Promerycochoerus carrikeri*. From a skeleton in the Carnegie Museum. Peterson, 1914.

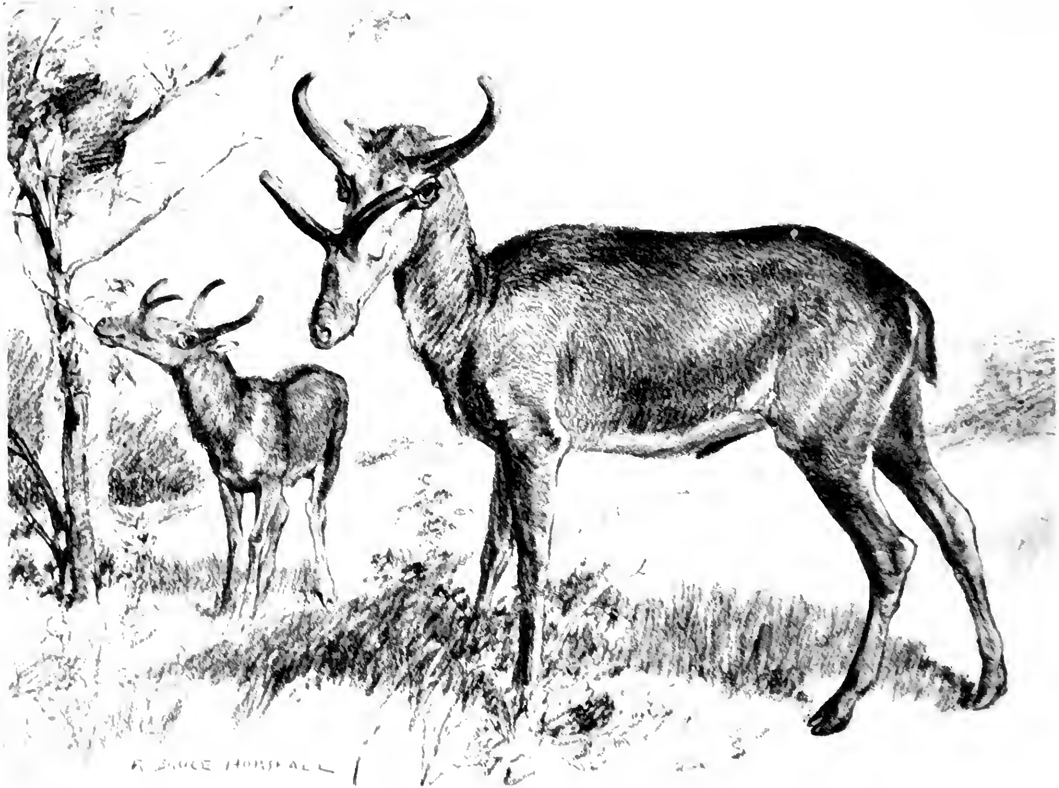


B. The Lower Miocene hornless deer, *Blastomeryx advena*. Restored from a skeleton in the American Museum of Natural History. W. B. Scott. A History of Land Mammals in the Western Hemisphere. 1913. Published by The Macmillan Company. Reprinted by permission.

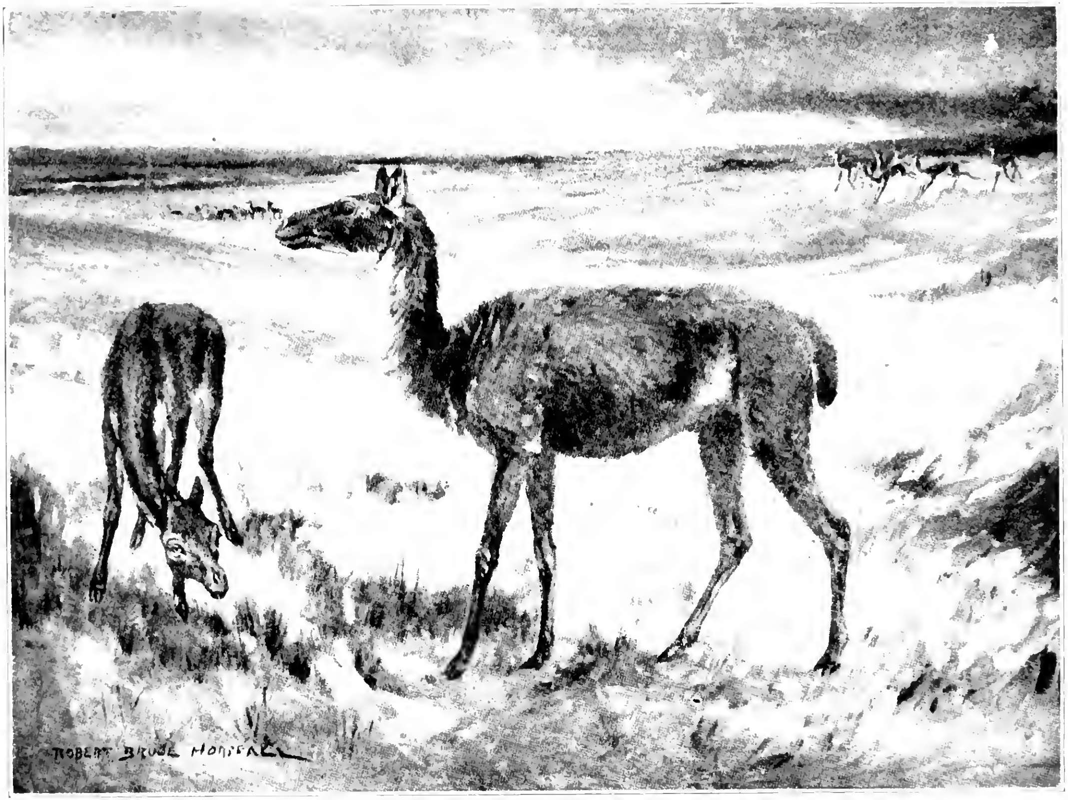


Skeleton of the six horned herbivore *Protoceras celer* of the Upper Oligocene. Scott. 1895.

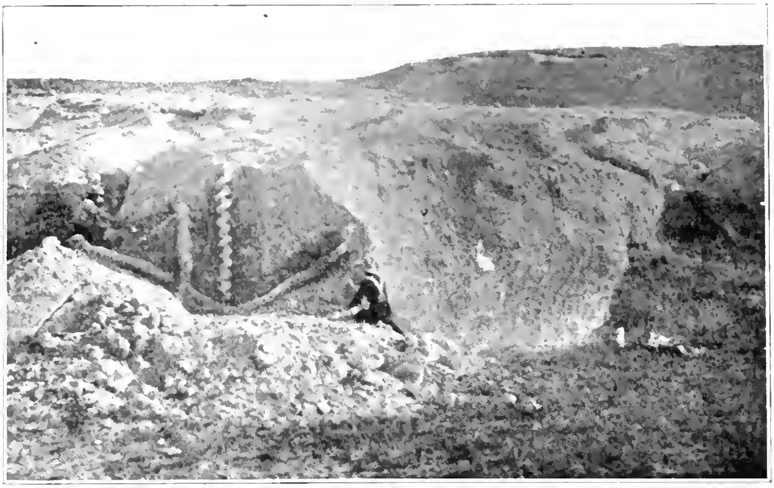
Restoration of the six horned herbivore *Protoceras celer* of the Upper Oligocene. Osborn. Copyrighted by the American Museum of Natural History. Reprinted by permission.



*Syndyoceras cooki*, a four horned ruminant of the Lower Miocene. Restored from a skeleton in the museum of the University of Nebraska. W. B. Scott. A History of Land Mammals in the Western Hemisphere, 1913. Published by The Macmillan Company.

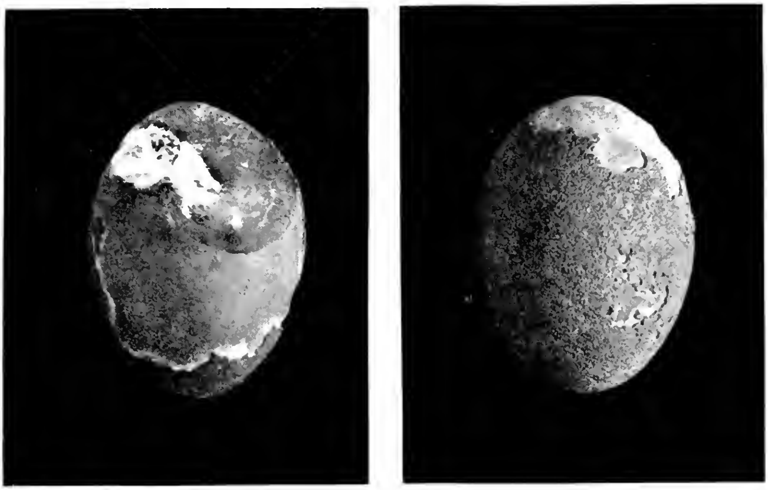


*Poebrotherium labiatum*, A White River camel of the Middle Oligocene, Restored from a skeleton in the museum of Princeton University. W. B. Scott, A History of Land Mammals in the Western Hemisphere, 1913. Published by The Macmillan Company. Reprinted by permission.

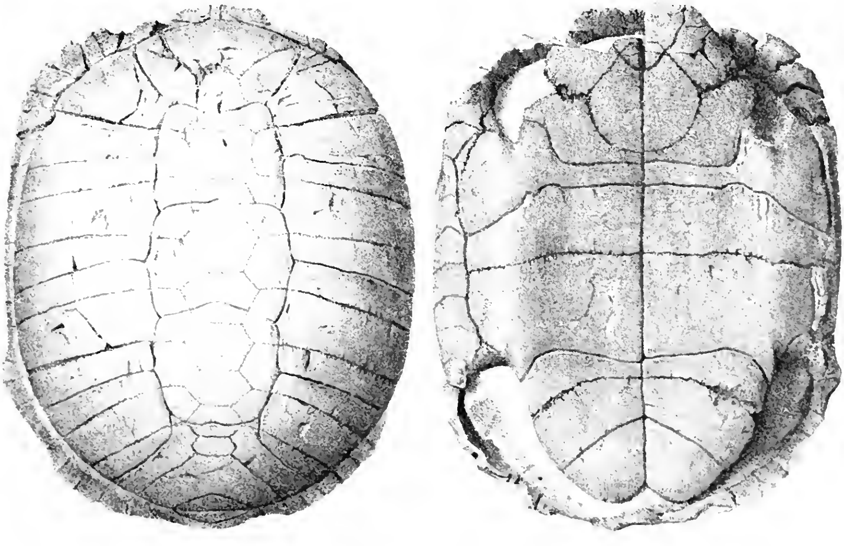


A. Daemonelix or "Devils corkscrews" in the Daemonelix beds near Harrison, Sioux county, Nebraska. Photograph by Barbour.

B. Anterior portion of head of the Oligocene crocodile, *Crocodilus prenasalis* found in Indian draw, 1899.



A. Petrified egg of a supposed anatine (duck like) bird of Oligocene age. Farrington, 1899.



B. *Stylemys nebrascensis*, the commonest fossil turtle of the Big Badlands, Leidy, 1853.

Good types of Sioux Indians who controlled the White River Badlands before the coming of white settlers. From the Indian Craftsman, Carlisle, Pennsylvania.

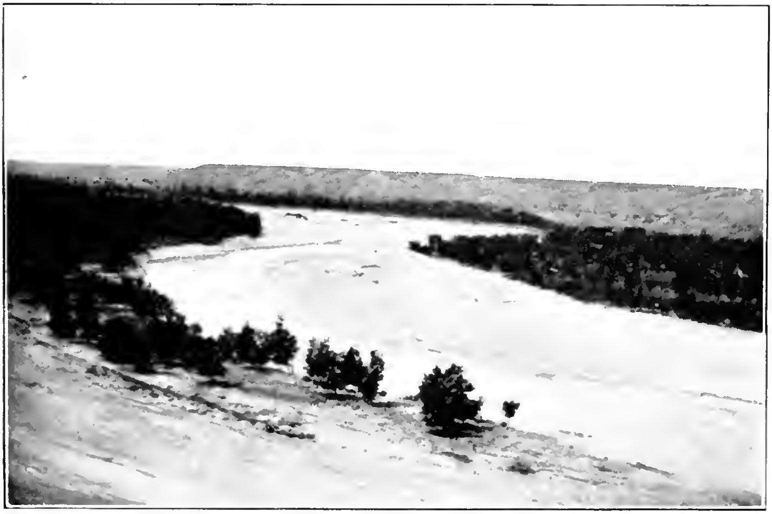
The Hall of Fossil Mammals of the American Museum of Natural History, New York City. Shows the manner of exhibiting fossil vertebrate collections to the public. Many of the cases in this room contain highly important specimens from the White River Badlands. Am. Mus. Guide Leaflet, 1903.

The Geological Museum of the South Dakota State School of Mines. Contains illustrative fossils and models of animals of the Big Badlands, 1920.

Sand-Calcite Crystals from the Miocene of Devils Hill. Foote Mineral Co., Philadelphia.

Photograph by O'Harra, 1909.

A. White River at wagon bridge near Interior.

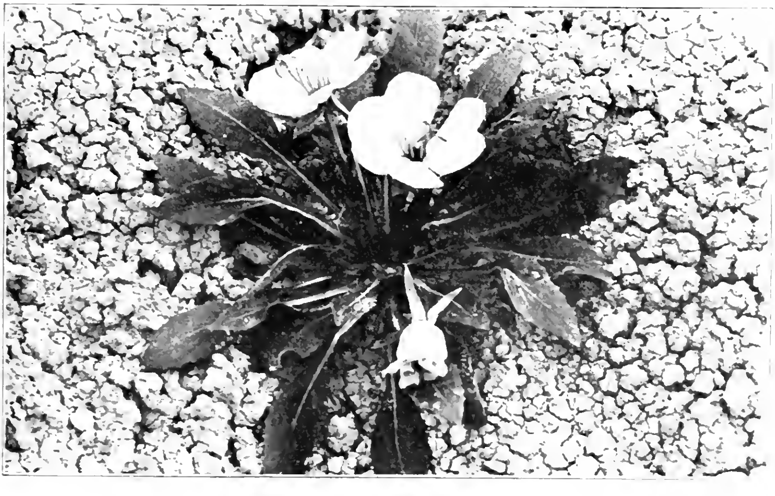


Photograph by O'Harra, 1899.

B. Cheyenne River near mouth of Sage Creek.

Photograph by O'Harra, 1909.

A. Sun-cracked surface of an alluvial flat showing loosening and curling of the drying mud.

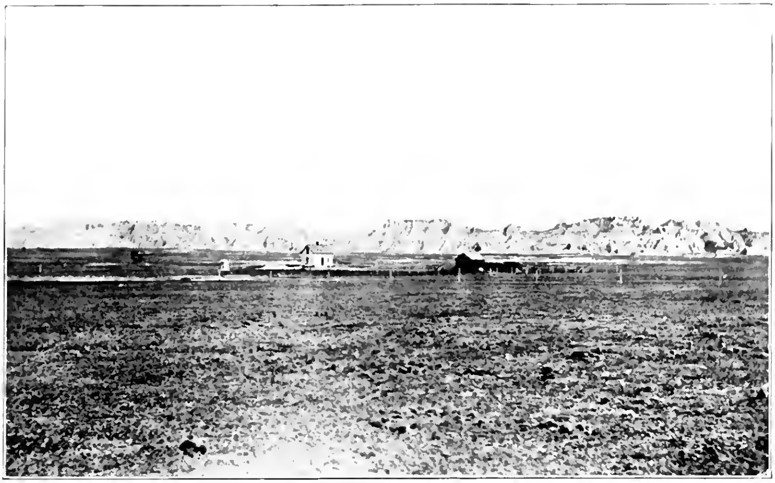


Photograph by Todd.

B. Spongy surface of disintegrating Titanotherium clay. The gumbo lily, as here shown, not infrequently finds root in the porous material.

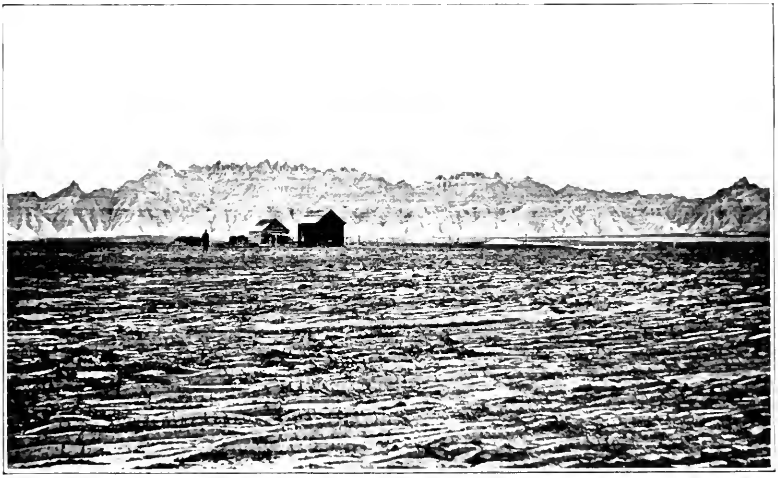
A. The old postoffice of Interior on White River in the heart of the Badlands before the coming of the railroads and the days of the automobile.

B. A cowboy home in Corral Draw in the early days of Badlands settlement.



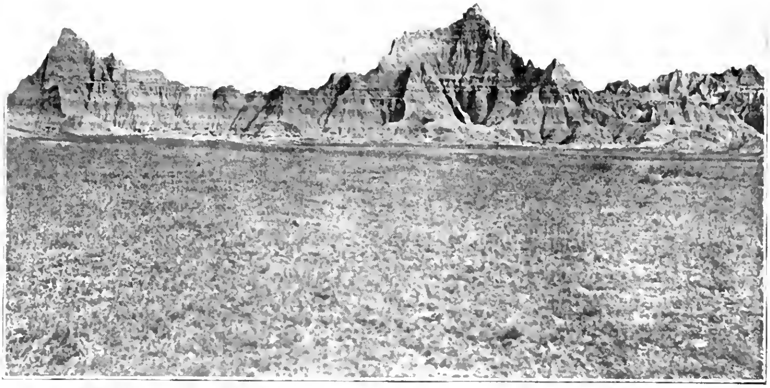
Photograph by O'Harra, 1911.

A. A new ranch home near the Great Wall north of Interior.



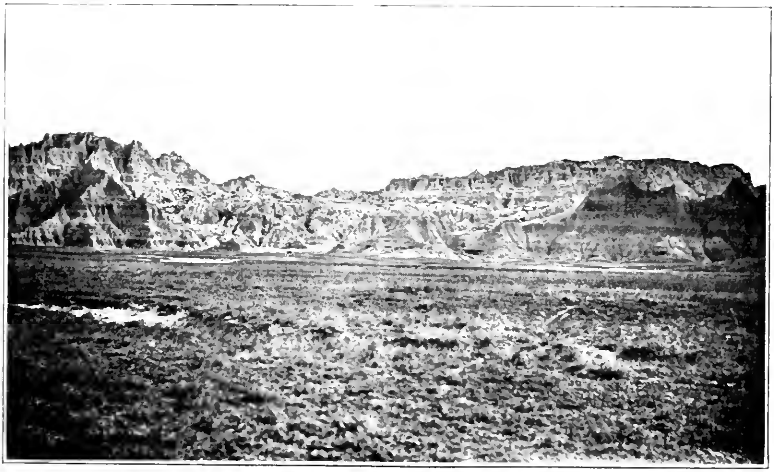
Photograph by O'Harra, 1911.

B. The beginning of a farm near the Great Wall northwest of Interior. Newly plowed sod in the foreground.



Photograph by O'Harra, 1911.

A. Detail of the Great Wall north of Interior.

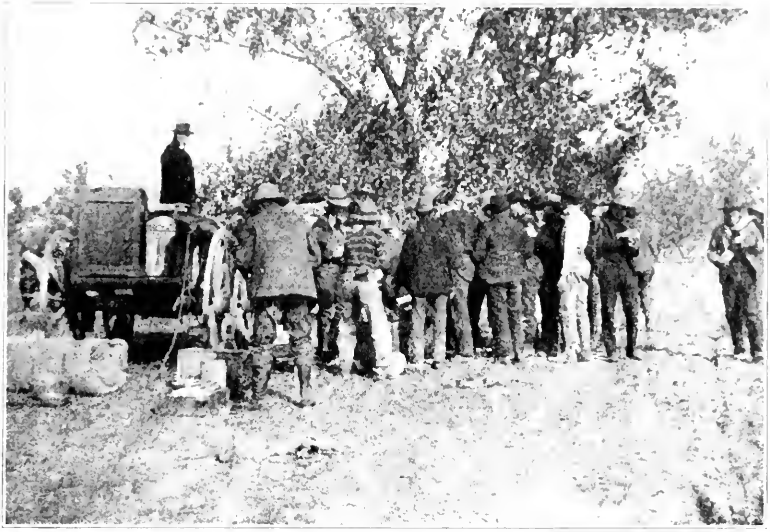


Photograph by O'Harra, 1912.

B. The Great Wall at Cedar Pass northeast of Interior. A roadway suitable for automobiles winds up this slope and reaches the top at the lowest skyline depression to the left of the center. See Plate 88.

A. Cattle descending from grass-covered table land to grass-covered valley below. Ricard Art Co., Quinn, S. D.

B. The 6L Ranch near Imlay showing success in soil cultivation. McNamara's Book Store, Rapid City.



A. Geology class of South Dakota State School of Mines in Indian Creek Basin, 1900.

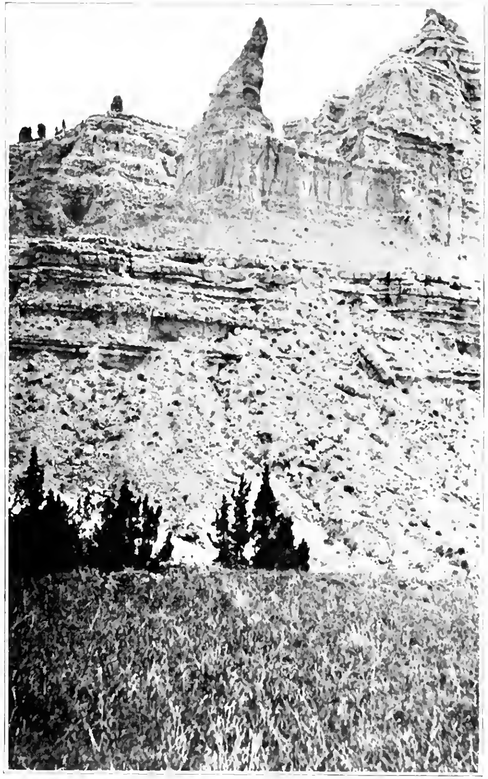
Photograph by O'Harra.

B. Geology class of South Dakota State School of Mines at top of Sheep Mountain (Cedar Point) the highest part of the Big Badlands.

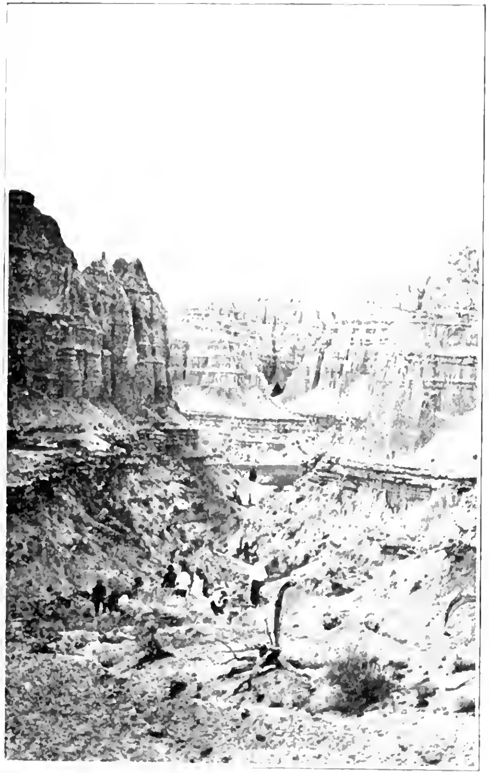
Going up the northern slope of Sheep Mountain table near Hines' ranch, South of Scenic. Note the small figure of the man on the left skyline.

A water canteen is an essential part of the collector's equipment during the dry season.

A. A resistant clay dike in the Big Badlands.

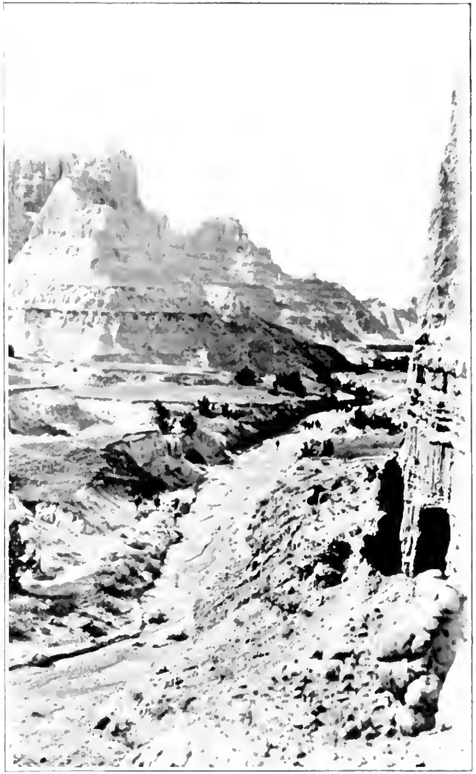


B. An erosion pinnacle near Sheep Mountain.



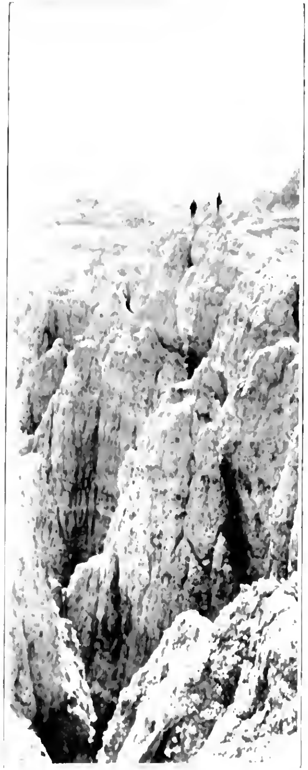
Photograph by O'Harra, 1915.

Midway down School of Mines Canyon,
See Plate 91.

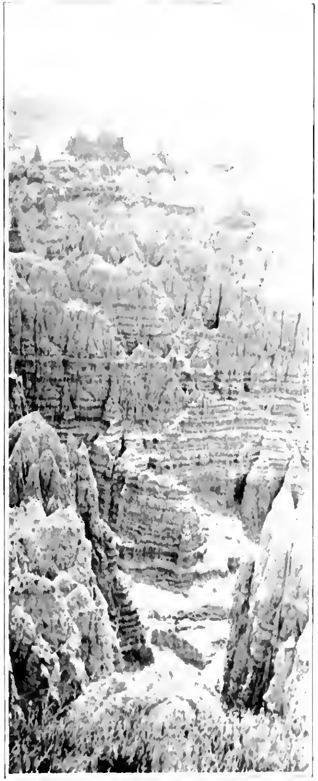


Photograph by O'Harra, 1915.

Geology class of the South Dakota State School of Mines in School of Mines Canyon near base of Sheep Mountain-



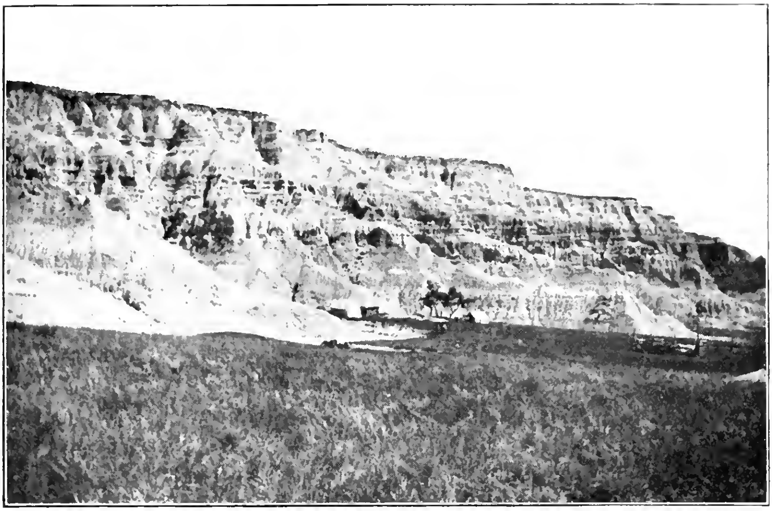
Steep walled canyon on eastern side of Sheep Mountain.



South side of Sheep Mountain looking toward White River.

Detail of the Great Wall near Big Foot Pass.

Photographs by O'Harra, 1915.



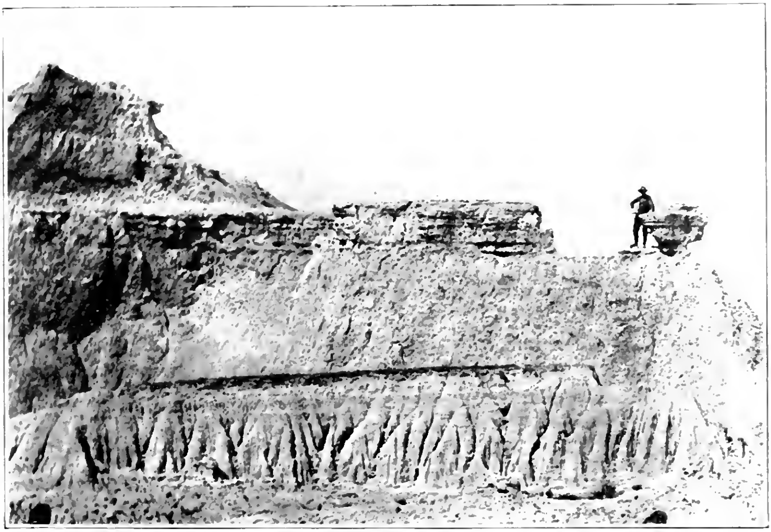
Photograph by O'Harra, 1899.

A. Rugged wall approximately 350 feet high separating the grassy valley of Indian Draw from the grass covered flat known as Sheep Mountain Table. Site of the School of Mines camp in the early overland trips of the Geology class to the Big Badlands. For a more general view see Plate 87.

Photograph by C. A. Best, 1920.

B. South Dakota State School of Mines students on Sheep Mountain Table. A short distance from the edge of the Wall shown in A.

A. Balanced rock on Great Wall near Big Foot Pass.

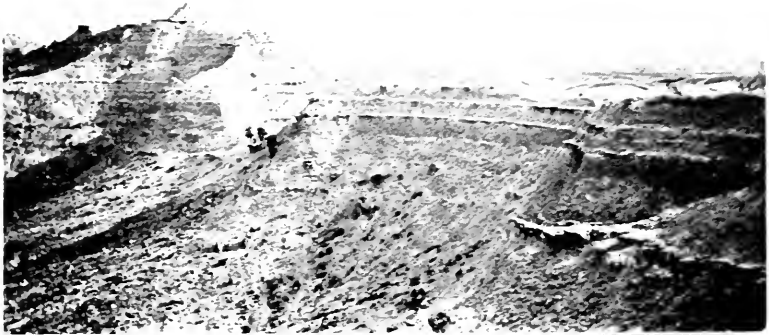


Photograph by O'Harra.

B. Balanced rock near head of Indian Draw.

Photograph by O'Harra, 1910.

A. Oreodon Beds near Big Foot Pass showing color bands.

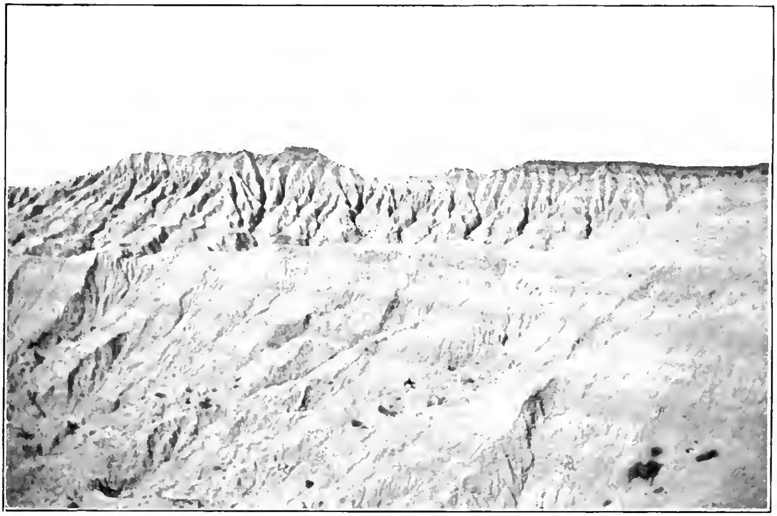


Photograph by O'Harra, 1912.

B. Erosion forms near head of Corral Draw.

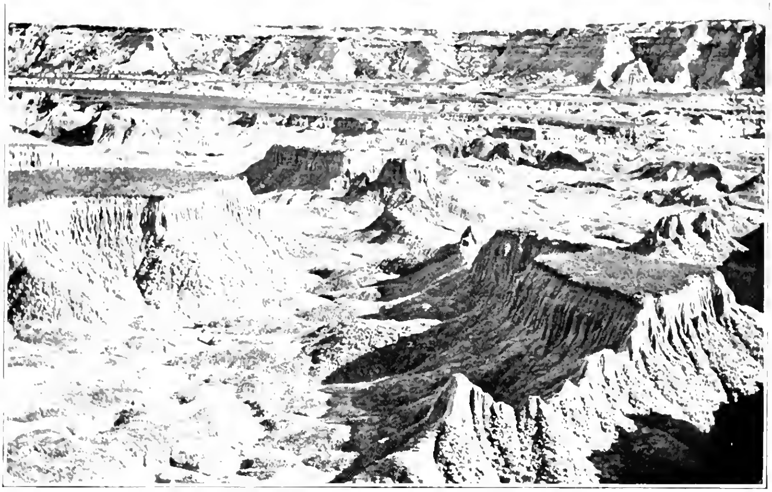
Photograph by O'Harra, 1909.

A. Erosion detail of Titanotherium Beds near Big Foot Pass.



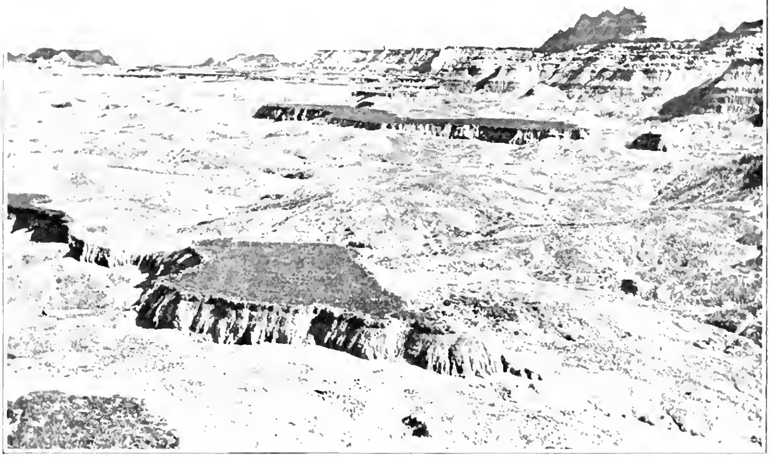
Photograph by O'Harra, 1899.

B. Erosion detail of Oreodon Beds in the valley of Indian Creek.



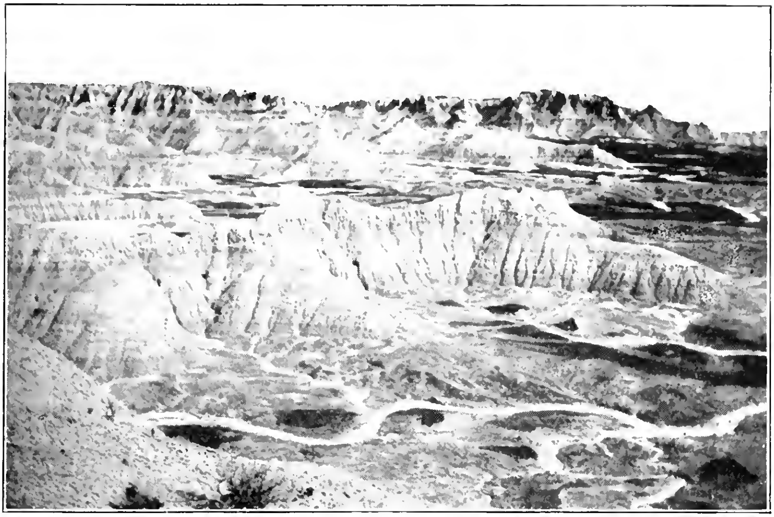
Photograph by O'Harra, 1910.

A. Erosion forms north of the Great Wall near Cedar Pass.



Photograph by O'Harra, 1910.

B. Erosion forms north of the Great Wall near Big Foot Pass. The flat remnants are protected by a thin covering of well-rooted grasses.

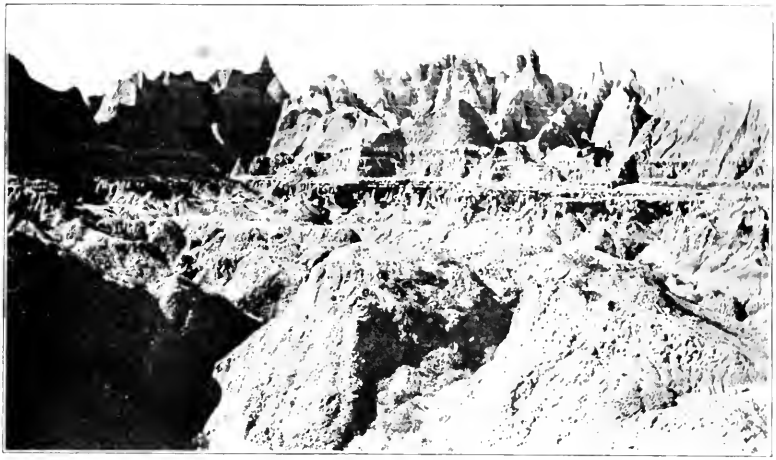


Photograph by O'Harra, 1899.

A. Looking southeast toward Sheep Mountain from Valley of Indian Creek.

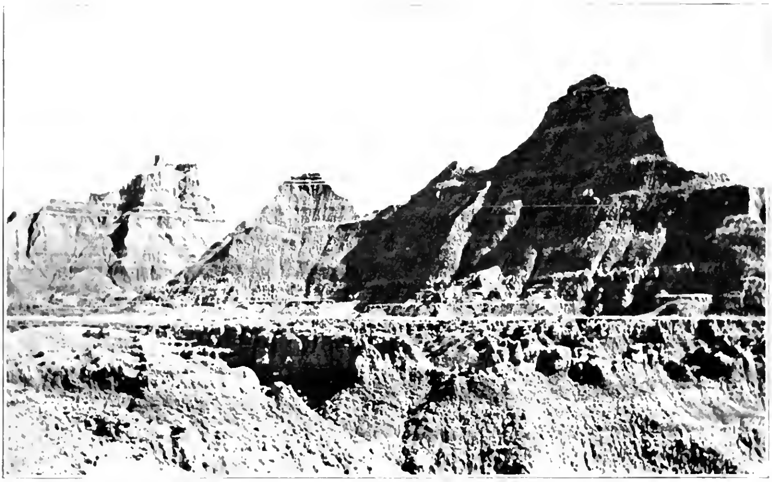
Photograph by O'Harra, 1912.

B. Erosion forms in Corral Draw.



Photograph by O'Harra. 1910.

A. Detail of Great Wall north of Interior chiefly Protoceras Beds.



Photograph by O'Harra. 1910.

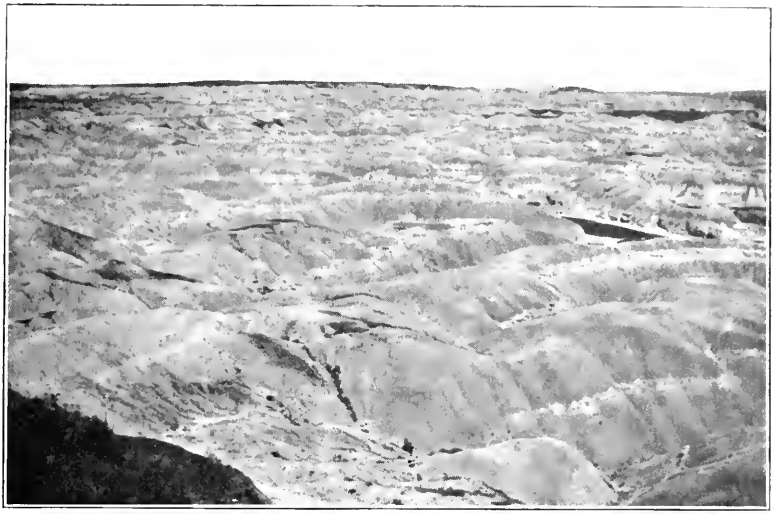
B. Detail of Great Wall north of Interior chiefly Protoceras Beds.

Photograph by O'Harra, 1909.

A. Clay balls in bed of little ravine near Big Foot Pass.

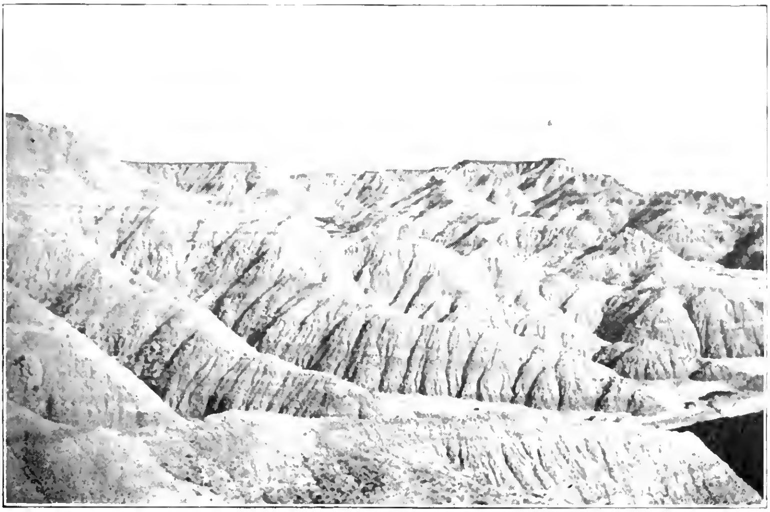
Photograph by O'Harra, 1899.

B. Conglomerate dike in valley of Indian Creek.



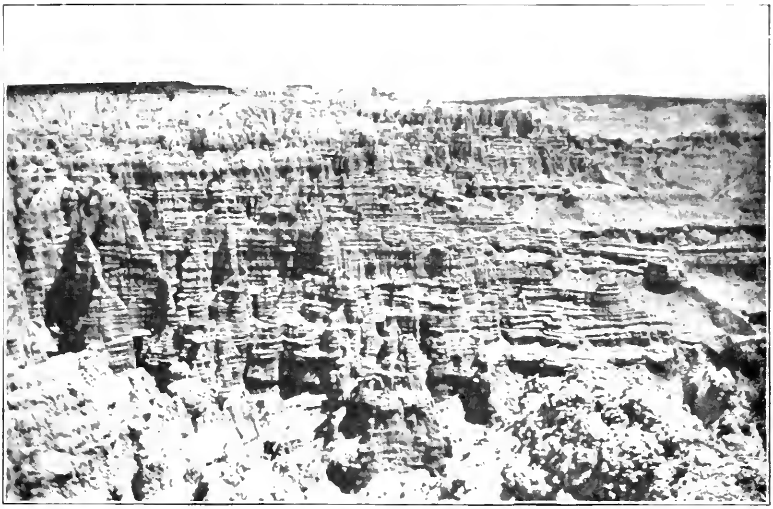
Photograph by O'Harra, 1899.

A. General view of Titanotherium Beds, Valley of Indian Creek.



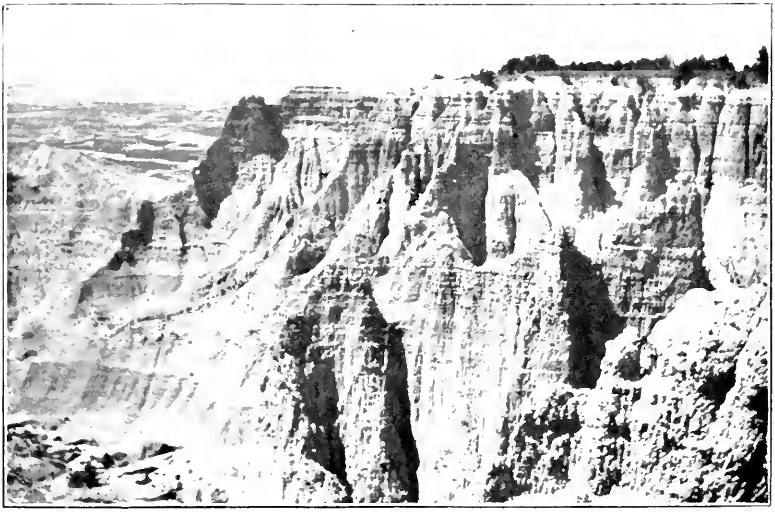
Photograph by O'Harra, 1899.

B. Oreodon Beds. Valley of Indian Creek.



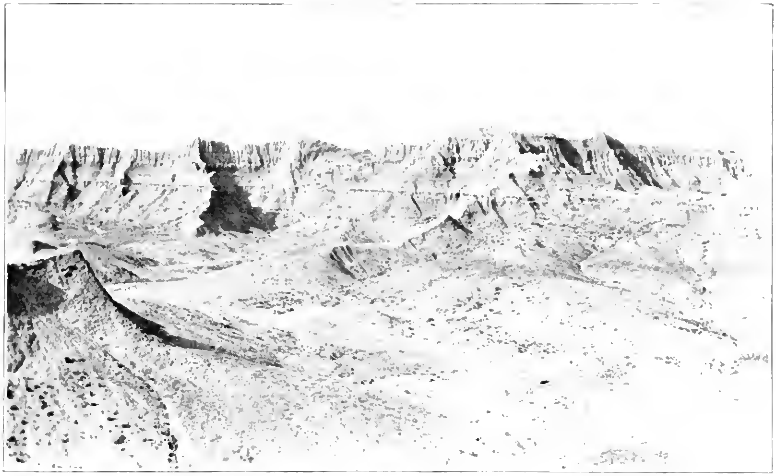
Photograph by O'Harra, 1899.

A. Protoceras Beds near top of Sheep Mountain.



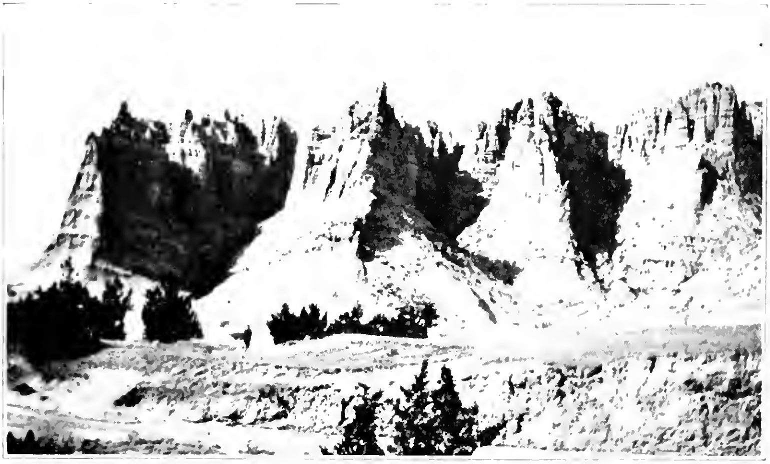
Photograph by O'Harra, 1899.

B. Protoceras Beds near top of Sheep Mountain.



Photograph by O'Harra, 1912.

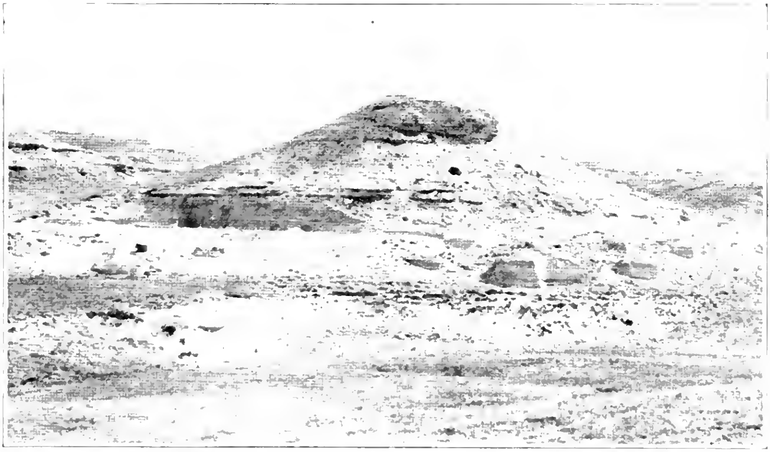
A. Oreodon Beds along the Indian Draw—Corral Draw divide.



Photograph by Best, 1920.

B. Erosion detail of the wall of School of Mines Canyon.

A. Agate Springs Fossil Quarries looking Southeast. University Hill on the left; Carnegie Hill on the right.



Photographs by Cook, 1915.

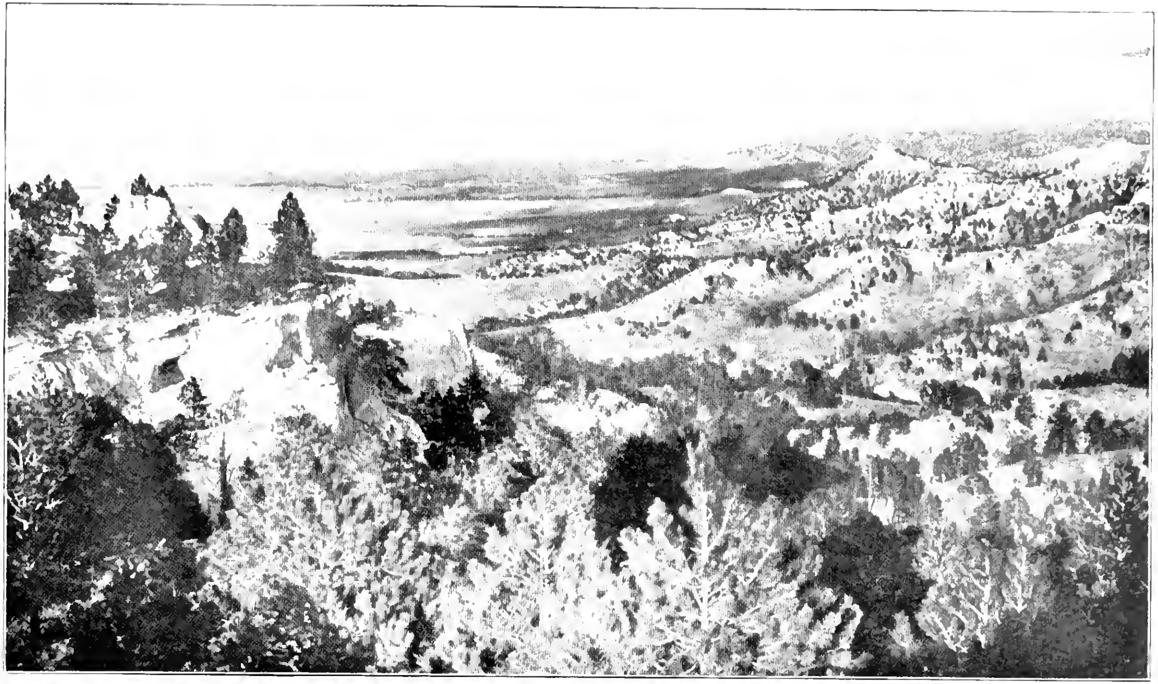
B. Stenomylus quarry of Amherst Hill, one of the Agate Springs fossil quarries.

Photograph by O'Harra, 1918.

A. General view of Slim Buttes, Perkins county, South Dakota, capped by White River Tertiary deposits.

Photograph by O'Harra, 1918.

B. Detail of the southern end of South Cave Hills, Harding county, South Dakota. Shows Fort Union sandstone of earlier Tertiary age than the White River Beds.



Photograph by E. H. Barbour.

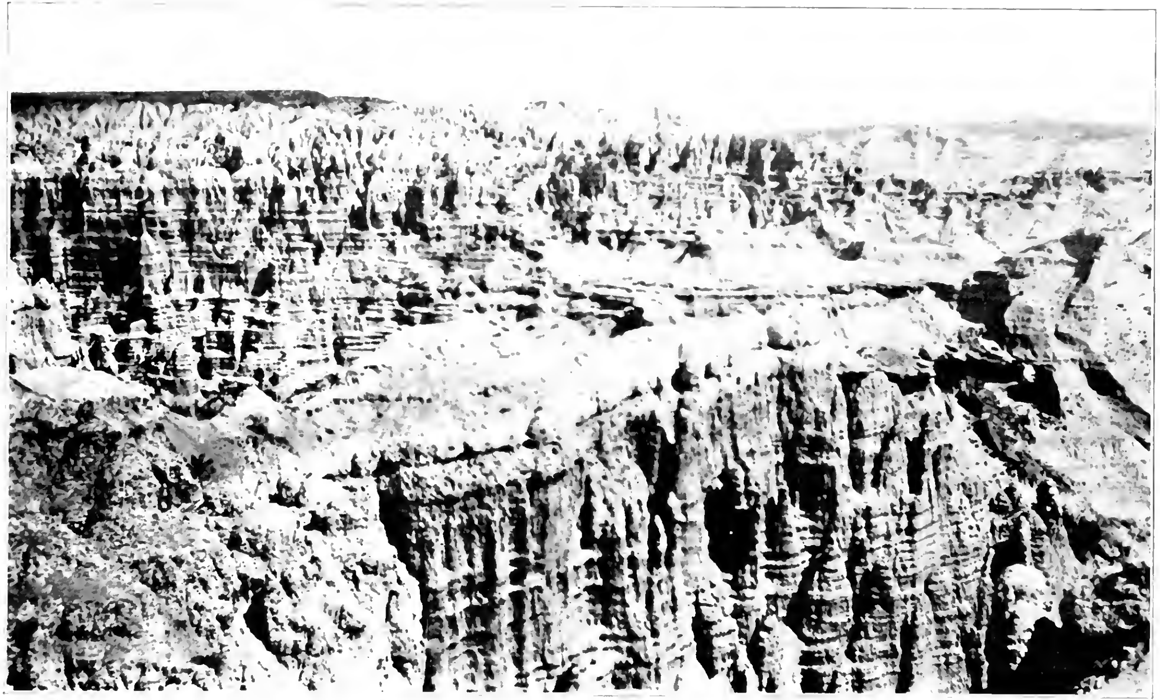
North face of Pine Ridge, looking northeast over Hat Creek Basin. Arikaree in the left foreground. Badlands of Brule Clay in the distance.

Photograph by O'Harra, 1920.

Geological students of South Dakota State School of Mines studying concretions near head of Indian Draw.

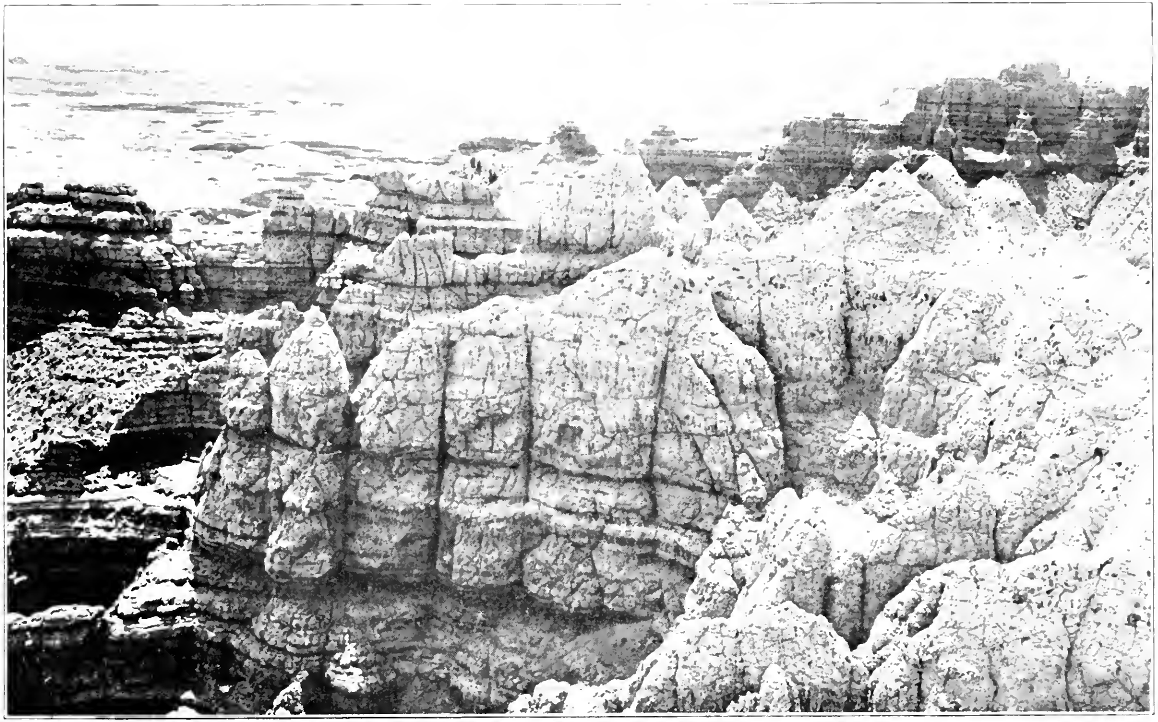
Photograph by Johnson, 1915.

A South Dakota State School of Mines geological party near the top of Sheep Mountain.



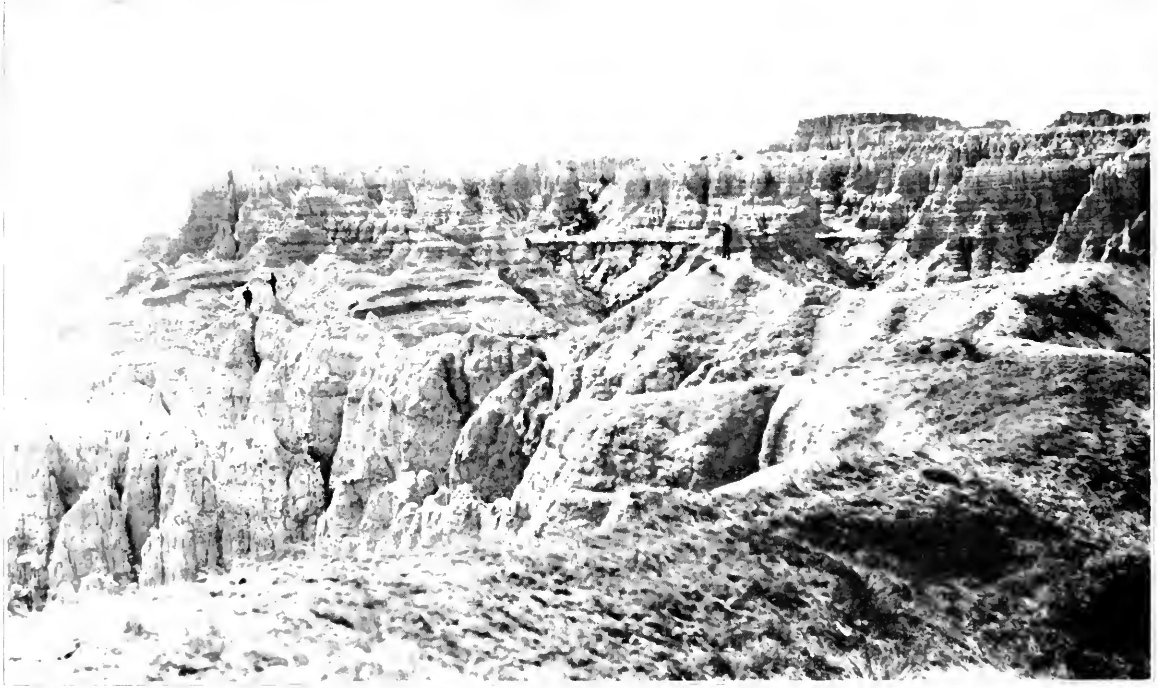
Photograph by O'Harra, 1920.

Protoceras Beds of Sheep Mountain. The ruffled nature of the precipitous walls is due to irregularity in hardness of the bedding materials.



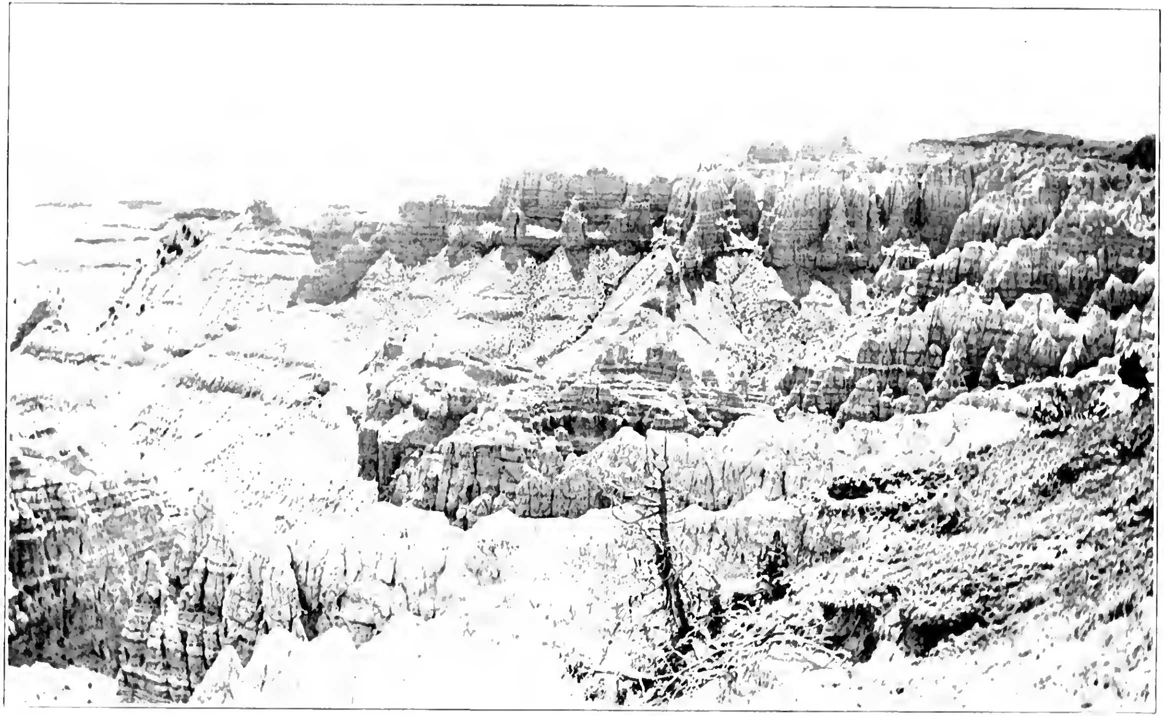
Photograph by O'Harra, 1920.

Characteristic steep-walled canyons in the Protoceras Beds of Sheep Mountain.



Photograph by O'Harra, 1920.

Venturesome climbing among the Protoceras Beds of Sheep Mountain.

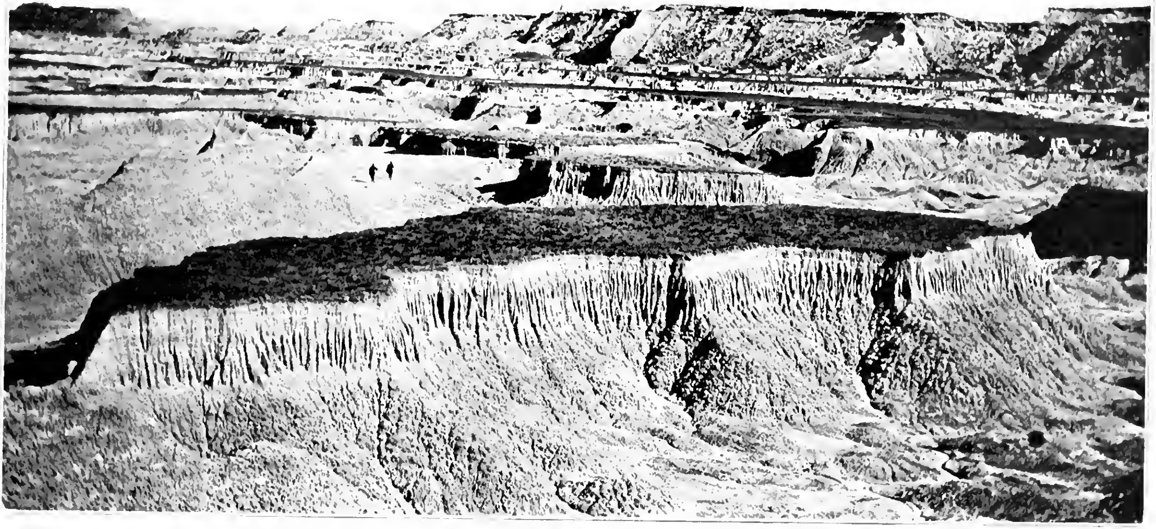


Photograph by O'Harra, 1920.

View across the eastern slope of Sheep Mountain; Protoceras Beds above. Oreodon Beds below.

Photograph by O'Harra, 1920.

Lingering fragments of Protoceras Beds as seen from the top of Sheep Mountain looking toward White River.



Photograph by O'Harra, 1910.

Erosion forms north of the Great Wall near Interior. The grass sod protects the last lingering remnants of the once continuous level. Oreodon Beds in the foreground, Protoceras Beds in the distance.

Photograph by O'Harra, 1920.

Panoramic view of erosion forms of Protoceras Beds South of Sheep Mountain.

Photograph by O'Harra, 1910.

Panoramic view of the Great Wall, looking west from Saddle Pass near Interior. Protoceras Beds above, Oreodon Beds below.

Photograph by O'Harra, 1909.

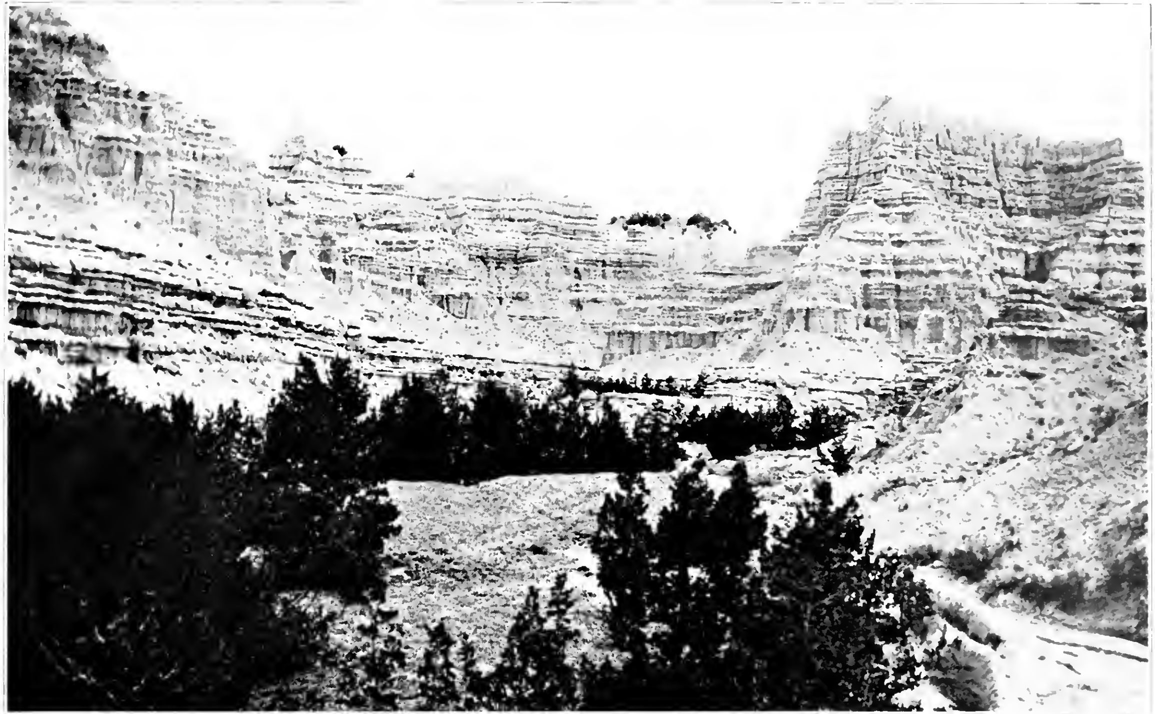
Roadway through the upper portion of Cedar Pass near Interior. See Plate 57 B.

Photograph by Best, 1920.

Sheep Mountain Table as it approaches Sheep Mountain proper (Cedar Point). The cedar fringed gullies are rapidly eroding into steep-walled canyons disclosing the fluted and frilled Protoceras Beds seen in the distance.

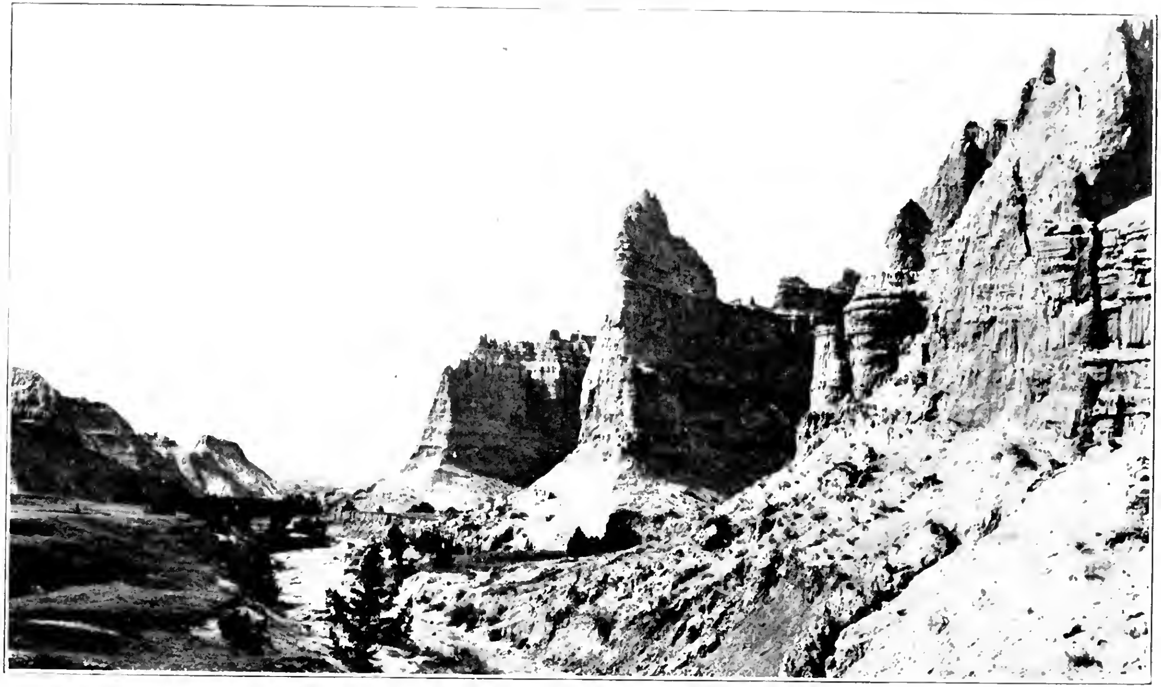
Photograph by Johnson, 1915.

Head of Indian Draw near the heart of the Big Badlands. Cabins in the lower left hand corner mark the site of the State School of Mines camping ground in the early overland inspection trips of the Geology classes.



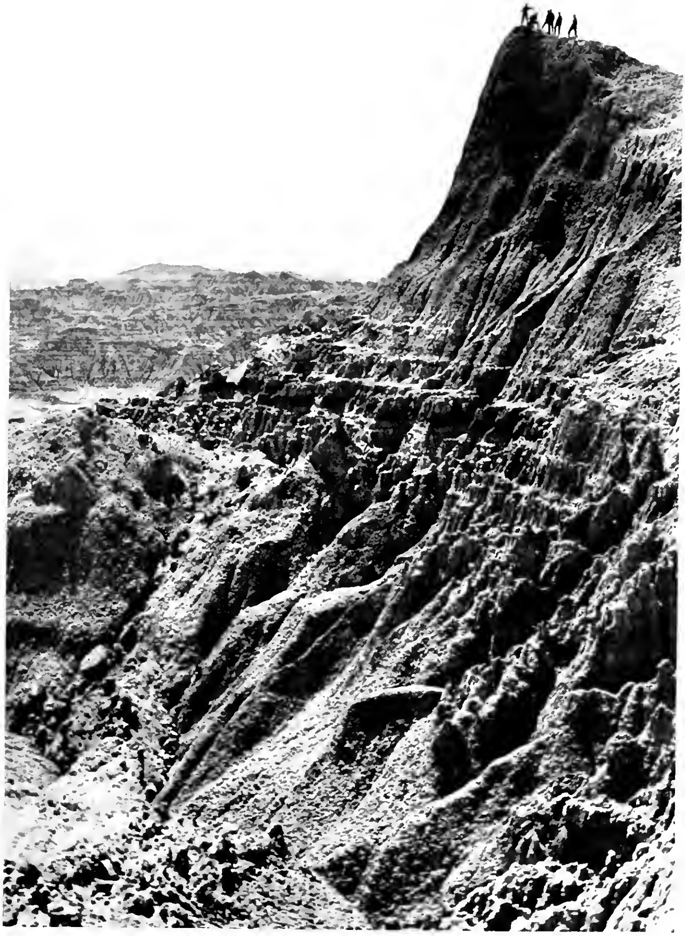
Photograph by O'Harra, 1920.

Midway down School of Mines Canyon. See Plate 62 B.



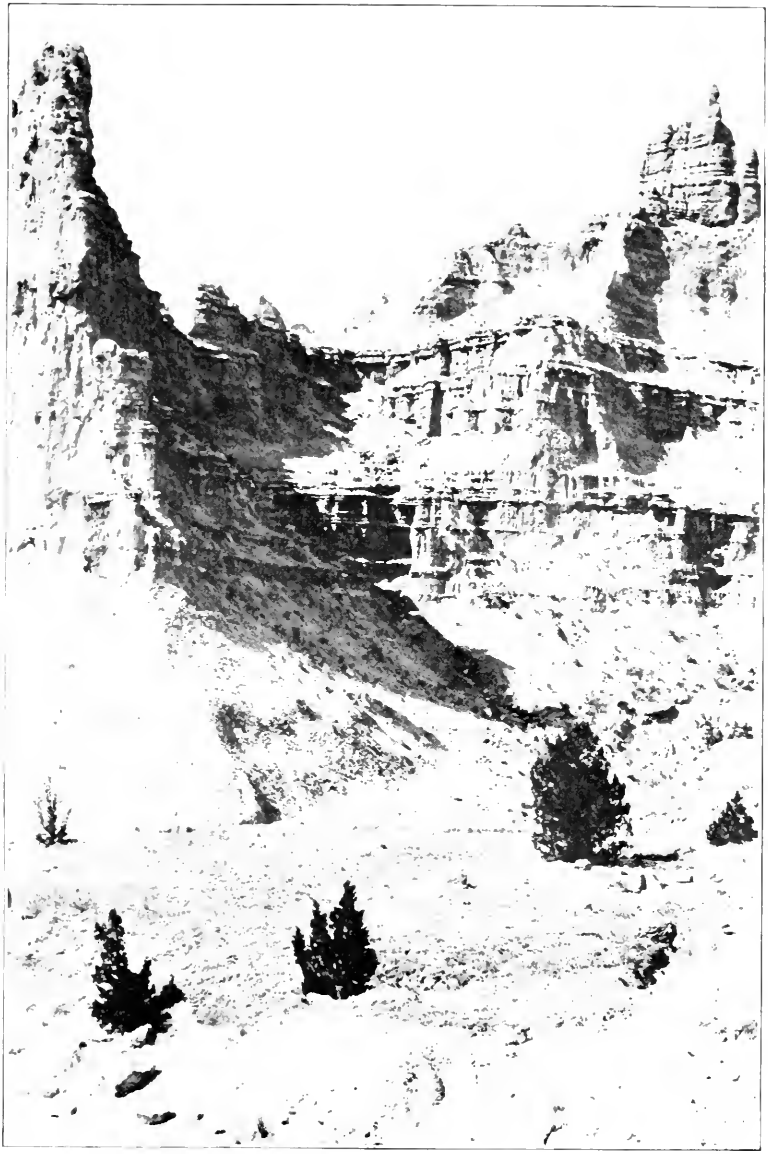
Photograph by O'Harra, 1920.

Near the Gateway, School of Mines Canyon.



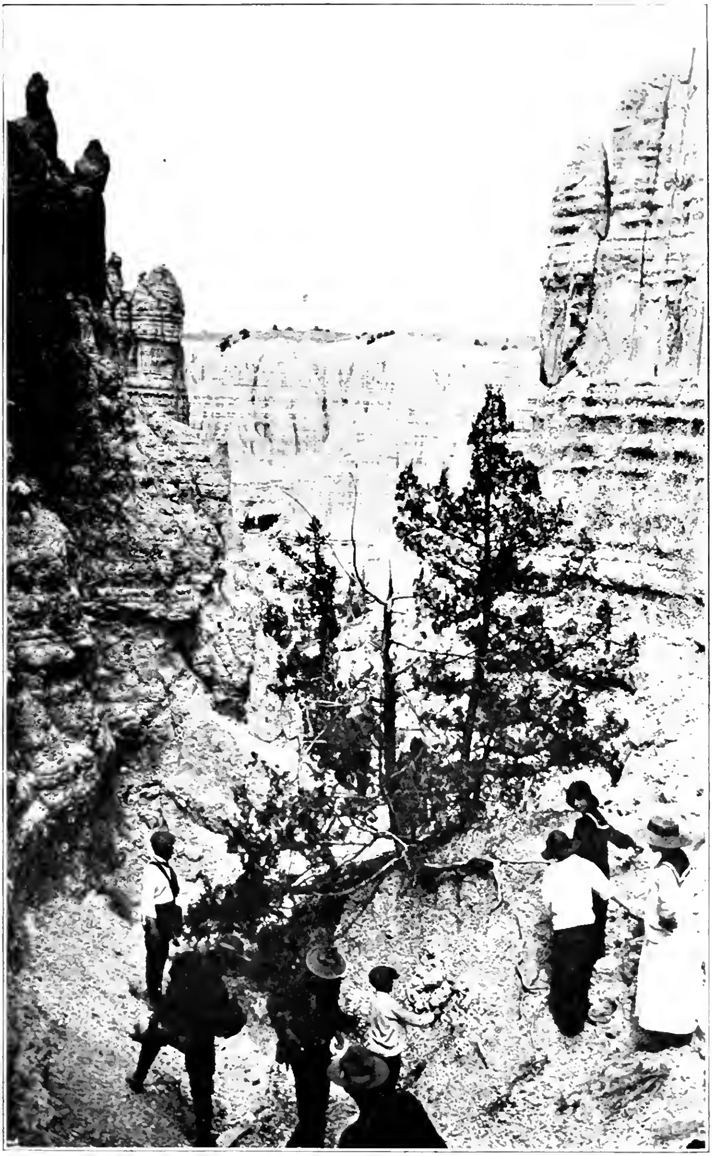
Photograph by O'Harra, 1910.

Details of Great Wall north of Interior. Chiefly Protoceras Beds.



Photograph by O'Harra, 1915.

Protoceras Beds and Oredon Beds of School of Mines Canyon.



Photograph by O'Harra, 1915.

A Geological party descending School of Mines Canyon.

Photograph by O'Harra, 1920.

A Guardian of the Gateway, School of Mines Canyon.