THE NATURE AND ORIGIN OF CONE-IN-CONE STRUCTURE

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ABSTRACT

The descriptive term "cone-in-cone structure" should be applied only to those occurrences in which the matrix is composed of an impure fibrous carbonate mineral (usually calcite) and in which a conical structure is made evident by the disposition of included dust or laminae of argillaceous material. Many examples are described in detail and figured in this paper. Non-carbonate occurrences (usually silica) showing this particular type of conical structure are to be regarded as replacements of original carbonate. Compaction cones in shales, shatter cones, which occur in a variety of rock types, and conical shear formations in coal originate quite differently from true cone-in-cone.

Cone-in-cone structure owes its origin to the concretionary growth of carbonate (calcite) during the very early diagenesis of the containing sediments. The muddy sediments must have attained the requisite physical conditions while the supply of ions and the appropriate physico-chemical conditions for crystallization existed. The sediments must have been in a partly compacted state so that nucleation of carbonate took place on the surfaces of lenses of clay instead of homogeneously throughout a watery mud, as in ordinary claystone concretions. The fibrous nature of the calcite, its orientation, and its differential growth, which produced the corrugated, partially conical clay layers so typical of cone-in-cone, are the result of the stress field in which the crystallization took place. The stress field was produced by the pressure of superincumbent beds—which must have been slight because of the early diagenetic time of development—and by the expansional force of the concretionary action itself. The latter may also have produced in the sediment the compaction needed for the formation of cone-in-cone structure; for example, as layers surrounding non-coned carbonate concretions. No external source of stress was required, but, if it had been present at the time of crystallization, it could have enhanced or modified the development of the structure. Variations in the conditions of crystallization and in the particular physical state and thickness of the sediment permitted

differences such as cone size, cone angle, and complexity between individual occurrences. The necessity for the presence in combination of the right conditions is what limits the appearance of cone-in-cone structure. On the other hand, the conditions as described above are sufficiently ordinary to explain the geographically and geologically widespread occurrence of the structure.

I. INTRODUCTION

Types of Cone Structures

Cone structures of a number of types have been reported in rocks. They are here classified as follows:

1. True cone-in-cone structures, developed in calcareous beds or in concretions; these have been described for more than a hundred years from widely distributed localities.
2. Cone structures in relatively pure calcite veins; these are closely related to type 1 and differ mainly in their simplicity.
3. Compaction cones, formed in shale as a result of differential compaction around small columnar competent structures (Woodland, in press).
4. Shatter cones (fig. 25), described in rocks of various lithologies in cryptoexplosion structures and interpreted by Dietz (1959, 1960, 1961, 1963) as being the result of meteorite impact (e.g., at Kentland, Indiana) and by Bucher (1963) as caused by the penetration of vapor of magmatic origin under high pressure into the pores of the rock. In this connection impact cones can be produced by striking a homogeneous rock, e.g., chert, with a sharp instrument (fig. 26). (See also Shoemaker, Gault, and Lugn, 1961.)
5. Cone-in-cone fractures in coal (of which the Museum possesses one fine example, fig. 27), described from New Zealand and explained as due to conchoidal shearing induced by tectonic stresses (Gage and Bartrum, 1942). (See also Lhoest, 1962).
6. Cone forms, preserved in siltstone and sandstone, which are infillings of cone-shaped depressions produced in surficial unconsolidated materials during the fall of the water table. Recent examples are described by Shaub (1937), but he gave no examples from consolidated rocks nor are any known to

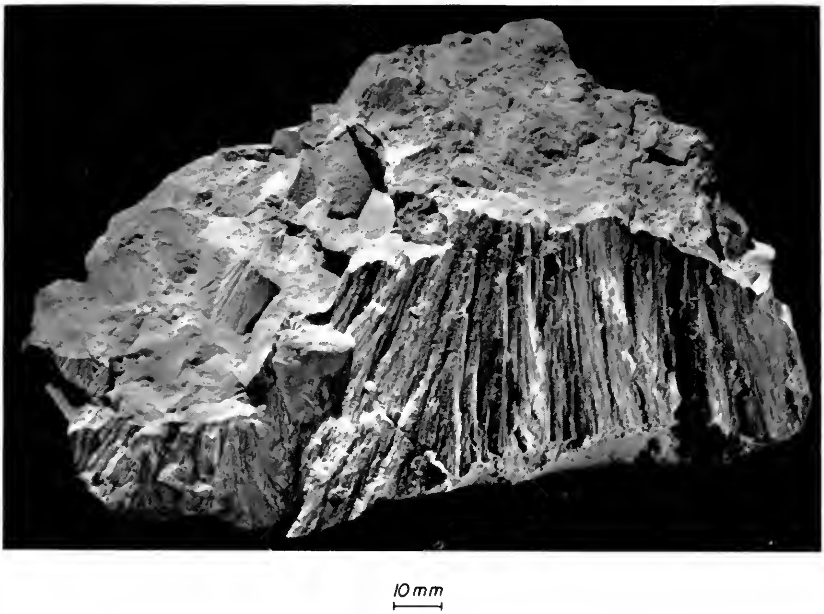

FIG. 25. Shatter cones in limestone, from Newton County Stone Quarry, Kentland, Indiana (G-3639).

FIG. 26. Impact cone in chert (G-3112).

FIG. 27. Conical shear surfaces in coal. Merthyr Tydfil, Wales (G-450).

me. (Shaub mistakenly equates the origin of slump cones with that of true cone-in-cone structure.) Boyd and Ore (1963), however, described patterned cones in siltstones and suggested that they were formed by the filling of conical depressions produced by upwelling currents of water in uncompacted and water-saturated silt.

This paper deals only with types 1 and 2; that is, true cone-in-cone and the related cone forms in calcite veins.

ACKNOWLEDGMENTS

Dr. Rainer Zangerl and Dr. Eugene S. Richardson, Jr., of the Department of Geology, Chicago Natural History Museum, first directed my attention to the problem of cone-in-cone structure. They were then engaged in extensive paleoecological and stratigraphic studies in the Pennsylvanian of west-central Indiana, and we spent some time together in the field examining and collecting from several cone-in-cone horizons in that area. I also wish to express my thanks to them for considerable help and discussion of problems during the course of the study and of the writing of the manuscript.

Many colleagues aided by the gift of specimens: Dr. David L. Dineley, University of Ottawa; Dr. Allison R. Palmer, United States Geological Survey; Mr. Jay Wollin; Miss Carole Stentz; Mr. Neal H. Brown; Mrs. June Zeitner; Mr. Harold Martin, Museum of Geology, South Dakota School of Mines and Technology; and Mr. Joseph Choate, Chicago Natural History Museum. Dr. Robert H. Denison, Department of Geology, Chicago Natural History Museum, lent specimens he collected in Quebec and New Brunswick, and Dr. John Clark of the same department made available specimens from Utah. Drs. Zangerl and Richardson also collected specimens especially for this study.

The following Antioch College students aided in various ways in the laboratory: Douglas Gilbert, James Martin, David Kuder, Frederick Echelmeyer, and Miss Selma Wiegner.

Some of the photographs shown in the text figures are the work of Mr. John Bayalis and Mr. Homer Holdren, of the Museum's Division of Photography. Figure 27 was made by Mr. Matthew Nitecki, of Walker Museum, University of Chicago. Dr. Tibor Perenyi helped in the drawings of figures 80–83. The invaluable aid of Mrs. Evelyn Shahroch, who typed several drafts of the manuscript, is also acknowledged gratefully, as is the assistance of my wife, Dr. Mary Woodland, who read the manuscript and suggested many improvements.

II. GENERAL OCCURRENCE OF CONE-IN-CONE

Cone-in-cone structure has been described from many areas of the United States and Europe and in beds ranging in age from Precambrian (Tanton, 1931, p. 42) to Tertiary. It is reported as occurring as lenticular calcareous beds of less than one inch up to about six inches in thickness. It occurs in shales and associated with shales and beds of sandstone (Gresley, 1894), as thin calcite veins in shales (Richardson, W. A., 1923), as layers on the upper and lower surfaces of concretions or actually comprising part of concretions, and as calcite veins separating the upper and lower impressions of trilobites and a fossil fish (Brown, 1954).

III. DESCRIPTION OF CONE-IN-CONE SPECIMENS

I collected specimens from three localities in Indiana and two in Wyoming. In these cases care was taken to mark the upper surface of the cone-in-cone layers. In addition a wide variety of examples has been studied from the collection in the Department of Geology, Chicago Natural History Museum, and from specimens provided by colleagues during the course of the work.

Although cone-in-cone structure has often been described in geological literature, salient features of the specimens studied, particularly those features that have a bearing on the genesis of the rock and its structure, are described here.

1. Woodland Valley, Parke County, Indiana
(G-3546–52, G-3557)[1]

MACROSCOPIC STRUCTURE

These specimens were collected from the bed of a stream in the Logan Quarry limestone member of the Staunton formation (Pennsylvanian).[2] The cone-in-cone layer is a thin but variable layer of about 23–24 mm. thickness. It is overlain by a richly fossiliferous bed some 13 mm. thick, composed of the shells of marine organisms such as molluscs, brachiopods, crinoid ossicles, and bryozoans. The shells are frequently whole, and spines are sometimes still attached to productids, indicating that the deposit probably represents a fauna that has suffered little transport.

Some of the shells have been replaced with pyrite. Below the cone-in-cone layer are dark blue-gray calcareous shales with occasional small shell fragments. Close inspection of the shale shows

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[1] Numbers preceded by G, P, and Li refer to specimens in the collection of the Department of Geology, Chicago Natural History Museum.

[2] Location and stratigraphic details of the Indiana cone-in-cone specimens are contained in Zangerl and Richardson (1963).

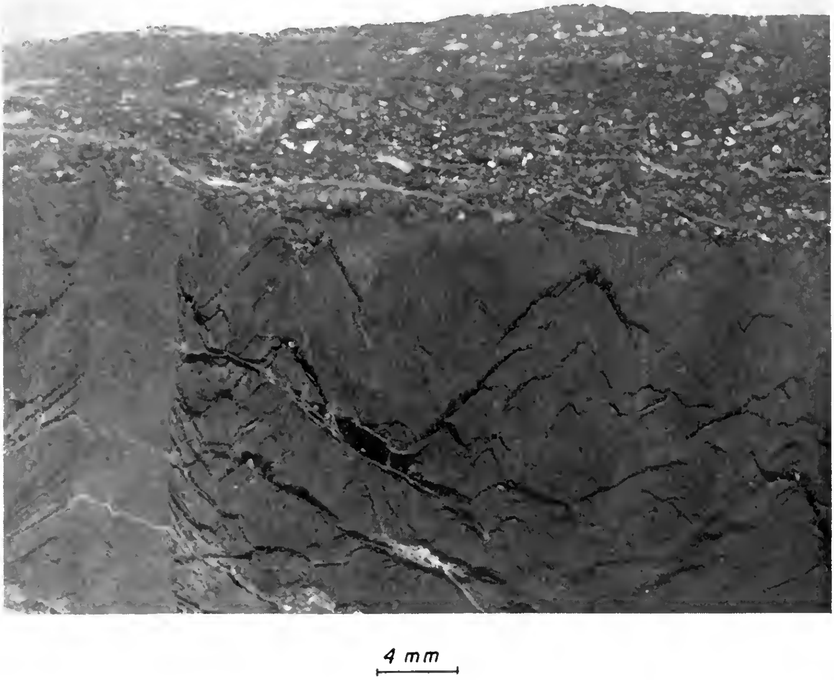

FIG. 28. Polished vertical section of cone-in-cone layer and overlying fossil breccia showing the cones interrupted by a vertical tubular plug of different lithology. Woodland Valley, Parke County, Indiana (G-3546).

that it is, in part, highly calcareous and contains cones, the largest of which is about 10 mm. high (G-3557). Unfortunately, these latter were not observed in the field and the specimen was not oriented.

The contact between the cone layer and the fossil layer is sharp but irregular, and some lenses of calcilutite and fossil fragments occur below the contact with cones above them. The cone layer itself contains only an occasional fossil fragment. The cones are not readily apparent, but partial cone surfaces can be seen on vertical fracture surfaces. The cone height varies from about 4.5 to 14.4 mm., averaging about 11.3 mm., and the cone angle varies from 38° to 45°, with the point directed upward. In polished vertical sections thin, soft, dark gray, shaly layers outline cone and partial cone forms. Under 30 × magnification the cone surfaces are so crowded as to interfere greatly with one another and to form thin overlapping partially conical structures—the conic scales of Gresley (1894). The base of the cone-in-cone layer shows some cone-cups

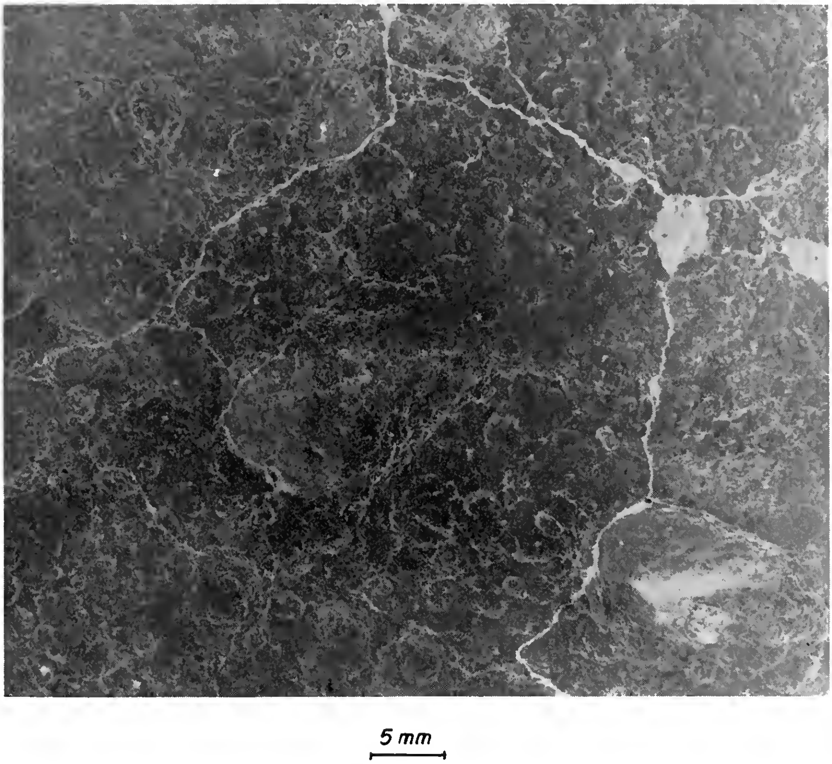

Fig. 29. Polished horizontal surface near lower boundary of cone-in-cone layer; dusted with alumina powder to emphasize structures. Woodland Valley, Parke County, Indiana (G-3547).

from which the cones have fallen out; the diameters vary from 1.6 mm. to 25.6 mm. The interior surface of the cone-cups has a characteristic corrugated surface to which adheres a layer of shaly material. The corrugations are irregular and form incomplete horizontal ledges around the cup. In vertical section the corrugations of the shaly layers are particularly prominent in the thicker shaly intercalations. The toothed surface of the cup is comprised of two surfaces—small, more or less horizontal surfaces alternating with small, nearly vertical, slightly curved surfaces. These surfaces are shiny and appear to be slickensided, particularly the near-vertical ones. The cone surface that lies within the cup is essentially smooth and regular, with shale filling the toothed spaces between it and the next superimposed cone scale. Some vertical sections cut through columns, 4–5 mm. across, which are lighter in color than the cone-in-

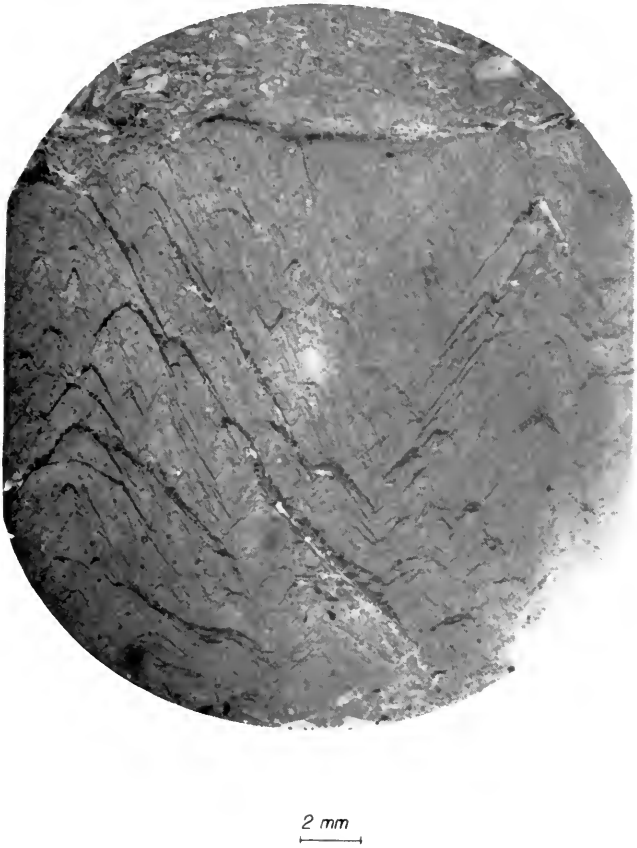

FIG. 30. Vertical thin section of cone-in-cone layer and overlying fossil breccia. Woodland Valley, Parke County, Indiana (slide no. 252).

cone matrix and which interrupt the conical clay layers (fig. 28). The columns may extend the entire thickness of the coned layer but others divide and come together within the coned layer and may, in the plane of the section, terminate within the layer.

Horizontal polished surfaces show concentric arcs, arranged to form overlapping circular series, composed of the shaly intercalations (fig. 29). Laterally the cone-in-cone layer passes into a zone where the cones are less distinct and there are many more shaly intercalations occurring as horizontal streaks and lenses, associated with pyrite blebs and fossils. The cone-in-cone layer thins and the overlying fossil layer increases to 30 mm. In the field the cone-in-cone layer appears to pinch out laterally although it could only be

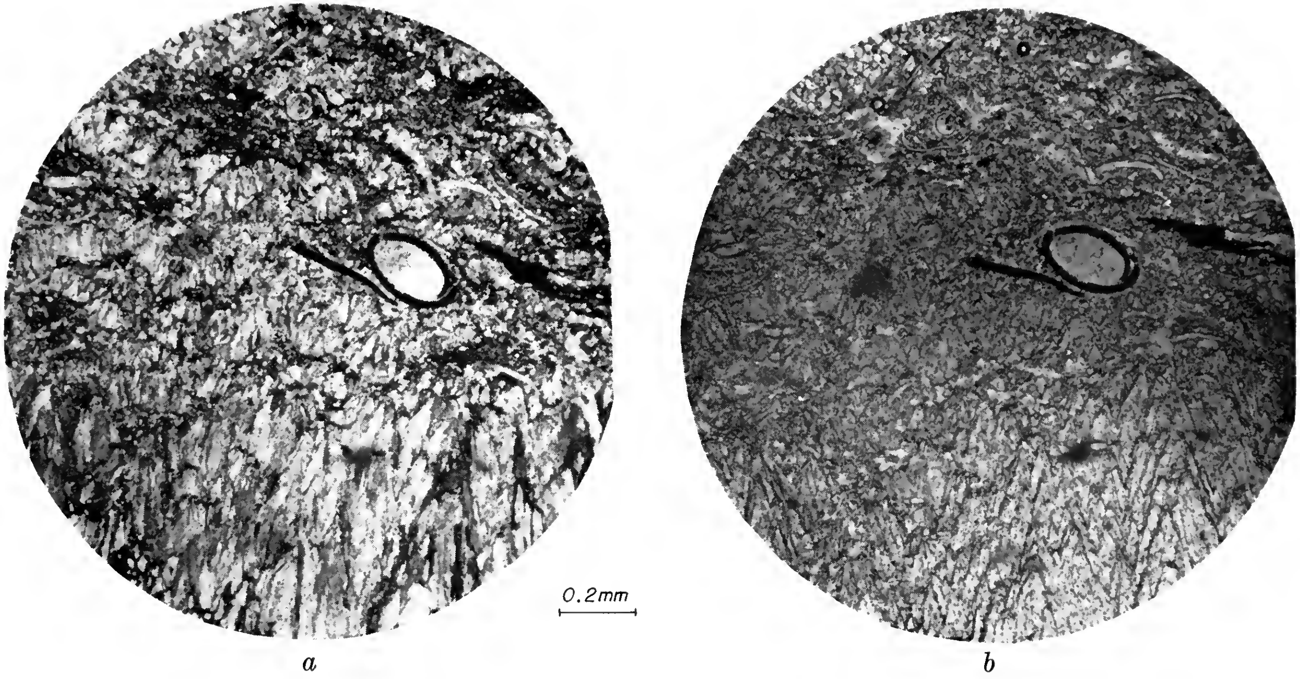

FIG. 31. Vertical thin section of cone-in-cone and overlying fossil breccia: *a*, crossed nicols; *b*, ordinary light. The opaque areas are pyrite that has replaced calcite. Woodland Valley, Parke County, Indiana (slide no. 252).

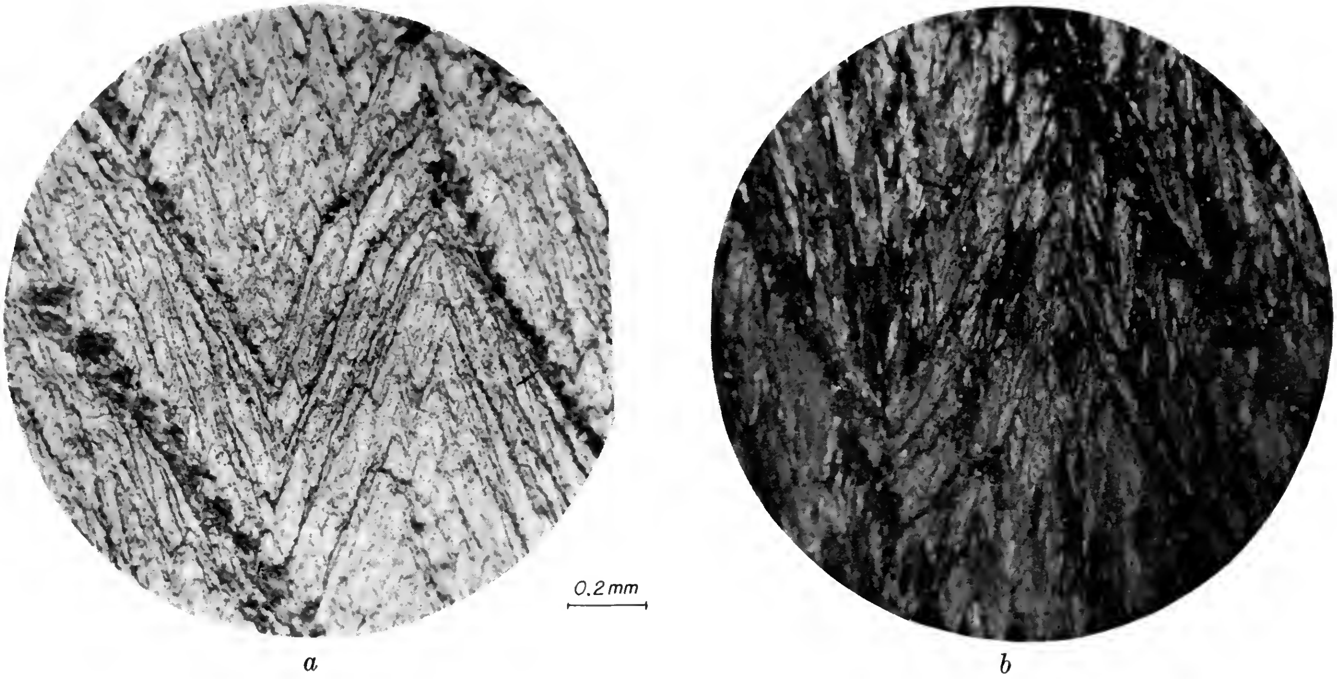

FIG. 32. Vertical thin section of cone-in-cone layer showing conical corrugated clay layers and microcones: *a*, ordinary light; *b*, crossed nicols. Woodland Valley, Parke County, Indiana (slide no. 252).

traced in one direction. However, it appears that the cones are developed within a restricted area.

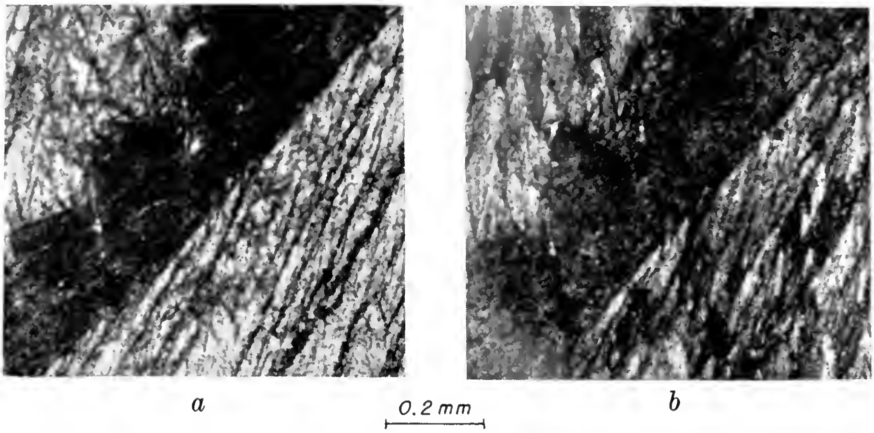

Fig. 33. Vertical thin section of cone-in-cone layer showing corrugated clay layer: *a*, ordinary light; *b*, crossed nicols. Dotson's Branch, Parke County, Indiana (slide no. 267).

MICROSCOPIC STRUCTURE

Vertical sections (slide nos. 252–3).[1]—The cone-in-cone layer generally has a sharp contact with the overlying shell breccia (fig. 30), but in places it is irregular, with lenses of the latter embedded in the coned layer and with fine-grained fibrous calcite zones in the lower parts of the breccia (figs. 31, *a*, 31, *b*). The calcite of the coned layer has a very characteristic structure; the grains, from about 0.025 mm. up to 0.19 to 0.29 mm. in length and up to 0.04 mm. in width, are more or less spindle-shaped and are aggregated into small conical bundles all pointing to the upper surface of the layer (figs. 31, *a*, 32, *b*). Many minute clay particles are arranged in fine layers forming partial cones in a complex meshwork (figs. 31, 32). Thicker layers of clay form partial cones pointing upward, with the upper surface toothed or corrugated in a characteristic manner. These thicker clay inclusions have variable angles with respect to the horizontal; they are sometimes parallel to the finer smaller cones but in many cases cut across the latter structure, although usually at a small angle (fig. 32). This feature is identical to that shown at a higher magnification in figure 33, although this specimen came from another

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[1] Slide numbers refer to thin sections in the collection of the Department of Geology, Chicago Natural History Museum.

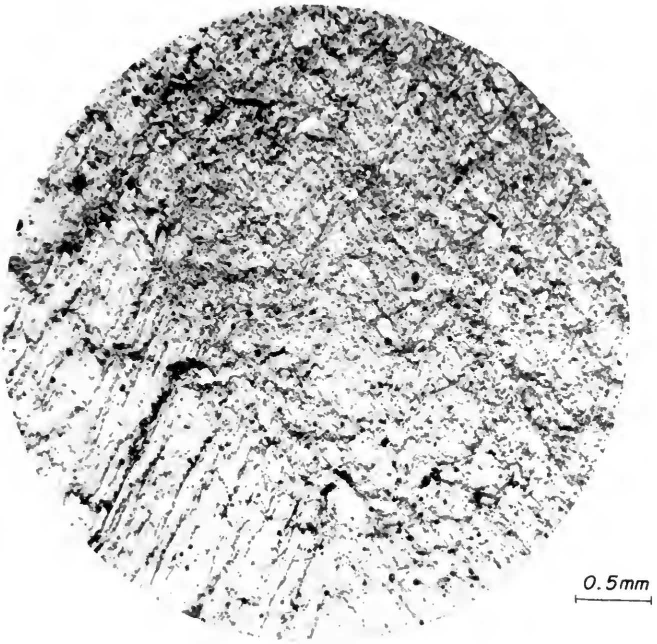

FIG. 34. Vertical thin section of contact between coned layer and transecting plug of different lithology that also shows microcones. Woodland Valley, Parke County, Indiana (slide no. 253).

locality. The variability of the cone angles of the thicker clay lenses and their discordance with the finer clay layers are produced when the section cuts through cones at variable positions; some, for example, are through the axis while others more commonly are tangential. The small cones give the appearance of greater uniformity because their small size produces an average overall effect of a cut through the axial zone of the individual cones. It is the thicker clay layers that form the macroscopic cones. The calcite fibres tend to have a vertical arrangement but their extinction is variable, although at a small angle to the perpendicular. This suggests that the "c" axes have a conical arrangement (see p. 277). The calcite adjacent to the thicker clay lenses is more irregular in shape and arrangement and more variable in grain size than elsewhere. The clay particles in these corrugated layers are oriented parallel to the smooth conical surface, near to the latter surface, and parallel to the more nearly horizontal surfaces of the "teeth" in the corrugated portion. The more or less vertical surfaces of the corrugation commonly have fine clay trails which pass upward into the calcite and form part of the system of small, partially conical clay lines. An occasional lens of coarse calcite is a fragment of recrystallized fossil shell with a thin layer of clay on the upper surface.

A thin section of one of the plugs of lighter-colored, apparently non-coned material shows a distinctly different texture, but an incipient development of microcones is present (fig. 34). The plug is composed of very fine grained calcite, pyrite blebs, much dispersed clay particles and aggregations of clay, and some shell fragments. The calcite has patches of microcones throughout, which are much finer grained than the surrounding cone-in-cone material. The boundary of the plug is not sharply demarcated under the microscope, although on a polished surface it is very clear even under 30 × magnification. In one portion the boundary is formed of a corrugated clay layer that is part of the normal cone-in-cone layer. This particular plug divides and encloses a central zone of normal cone-in-cone. The plug thus originated before the development of cone-in-cone. Apparently it represents an intrusion of material from above, probably as a result of the activity of burrowing organisms. It penetrated the full thickness of original sediment that is now represented by the cone-in-cone layer, and it terminates above at the base of the shell breccia. The appearance of the plug suggests that at the time of its formation the cone-in-cone layer (not then coned) had much the same thickness as it has today. The cones then developed in both the plug and the surrounding matrix as a consequence of deposition and perhaps recrystallization of calcite in the pore spaces without much expansion in thickness. Such an explanation, however, is not in accord with the origin of the cone structures in the trilobite and in the veins from New Brunswick and Quebec (see pp. 238, 251, 247). An alternative explanation is that the intruded material was present in the sediment and expanded in height along with the increase in thickness of the cone-in-cone layer and the disruption and displacement of clay layers during the addition and crystallization of the carbonate.

The shell breccia (fig. 31) is composed of abundant shell material, apparently only in part recrystallized but in places replaced by massive pyrite. Original open spaces in the fossils are filled with calcite. The interstitial material is fine-grained calcite; in part, near the top of the cone-in-cone layer, this calcite has a fibrous texture similar to that of the cones but much finer (fig. 31, *a*).

A thin section (no. 266) of a layer beneath the cone-in-cone layer is seen to have well-developed microcones but only a few thicker

FIG. 35. Vertical thin section of shale lens in coned layer below main cone-in-cone layer; note that the cones both above and below the lens point toward each other. Woodland Valley, Parke County, Indiana (slide no. 266).

corrugated clay cones. Much clay is present in horizontal wavy lenses, and fossil debris is common both in the clay layers and in the coned portions. The shell fragments usually have a clay layer on one surface. One area of the slide contains a relatively thick lens of fine-grained structureless calcite and clay with shell fragments (fig. 35). The fibrous calcite around the lens has well-developed partial cones. The structure is confused and, in general, it is not possible to determine the direction of the apices. But, utilizing the corrugated surface of the cones, it is seen that the cones on each side of the lens are directed toward the lens; that is, the cones point toward each other. This indicates a difference in direction of growth of the calcite, presumably away from the lens.

Horizontal sections (slide nos. 254–5).—Many incomplete arcs of clay occur in a matrix of fine-grained calcite with an occasional fossil fragment and pyrite grains (fig. 36). The calcite is 0.012 to 0.05 mm. across and under conoscopic observation the "c" axes are seen to be nearly vertical and to lie, as a rule, within the field of view of the microscope. The clay arcs are intergranular and mark the intersection of the partial cone surfaces with the plane of the section.

FIG. 36. Horizontal thin section of cone-in-cone layer. Woodland Valley, Parke County, Indiana (slide no. 254).

2. DOTSON'S BRANCH, PARKE COUNTY, INDIANA
(G-3553–56)

MACROSCOPIC STRUCTURE

This occurrence is exposed in the bed of a stream and is part of the Holland limestone member of the Staunton formation (fig. 37). The cone-in-cone layer passes laterally into a band containing concretions. The cones appear to be limited to a zone of about four feet, measured across the stream bed.

The cone-in-cone layer has a maximum thickness of about 62.4 mm. Above it is a rubbly limestone with many brachiopod shells and below it is shale. The cones are well defined, with lineations from peak to base formed by bundles of fine calcite needles. The cones point to the original upper surface of the bed (fig. 38). The

FIG. 37. Cone-in-cone layer (knife 90 mm. long). Dotson's Branch, Parke County, Indiana.

FIG. 38. Polished vertical section of cone-in-cone layer showing corrugated cone cups in lower center and right. Dotson's Branch, Parke County, Indiana (G-3554).

Fig. 39. Polished vertical surface etched with dilute hydrochloric acid to bring out corrugated conical clay layers and microcones. Dotson's Branch, Parke County, Indiana (G-3553).

maximum height of the cones is about 36.5 mm., but the height is usually about 29.0 mm. The cone angle of one specimen measured near the peak is about 30°; just below the middle it is 52° and at the base 106°. No single cone or partial cone extends from the base to the top of the layer, but a series of cone-in-cones around a common axis does extend the entire thickness. Shaly intercalations are well developed and define the cones (fig. 39). In addition to the thicker layers there are many finer conical or partially conical inclusion layers; the clay material is also aggregated into lenticles only partly related to the conical structure. The cone-cups exhibit well-marked corrugations that give the clay insertions a toothed or zigzag appearance on their outer conical surface. The corrugated surface is comprised of near-vertical surfaces (1.48 mm. high, in one example near the base) and of surfaces (2.27 mm. broad) that dip outward from the cone axis at about 108° to 110°.

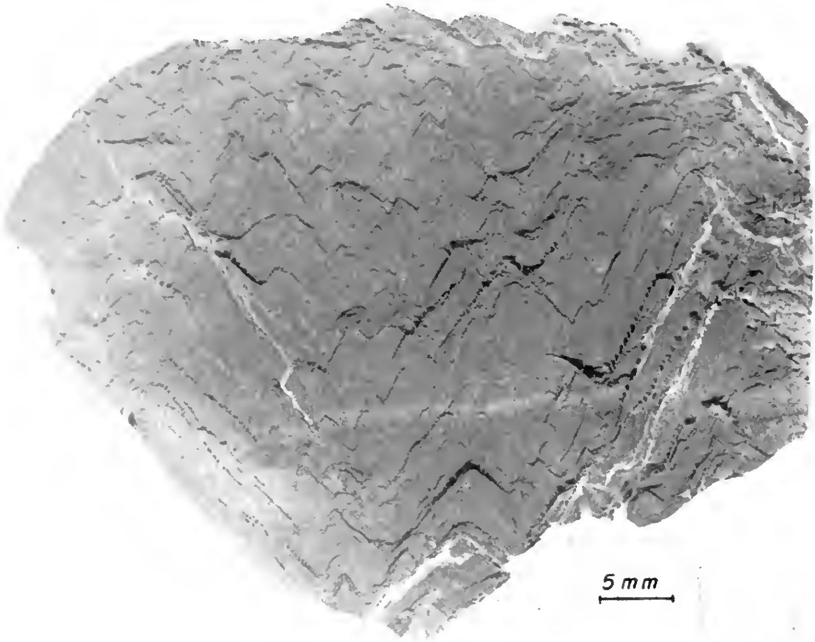

FIG. 40. Polished vertical section of cone-in-cone layer showing fine horizontal banding. Dotson's Branch, Parke County, Indiana (G-3553).

MICROSCOPIC STRUCTURE

Vertical section (slide no. 267).—The microscopic structure is identical to that of the Woodland Valley specimens. Near the base of the cone-in-cone layer there occurs a fine banding which on a polished surface appears as a series of slightly undulating lighter- and darker-colored bands 0.14 to 0.28 mm. wide (figs. 40, 41). Thicker corrugated conical clay layers cross the bands, with slight displacement (e.g., 0.18 mm. in one case) of the bands at these intersections (fig. 40). The bands are the result of relatively increased concentrations of clay—particularly in the apices of the small, partially conical, clay laminae forming microcones—alternating with zones with relatively less clay content (fig. 42). The fact that the microcones occur without any change across the bands and the fact that the bands themselves show displacement suggest that they owe their existence to a pre-cone effect. However, the thicker corrugated clay cones cross the bands without interruption (fig. 40). It is difficult to envisage how the clay layer could be displaced vertically through pre-existing horizontal bands without the destruction of the latter in the affected zones. The bands probably originated during the crystallization of the calcite in such a way as to cause small, local, vertical displacement of clay particles, which produced horizontal zones containing relatively less clay alternating with zones containing relatively increased amounts. The cause of this differential distribution of clay in these thin zones is not known, but it may represent short interruptions or changes in the crystallization process (see Reis, 1914, p. 288).

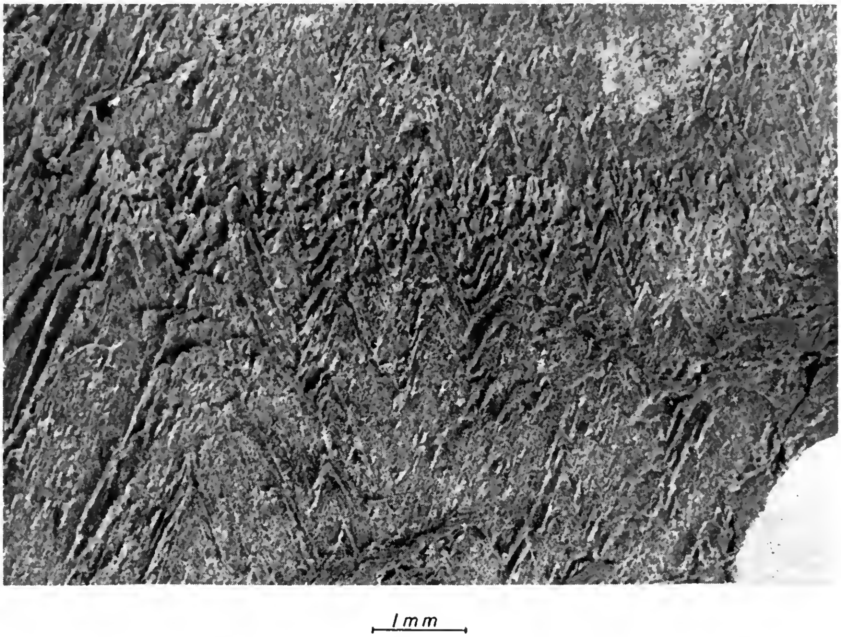

FIG. 41. Polished vertical section etched with dilute hydrochloric acid to show nature of horizontal bands in cone-in-cone layer. Dotson's Branch, Parke County, Indiana (G-3553).

Small fossil fragments occur sparsely with a clay lens above (fig. 43). In some instances the fossil is separated from the clay lens by a thin zone of very fine-grained fibrous calcite and has beneath it a similar thin zone of calcite that merges into the coarser fibrous calcite. In other instances, fine calcite between the fossil and the clay lens is absent and is only slightly developed below the fossil.

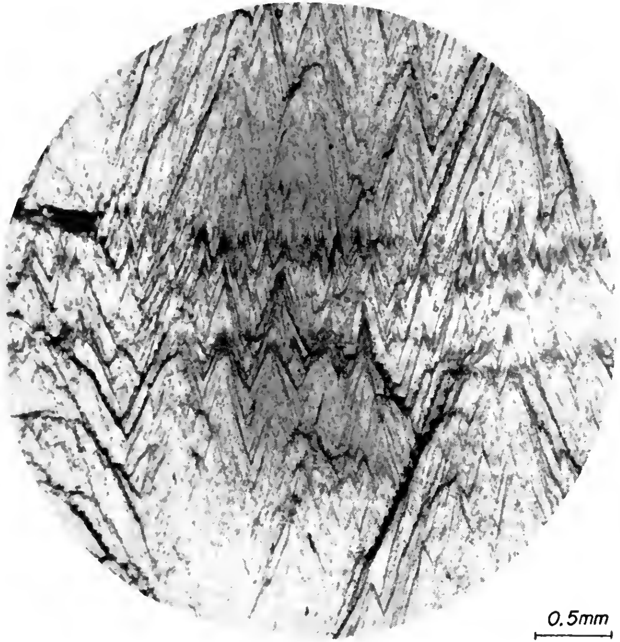

FIG. 42. Vertical thin section of cone-in-cone layer showing nature of horizontal bands. Dotson's Branch, Parke County, Indiana (slide no. 267).

FIG. 43. Vertical thin section of cone-in-cone layer showing shell fragment and associated shale lens; crossed nicols. Dotson's Branch, Parke County, Indiana (slide no. 267).

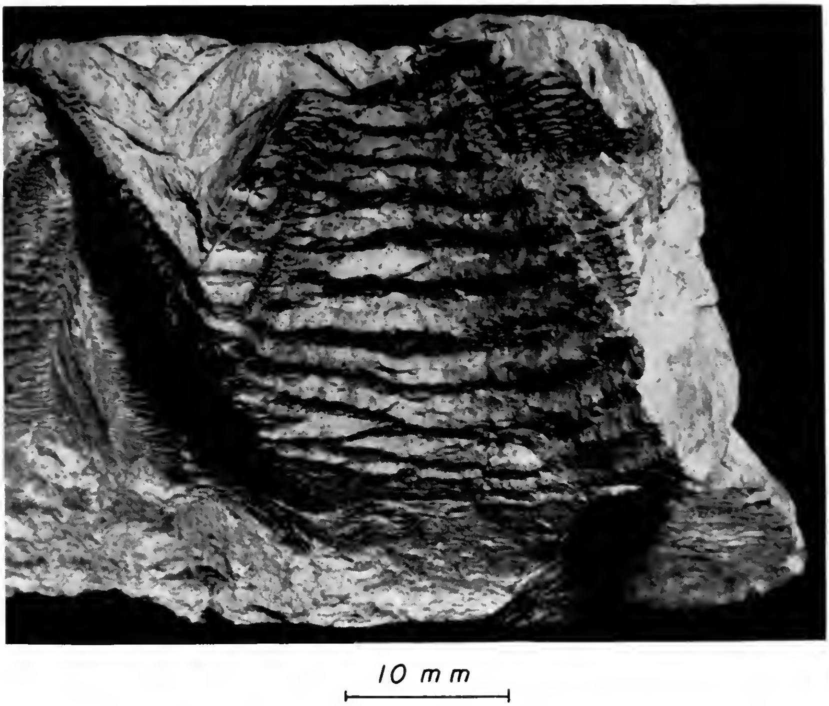

Fig. 44. Well-developed corrugated cone cups. Coal Creek, Fountain County, Indiana (G-3560).

3. South Trumpet Valley, Parke County, Indiana (G-3558)

Small specimens (Logan Quarry limestone member, Staunton formation) collected from the stream bed are very similar to the Woodland Valley occurrence. Their maximum thickness is about 20.0 mm. The cones point upward and the coned layer is overlain by fossiliferous rubble.

4. Trumpet Valley, Parke County, Indiana (G-3559)

A few fragmentary specimens (from below Logan Quarry shale, Staunton formation) were collected in the bed of the stream but they are not oriented as to top and bottom. The cone-in-cone layers are at least 73.8 mm. thick. Cone surfaces show longitudinal striations from peak to base, while cone-cup surfaces are corrugated. Cone angles are very acute, with angles, measured near the peak, of 25° in one case and 28° in another.

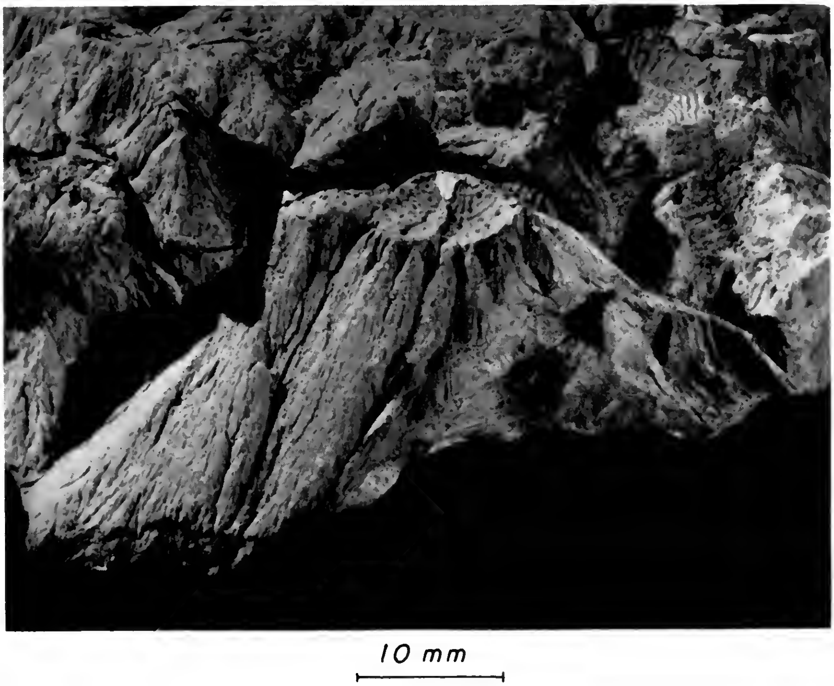

FIG. 45. Valve of *Desmoinesia muricatina* overlying a cone of a cone-in-cone layer; a spine extends steeply along a conic scale. Coal Creek, Fountain County, Indiana (G-3560).

5. Coal Creek, Fountain County, Indiana (G-3560)

One specimen from above Coal IIA, Staunton formation, was collected by Dr. Zangerl. It has a thickness of nearly 32 mm. and the maximum individual cone height is 29.81 mm. The maximum cone base is 33.86 mm. The cone surfaces have both longitudinal and transverse concentric striations. The inner cone surface or cup is irregularly corrugated, the characteristics of which are shown in figure 44. The average cone angle of the specimen is about 68° but it flares out toward the base so that the corresponding angle here would be about 108°. The cones point to the surface, which contains several brachiopod shells. One valve of *Desmoinesia* lies on the surface (top?) at the focus of a series of conic scales. One spine is clearly visible as being in position and was still attached to the shell at the time of collection (fig. 45). The shell material of this part of the valve has come away and the impression clearly shows the point of attachment of the spine to the shell. The spine extends

FIG. 46. Corrugated surface of cone-in-cone layer; an interior surface along which the specimen separated. Viewed toward an exterior surface, the ridges are analogous to cone structure. One mile south of Mecca, Parke County, Indiana (G-3843).

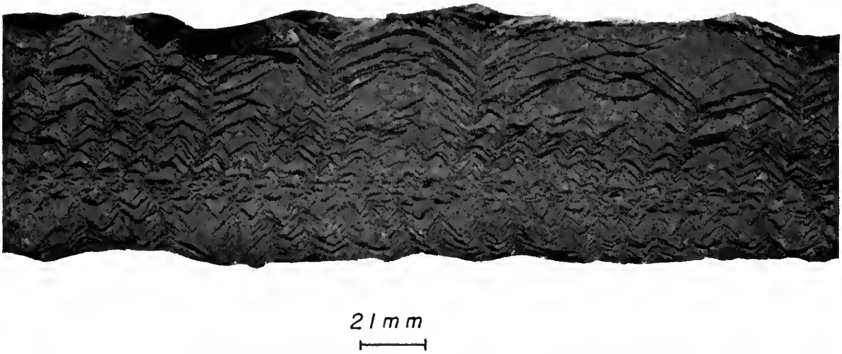

FIG. 47. Polished vertical section of cone-in-cone; note upper and lower layers, separated by thin intermediate zone. Conical forms are black shale, with apices toward the interior. One mile south of Mecca, Parke County, Indiana (G-3843).

steeply down the surface of a conic scale for about 13 to 14 mm. and then flattens out for a further 7 to 8 mm., occurring apparently in a shaly intercalation between conic scales. There are a few fractures in the spine but there has been only slight displacement. This occurrence indicates that the spine must have been embedded in a matrix sufficiently strong to support it. Any differential movement between the cones, which must have developed after the brachiopod with its spines was emplaced, was not of a violent nature and presumably not of a shearing type. The presence of this delicate carbonate spine in the clay also supplies evidence that the clay is not a residue concentrated by solution of carbonate.

6. OLD MINE DUMP, DUEE HOLLOW, ONE MILE SOUTH OF MECCA, PARKE COUNTY, INDIANA (G-3843)

MACROSCOPIC STRUCTURE

As this specimen was collected from a waste heap its original orientation is not known. It is about 18 mm. thick and is interesting because both of its surfaces, which presumably were parallel to the bedding, have irregular corrugations, somewhat like ripple-marks (fig. 46). The corrugations have a reticulate pattern and their amplitude is about 2 mm. on one surface compared to 1 mm. or less on the other. In a polished vertical section these corrugations can be related to the partial cone structures in the specimen, which is divisible horizontally into three layers (fig. 47)—two outer coned layers separated by a thin non-coned zone. One coned layer is 4 mm. thick while the other is 12 mm. thick, and both show partial cones formed by layers of black shale separated by calcite. Toothed surfaces of the shale indicate that the cones of each layer point toward the interior. In the intermediate zone, some 2 mm. thick, small saucer-shaped wisps of shale lie parallel to the horizontal. As the cones tend to occur in vertical stacks and also in discontinuous rows, the surfaces of the specimen are corrugated. Most of the stacks of cones have a distinct narrow axis of lighter color composed of very fine calcite (fig. 48). The axis is actually a thin sheet axial to a short row of related partial cones, each of which forms a trough section of the corrugated surface (figs. 49 and 50).

MICROSCOPIC STRUCTURE

Vertical section normal to corrugations of surface (slide no. 825).—The coned zone shows undulating, discontinuous, very dense shale layers up to 0.28 mm. thick, forming macrocones up to 1.16 mm. high. The outer surfaces of some of these shale layers have the characteristic toothed structure. The shale is opaque even when very thin and in this respect is similar to the Mecca Quarry shale (Zangerl and Richardson, 1963) reported by Ashley (1899, pp. 363, 371) as occurring above the coal of this locality. The calcite between the shale lenticles is fibrous, with fibres up to about 0.1 mm. long, and occurs in microcones about 0.23 mm. high outlined by very fine shale layers.

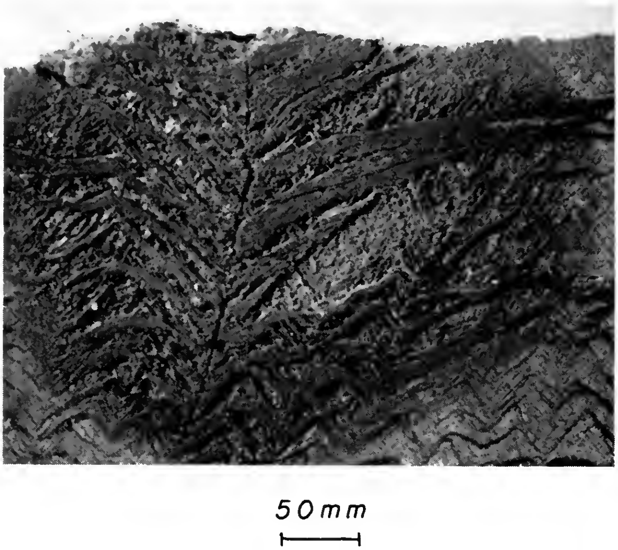

FIG. 48. Etched vertical section of one stack of cones shown in figure 47. Note axial zone that disrupts conical sheets of black shale. Fine calcite has been dissolved, leaving a furrow.

Vertical section parallel to corrugations of surface (slide no. 826).—This section is closely similar to that above except that the macrocones do not exhibit the same degree of regularity. In part the shale layers form large arcs, indicating that the section was cut tangentially along a row of partial cones.

Horizontal section (slide no. 827).—Wide arcuate shale layers are present, representing the intersections with macrocone shale layers that actually have the form of linear troughs rather than partial cones. Between the macrocone shale layers is the fibrous calcite that contains arcuate sections of the partial microcones.

The cone-in-cone layer probably developed at the top of the Mecca Quarry shale when the lithology was transitional to shales of the Velpen limestone member (Zangerl and Richardson, 1963), as Ashley (1899, p. 363) records limestone bands and cone-in-cone in the area where this specimen was found. Dense black carbonaceous layers may have alternated with thin clay or silt layers (as represented, for example, in pl. 8, C, or pl. 10, F, Zangerl and Richardson, 1963). The calcite crystallized following nucleation on the surfaces of the carbonaceous layers, and continued fibrous growth produced the microcone and the linear macrocone structures. The time of development would have been shortly after deposition of the black shales when the environment had changed and the marine waters were bearing lime in solution. The axial sheets of the partial cones evidently controlled the development of the structure. The axial sheets may have been fine cracks or disturbances in the original sediments before the crystallization of any carbonate but their origin is unknown.

It is pertinent to mention here that Mykura (1960) records cone-in-cone veins and limestone bands that have replaced coals obviously long after deposition and coalification. The calcite replacement is part of a process during which the coal was partly or completely removed by oxidation. Residual coaly material and mineral impurities of the coal form layers outlining the cones (see Mykura, 1960, pl. VII, C). This is a special case of delayed development of cone structure. The oxidation of the coal evidently produced conditions in the residue physically suitable for cone-in-cone to form so long as calcium carbonate was available in the circulating water. Deposition and growth were probably synchronous with oxidation or followed immediately or shortly thereafter.

7. Montgomery Creek, Parke County, Indiana (Li-4709)

MACROSCOPIC STRUCTURE

The limestone beds comprising the Velpen member (Linton formation) are dark gray and very impure, a representative seven-gram sample containing over 36.6 per cent of insolubles. Organic content is, however, very small, as the loss in weight on heating the residue to 700° C. is only 3.5 per cent of the total sample and much of the loss represents oxidation of the pyrite. Fossil fragments are abundant more or less throughout the matrix but tend to be more prevalent in some ill-defined bands. The matrix has a general dark gray

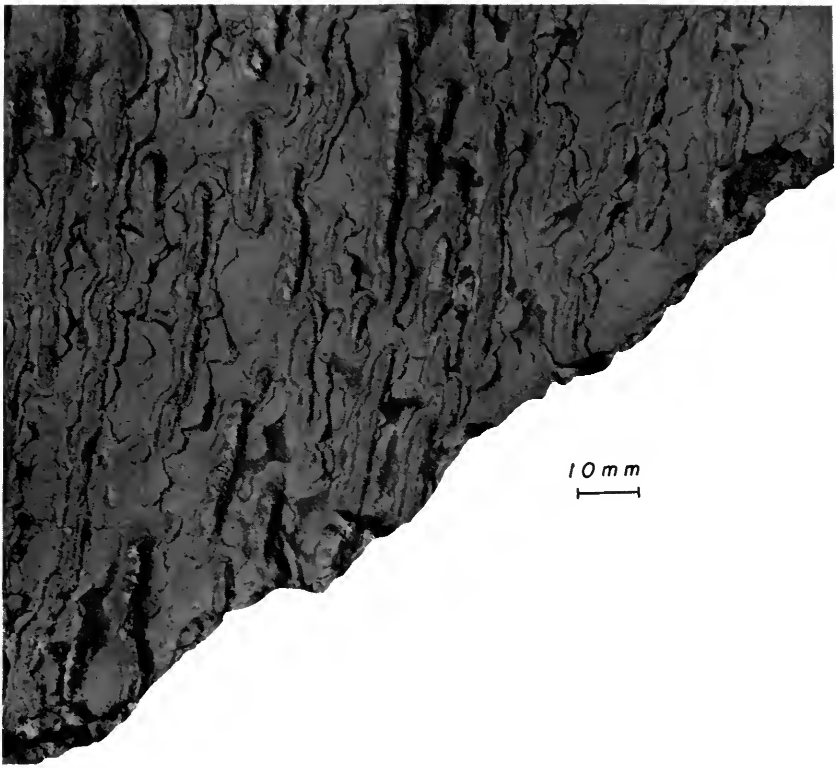

FIG. 49. Polished horizontal surface of cone-in-cone from specimen G-3843, shown in figures 46–48. Note that deeper troughs (analogous to cone-cups) remain.

color with streaks and lenticles of darker gray ranging in thickness from large masses up to 10 mm. down to mere wisps just visible to the naked eye. Pyrite is common; it replaces the shells and also occurs as blebs throughout the matrix.

MICROSCOPIC STRUCTURE

Vertical section (slide no. 370).—The rock is very dense and its structure remains much obscured by opaque matter even when the section is very thin. The clay material is disseminated throughout, obscuring the crystalline calcite base; the latter is very fine grained, the grains rarely exceeding 0.005 mm. and usually less than 0.0025 mm. in diameter. Much of the clay is aggregated into wisps and lenticles; in some patches these form microcones. In the better-defined zones the cones are clear and the calcite is somewhat less

FIG. 50. Enlarged view of the right end of the specimen shown in figure 49. The arcuate black structures are intersections with black shale layers forming partial cone-cups or troughs. The light-colored vertical lines are carbonate-rich axial sheets of trough zones, each of which contains a stack of structures analogous to cones.

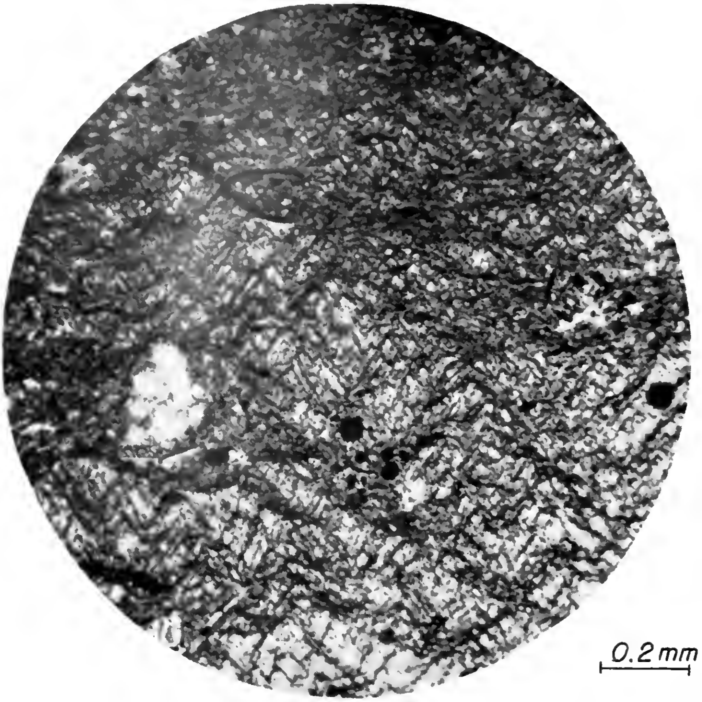

FIG. 51. Vertical thin section of Velpen limestone, Barren Creek, Wabash Township, Parke County, Indiana, showing microconed zones (slide no. 293).

charged with inclusions. The individual cones are about 0.2 mm. in height, and the clay layers 0.008 to 0.02 mm. thick. Fibrous texture is not evident because of the fine grain size and the high clay content. Because of the merging mass of cones it is not possible to determine the true apical direction of any zone; the cones appear the same in either direction and there are no corrugations of the fine layers to help in determining the orientation. The coned patches contain some fossil fragments and pyrite blebs. Some zones occur on shell fragments; others grade into the rock matrix. The coned zones pass into areas of greater clay content where incipient coning can just be made out, thence to zones where the clay wisps have a more crescentic shape, and finally to zones where there is no evidence of coning or concretionary formation.

8. BARREN CREEK, PARKE COUNTY, INDIANA (LI-4708)

An etched vertical surface and thin sections (slide nos. 291–3) of this specimen of the Velpen limestone member show the same relationships of microconed zones passing into zones of incipient cones and into areas of considerable clay material, which is finely pitted, indicating where disseminated calcite has been dissolved out. The thin section (fig. 51) has structures identical to those described above from Montgomery Creek.

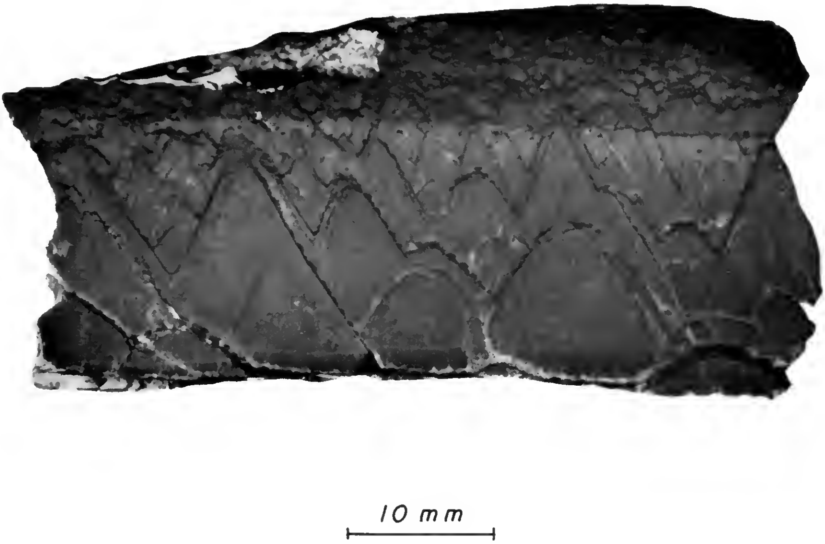

FIG. 52. Polished vertical section of cone-in-cone showing transition zone (upper portion). North East, Pennsylvania (G-3568).

9. Town of North East, Pennsylvania (G-94 and G-3568)

MACROSCOPIC STRUCTURE

The cones in specimen G-94 are well formed but interfere with one another so that they are invariably only partial cones. They extend from one surface of the specimen to a level 27.20 mm. from their bases, where they pass into a non-coned zone that does, in part, have a fibrous texture and a suggestion of microcones; otherwise, the material filling in between the cone peaks appears to be a structureless calcilutite. The projected cone angle, which is 36° at the peak, increases to 104° near the base. A polished surface of a similar specimen (G-3568) clearly shows the shaly intercalations between the cones, and the non-coned layer is seen to contain more or less horizontal thin clay lenses (fig. 52). Cone angles at the peaks vary from 56° to 64°.

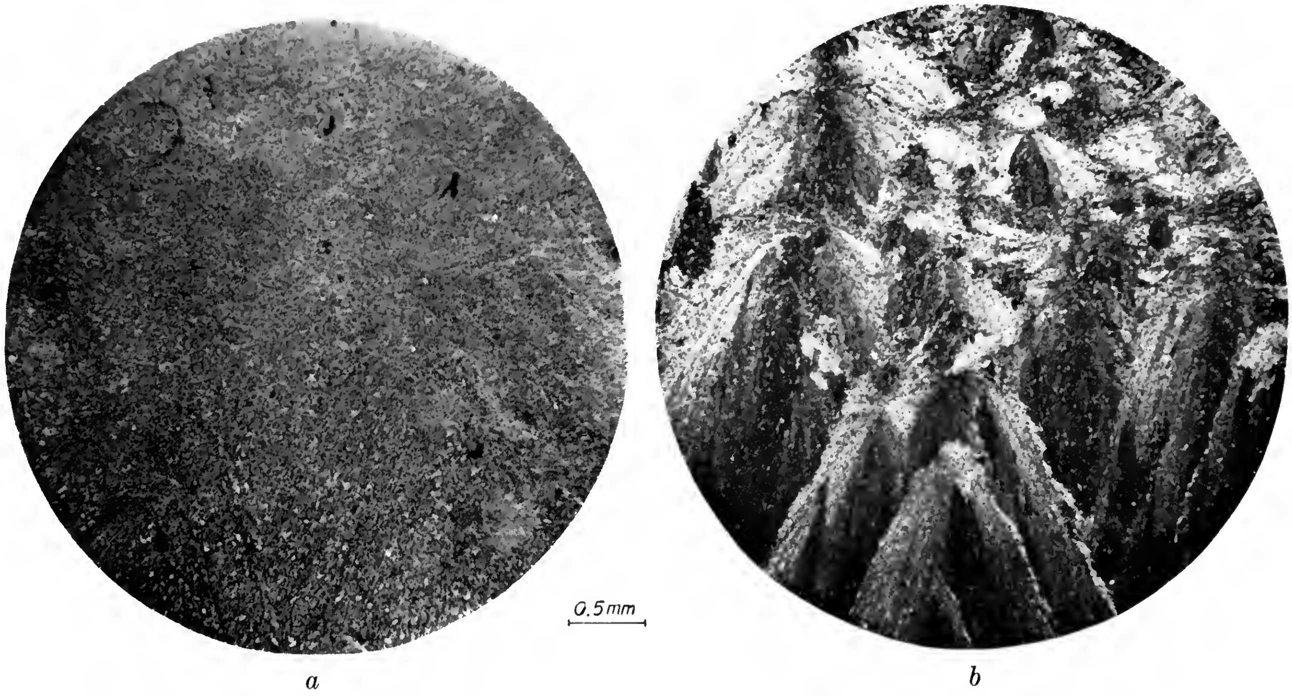

FIG. 53. Vertical thin section of cone-in-cone layer and transition zone: *a*, ordinary light; *b*, crossed nicols. North East, Pennsylvania (slide no. 276).

FIG. 54. Vertical thin section of cone-in-cone layer showing corrugated clay layers and calcite spindles; crossed nicols. North East, Pennsylvania (slide no. 276).

MICROSCOPIC STRUCTURE

Vertical section (slide no. 276, made from G-3568).—The calcite appears to be very fine grained with abundant clay included, much of which is arranged into interfering conical surfaces (fig. 53, *a*). Under crossed nicols, however, the section shows spindle-shaped areas, each of which nearly extinguishes as a unit and the long direction of which is more or less parallel to the cone axes (figs. 53, *b*, 54). The thicker corrugated clay layers define the macroscopic cones of the specimen. The conical surfaces all point toward the same surface. In this direction the matrix passes into a zone where the calcite is much more irregular, the clay content is increased, and conical clay surfaces are absent (fig. 53, *a*). In the transition zone the calcite spindles become more irregular and smaller and finally disappear (fig. 53, *b*). This passage from a coned to a non-coned layer is thus gradational under the microscope, but to the naked eye it is a sharp line marked by a color difference on the polished surface

Fig. 55. Vertical thin section of cone-in-cone layer showing fine horizontal bands. North East, Pennsylvania (slide no. 276).

(fig. 52), although close examination does indeed show that some of the cone apices pass across the contacts.

Near the boundary toward which the cones open are several thin, faint bands caused by alternating zones of more and fewer clay inclusions (fig. 55). The microcones continue through these zones without interruption. The bands are identical to those described in the Dotson's Branch specimen.

10. Concretion, North East, Pennsylvania (G-151)

MACROSCOPIC STRUCTURE

This is a large "double-eyed" concretion 55.0 cm. long, with one eye 35.0 cm. across and the other 28.0 cm. (fig. 56). The maximum thickness of the concretion is 90 mm. One surface has marginal concentric markings apparently denoting original bedding laminae, while the other has characteristic arc-like structures representing the clay

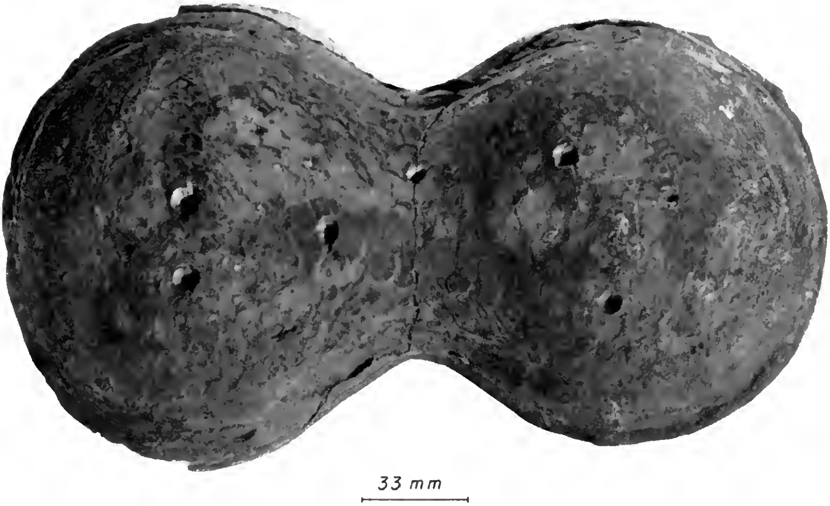

FIG. 56. Surface of large "double-eyed" concretion showing cone cups. North East, Pennsylvania (G-151).

bases of partial cones. The arcs extend across the waist portion joining the "eyes" and are concentrically arranged around the centers of the eyes. Occasionally a combination of arcs forms an entire circle; in a few of these the complete cone has fallen out, revealing a corrugated cone-cup. The central portion of the opposite surface has small (up to ca. 3 mm.), circular marks caused by the bases of incipient cones.

The coned layer of one "eye" has split from the remainder of the concretion because of a clay parting. In section at the "waist" the separated layer is seen to have a maximum thickness of 24 mm., thinning to the margins. The outer 21 mm. are coned and pass in the interior to a non-coned layer containing much pyrite. At the center of the "eye" the layer is 30 to 31 mm. thick. The coned layer is concavo-convex. The internal concave surface has incomplete concentric "steps" in the clay parting with lineated slickensides stepping down toward the center of the concretion. The counterpart of this surface has a slight central swelling with slickensided "steps" around. A vertical section of the opposite part of the concretion has a maximum thickness of 58 mm. and is very fine grained. It shows, in part, a weak color lamination parallel to the surface and also has irregularly shaped zones, greenish in color, set in the purplish base of the interior portion. The external zone, 5 mm. thick, shows very faint incipient cone structures. On the inside of this zone is a 1 mm. thick zone bearing very small clay lenses.

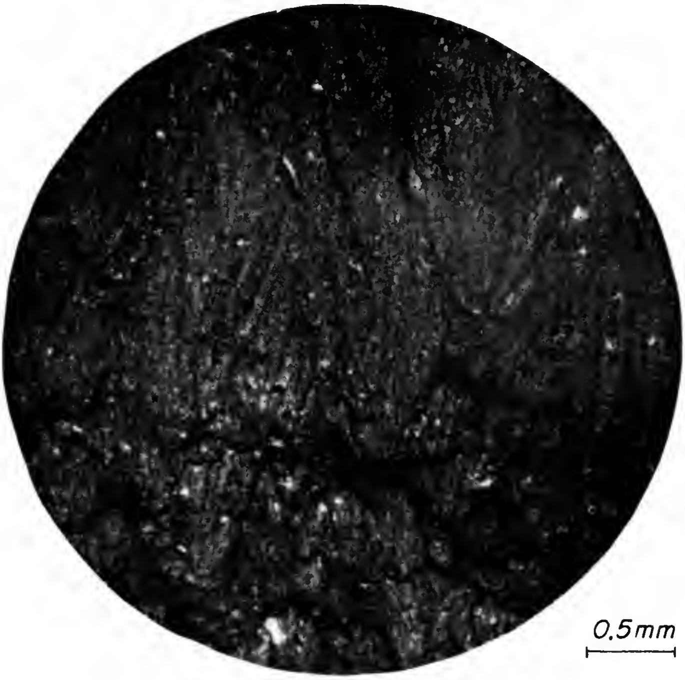

FIG. 57. Vertical thin section of weakly coned layer of specimen G-151, a concretion from North East, Pennsylvania (slide no. 277).

MICROSCOPIC STRUCTURE

Specimen G-3568, already described (p. 219), is identical in appearance to the cone-in-cone layer of this large double concretion and doubtless the microscopic structure is similar. The thinner layer on the opposite surface of this concretion shows only incipiently developed cones on a polished surface. Under the microscope (slide no. 277) microcones formed of lines of inclusions are visible but are not well developed (fig. 57). The cones point toward the center of the concretion. The coned zone passes inward to a zone where there is increased clay, now in saucer-shaped lenses, their concave surfaces facing the outside. This zone in turn passes into the regularly banded interior, composed of fine-grained calcite and clay. The banding is caused by varying quantities of the clay component. The coned pattern appears to be of very fine grain with calcite ranging from 0.008 to about 0.07 mm. but mainly between 0.015 and 0.023 mm. Between crossed nicols, however, there are larger fan-like areas of extinction whose orientation is related to the conical lines of clay. The banded zone is homogeneous between crossed nicols while the zone of saucer-shaped inclusions has clearly a transitional appearance. These structures are identical with the specimen G-3568 previously described except for their poorer development.

The occurrence of a coned fabric can thus pass by transition into a non-coned concretionary fabric. The development of the cones is accompanied by the appearance of the coarser spindle- or fan-shaped areas, with the orientation of the "c" axes of the calcite similar or nearly similar. The fabric suggests that the original fine-grained carbonate recrystallizes during the time the conical structure is forming. If such is the case, the cause of the recrystallization, why it should be restricted to the outer zones of the concretion, and why one layer is thicker and better developed than the other remain as unanswered questions. On the other hand, the fabric of the veins described later (p. 251) and of the Woodland Valley and Dotson's Branch specimens does not provide evidence of recrystallization. In fact, it is difficult, if not impossible, to see how the thicker corrugated clay cones could be formed and consistently point in the same direction in a particular layer by recrystallization of an existing carbonate-clay rock. It is probable, therefore, that the calcite crystallized directly, so that aggregates of minute fibres with almost the same lattice orientation form the spindle-shaped groups so characteristic of the microscopic structure viewed between crossed nicols.

11. Elk Creek, Girard, Pennsylvania

In August, 1963, I made a brief examination of cone-in-cone occurrences exposed in Elk Creek, three miles east-southeast of Girard, just north and south of the Gudgeonville covered bridge. North of the bridge the steep west bank, some 50 to 60 feet high, exposes shale of the Conneaut Group, upper Devonian. The gray, finely laminated shale breaks with an irregular fracture and weathers to a light brown color. Intercalated with the shale are thin (less than 1 inch thick), harder, siltstone bands. About five feet above the creek bed is a zone of ellipsoidal calcareous concretions which protrude several inches from the shale (fig. 58, *a*). The vertical faces of the concretions I examined were rough fracture surfaces produced by erosion (fig. 58, *b*), and these vertical sections were approximately ellipsoidal in outline, although the ends were blunt instead of smoothly rounded in some cases. All have an upper and lower cone-in-cone layer separated by a central non-coned layer. The cones all point toward the interior of the concretion. The enveloping shale layers are curved around the concretion but, on tracing to the periphery the layers lying on and immediately below the concretion, some 2 inches of shale lateral to it are not traceable over or under it. This represents the amount of material incorporated into the concretion during its growth. One concretion is 30 inches across and 10.25 inches thick, with an upper coned layer of 4 inches and a lower of 3.5 inches. Another section of a concretion (fig. 58, *b*) is 40 inches in diameter with an upper coned layer of 3 inches maximum thickness, a lower of 3.25 inches, and an intermediate non-coned layer of 2 inches.

Downstream, some 50 yards below the bridge, many cone-in-cone concretions are exposed in the creek bed. The shale has been eroded to reveal concretions, all at the same horizon, with variable shapes in plan view—ellipsoidal, discoidal, and more irregular; maximum dimension is 5 feet. They are spaced irregularly, some being as close as 4 feet and others up to 21 feet apart.

The concretions probably represent a period of increased liminess in the water, so that, although there was no deposition of carbonate as a sediment, the waters circulating through the sediments just below the sediment-water boundary became supersaturated. Deposition of carbonate began at a number of centers and continued long enough to produce the large coned concretions.

The detailed structure of the specimens G-3832–42 is similar in all essential respects to the structure of those described above (G-94, G-3568, and G-151).

12. CONCRETION, NORTH EAST, PENNSYLVANIA (G-638)

MACROSCOPIC STRUCTURE

The specimen is incomplete and represents approximately half the concretion, which had broken vertically across the originally discoid body (fig. 59). Its maximum thickness is nearly 58 mm. and its original diameter would have been about 200 mm. In vertical section the central portion of the concretion is horizontally bedded and contains thin wisps of clay material horizontally arranged (fig. 60). In some bands and patches the clay wisps are dark-colored, in others they are buff-colored (oxidized?). The two outer coned layers taper to zero

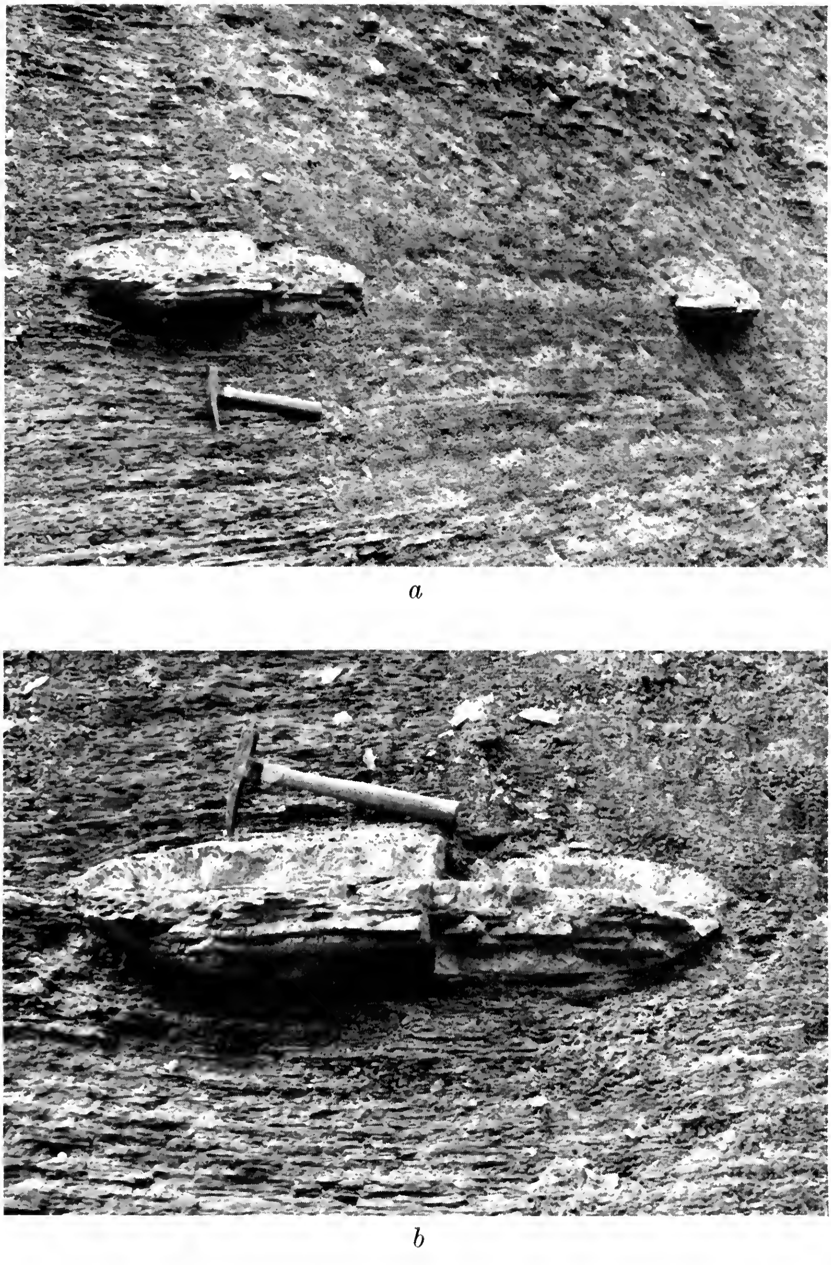

Fig. 58. Concretions bearing cone-in-cone structure in upper and lower layers: *a*, two concretions exposed by weathering; *b*, close-up of concretion at left in *a*. Elk Creek at Gudgeonville covered bridge, three miles east-southeast of Girard, Pennsylvania.

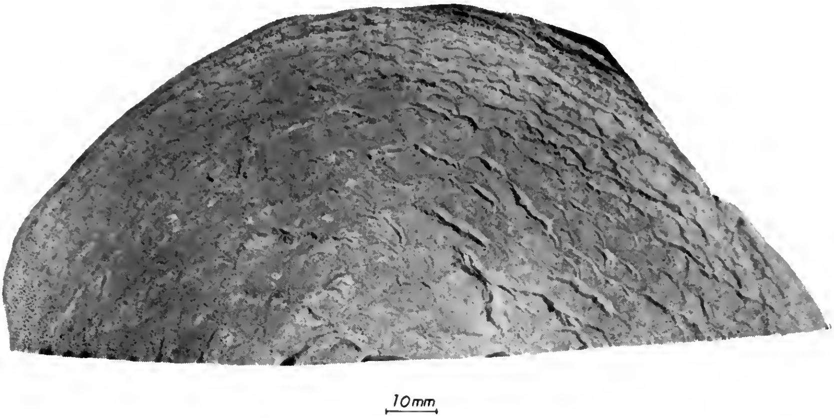

FIG. 59. Surface of silicified coned concretion. North East, Pennsylvania (G-638).

thickness at the margins and have a maximum thickness in the middle of about 17 mm. and 14.3 mm., respectively. The partial cones are defined by buff-colored clay layers that bear the characteristic toothed surface and form the corrugations in the cone cups visible on a fractured surface. The cone apices point toward the center of the concretion. The intersections of these partial cones of clay with the concretion surfaces are marked by strongly developed arc-like furrows concentrically arranged, so that their concavities face toward the vertical axis of the concretion. Toward the axis the arcs are larger and form more nearly complete circles. In vertical section the partial cones of clay are seen to be systematically arranged. In the thickest part of the layers near the center they tend to form more complete cones, but toward the periphery the part of the cone inclined from the middle of the concretion toward the exterior is preferentially developed (see fig. 60). The acute angle formed by the clay layer with the horizontal decreases outward from about 65° in the middle. Near the periphery the clay layers clearly pass internally into the horizontal clay layers of the central bedded portion of the concretion (fig. 60).

Except for the trilobite specimens (PE-6164, P-196, and P-200) described below (pp. 243, 246), this coned concretion is unlike any other examples in that it is siliceous—a very fine grained, dense chalcedony.

MICROSCOPIC STRUCTURE

Vertical section (slide nos. 273–274).—Corrugated clay layers forming partially conical surfaces are well developed (fig. 61) and point

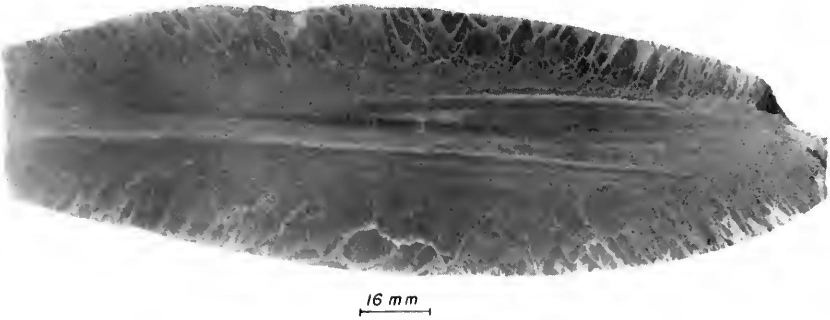

FIG. 60. Polished vertical section of silicified coned concretion. North East, Pennsylvania (G-638).

toward the central region of the concretion. The matrix is composed of very fine silica with disseminated dust and a little fine carbonate. There are some small thin cones of clay but they are not present throughout the matrix.

It is considered that the concretion was originally formed of calcite and later replaced by silica, with the preservation of the partially conical clay structures but with the destruction of the microfabric.

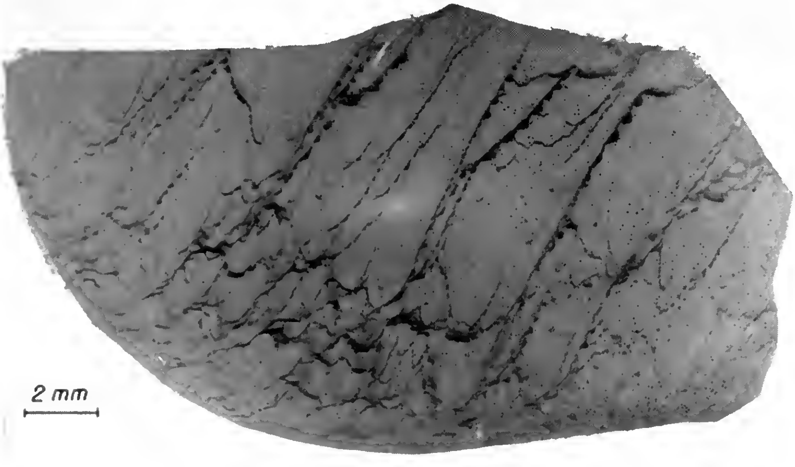

FIG. 61. Vertical thin section of silicified coned concretion. North East, Pennsylvania (slide no. 274).

13. JUDIQUE INTERVAL BROOK, CAPE BRETON ISLAND, NOVA SCOTIA (G-3586)

Dr. David L. Dineley, of the University of Ottawa, kindly made this large concretion available. The specimen is from the Horton Group (Mississippian). It is about 400 mm. long, with a maximum width of 260 mm. and thickness of 140 mm. It has a somewhat irregular form, partly due to breakage and loss. Cone-in-cone is evident in the upper and lower portions but a better understanding of the structures can be obtained in a vertical section.

The upper coned layer has a maximum thickness of about 57 mm. Conical clay layers are well developed and show an ordered arrangement of a series of cones around common vertical axes extending the whole thickness of the layer. An unusual feature of these cones is that they appear to point upward and away from the central zone, contrary to the usual arrangement. However, the corrugations of the clay layers are on the lower surfaces, thus showing that the true cones actually point downward toward the center of the concretion. Etching by dilute hydrochloric acid brings the structure of the clay into sharp relief (fig. 62). The outer portion of the layer is composed of fibrous calcite and there are the usual fine microcones of clay as well as the macrocones. The axes of the cone stacks show up as a high density zone of very fine clay in which a cone structure is barely discernible in places (fig. 63). Radiating from these columns are the thicker conical clay lenses forming the macrocones and also the finer microcones set in a fibrous calcite matrix. The columns do not extend completely to the inner margins of the coned layer. The inner part of the coned zones passes into finer microcones with a greater quantity of fine clay.

14. SOUTHWEST MABOU RIVER, CAPE BRETON ISLAND, NOVA SCOTIA (G-3587)

This specimen was collected by Dr. Dineley, of the University of Ottawa, who kindly made it available to me. It occurs in the Horton Group (Mississippian) about 6.4 miles northeast of Judique North. It is about 80 to 85 mm. thick and is bounded top and bottom by dark shale.

Cone-in-cone layers are prominent in the upper and lower parts, although commonly the clay is in the form of lenses, which may be more or less horizontal but are usually saucer-shaped. The conical clay lenses and many of the saucer-shaped lenses bear conspicuous

Fig. 62. Polished and etched vertical section of coned concretion; cones point downward toward center of concretion. Cape Breton Island, Nova Scotia (G-3586).

corrugations that face the interior of the mass. The cones of both layers point toward the center. The saucer-shaped clay lenses, however, generally are convex toward the upper and lower surfaces respectively, but the presence of corrugations on the inner surfaces shows them to be analogous to cones. A cone-cup on a fractured vertical surface bears beautifully slickensided corrugations.

Etching of a vertical surface with dilute hydrochloric acid brings out the structures very clearly. The lower coned zone in one etched band is about 50 mm. thick (fig. 64); the calcite is coarsely fibrous

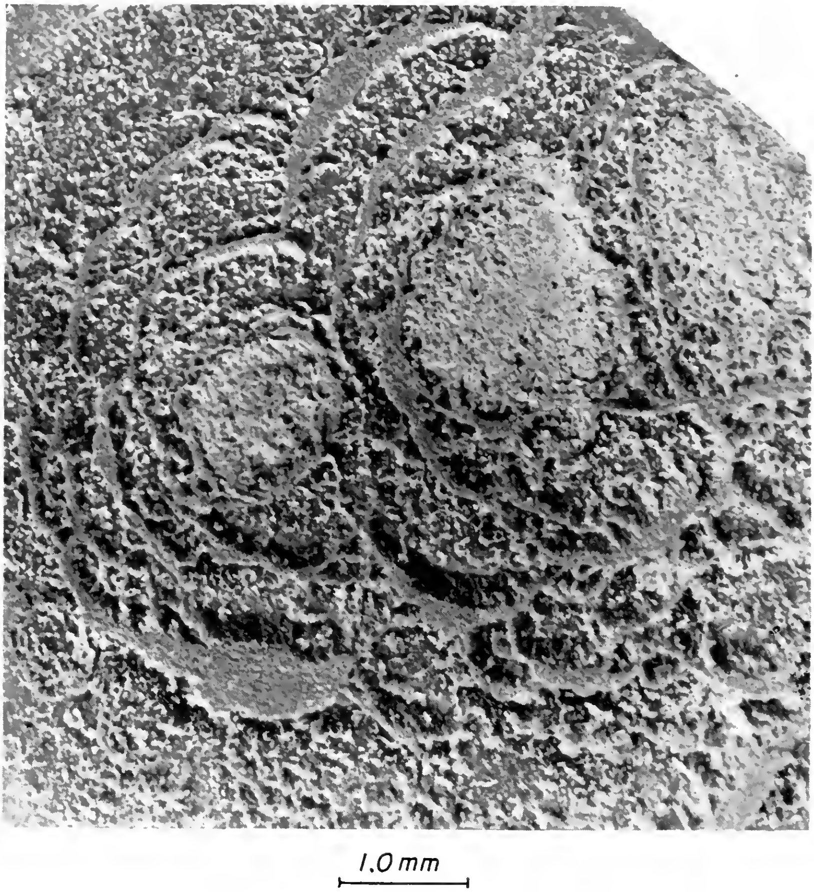

Fig. 63. Polished and etched horizontal section of cone-in-cone layer of concretion. Cape Breton Island, Nova Scotia (G-3586).

and there are many small partial clay cones throughout the calcite as well as the macroscopic clay cones and lenses (fig. 65). Toward the interior the macrocones die out and the small clay cones become very much tinier and very abundant; consequently the clay increases in quantity and the calcite is much finer grained. In turn this passes to a zone about 10 mm. thick in which there are no macrocones or microcones and the structure is homogeneous and fine-grained. The upper coned layer is about 19 mm. thick; the calcite is finely fibrous and the microcones are very tiny and abundant. The macrocones are not so well developed as in the lower zone. Masses of fine pyrite and probably sphalerite occur in the clay laminae. The cone axes

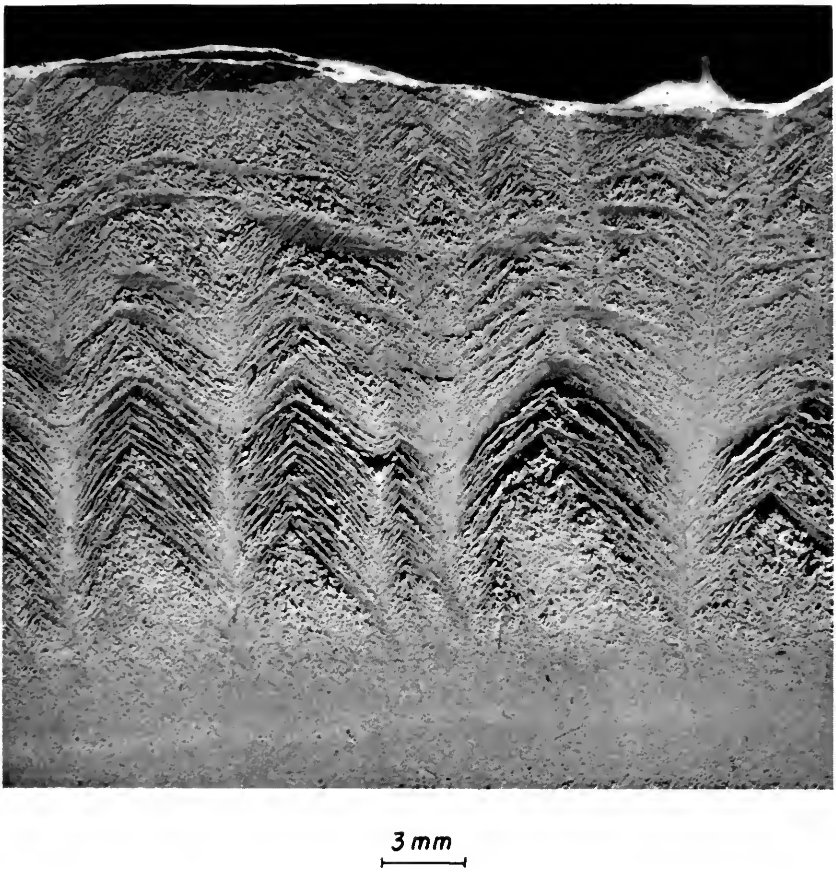

FIG. 64. Polished and etched vertical section of coned concretion showing fine-grained cone axes with cones pointing downward toward center of concretion. Cape Breton Island, Nova Scotia (G-3587).

have a structure (fig. 64) similar to that described in the preceding example (G-3586).

The structures present are intermediate between those of the Cunningham Brook calcite veins, described below (p. 251), and typical cone-in-cone such as that of Woodland Valley or Dotson's Branch. The specimen has many of the characteristics of the veins, although on a more massive scale.

The abundant, finely dispersed clay of the axial columns represents the discrete clay layers of the cones expanded and spread through a greater vertical distance by fine-grained calcite. The cause

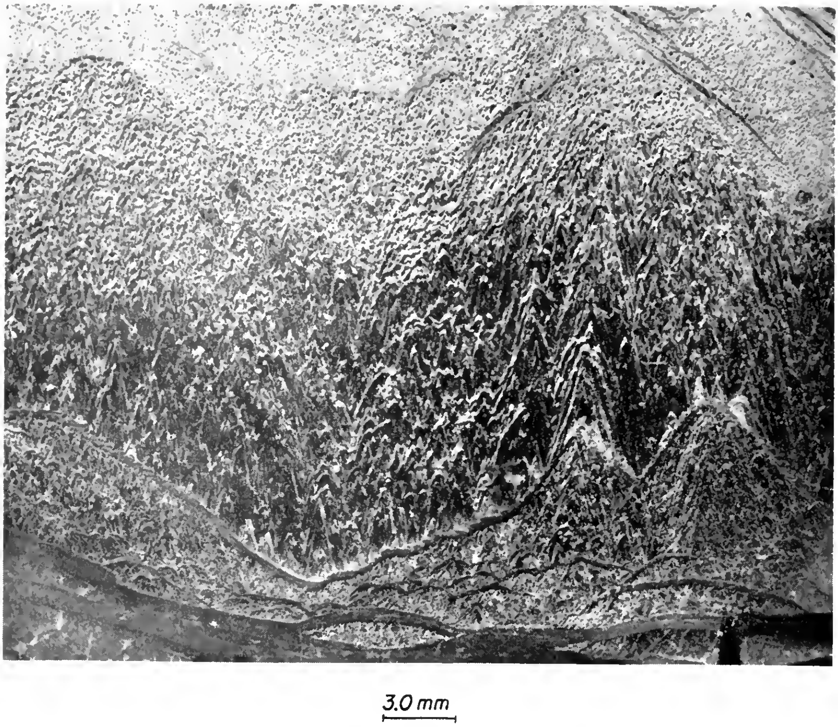

FIG. 65. Polished and etched vertical section of coned concretion showing microcones; cones point upward toward central non-coned portion of concretion. Cape Breton Island, Nova Scotia (G-3587).

of this difference in calcite crystallization is problematical, but it may have been produced by a physical difference in the thin clay layers at the time of the concretionary growth, for example, as a result of small circular vertical disturbances caused by burrowing organisms or more likely by gas bubbles. (The columns are much more prevalent in the upper coned layers.)

The central zone, some 29 mm. thick, is fine-grained and contains much fine, disseminated, structureless clay. This passes into a lower coned layer about 54 mm. thick, the inner part of which is similar to that of the upper coned layer. The outer portion is again composed of fibrous calcite and contains microcones of clay. The macrocones, however, are considerably less well formed than those in the upper coned layer. The clay is present mainly as relatively thick, irregular lenses. Pyrite aggregates occur in both coned and non-coned portions of the concretion.

15. CONCRETION, SMITHVILLE, OKLAHOMA (G-3610)

Mr. J. Choate kindly supplied this specimen, which he collected as a loose piece from a road cut 5 miles southwest of Smithville. It is from the Ten Mile Creek formation (Mississippian).

Honess (1923, pp. 192–193) describes the occurrence of cone-in-cone in the southern Ouachita Mountains as follows: "These cone-in-cone concretions are lenticular masses one foot to three feet across, by 3 to 6 inches thick, ordinarily, and occur in beds of black shale in close proximity to each other in the layers where they occur. The concretions have a central, horizontally schistose core of dark bluish gray, siliceous-argillaceous, finely granulated material out of which, all about this central mass, normal to the surface curvature, spring myriads of the cone-in-cones, growing outward and forming a shell one to two centimeters thick."

MACROSCOPIC STRUCTURE

Specimen G-3610 is a portion of a concretion about 100 mm. thick and elliptical in section. The central portion is fine-grained, dense, and structureless, possessing thin, irregular, silty, micaceous lenses and carbonaceous smears. On this core are two unequal, coned, concavo-convex layers, one up to 40 mm. thick, the other about 16 mm. The partially conical shale lenses are relatively thick, with carbonate conical scales separating them. The shale layers flare out toward the surface of the concretion and form layers nearly parallel to the convex outer surface. This surface shows the typical arc forms of the partially conical shale layers. The cones point toward the interior of the concretion, and just within the inner border of the layer there is a zone, ca. 2 mm. thick, which has well-defined, small, wavy shale lenses and which, as the shale lenses become finer, passes imperceptibly into the central region of the concretion.

MICROSCOPIC STRUCTURE

A thin section (slide no. 290) of the outer zones shows that about 5 mm. from the inner border of the coned layer the concretion is composed of wavy shale lenses about 0.02 to 0.04 mm. thick separated by "augen," 0.04 to 0.08 mm. across, of quartz or chalcedony and a little carbonate, whose grain size is mainly 2 to 5 microns but with some grains up to 12 microns across (fig. 66). Toward the coned zone is a narrow transition zone where the wavy shale lenses are a little thicker (up to 0.07 mm.) and the "augen" are a little larger,

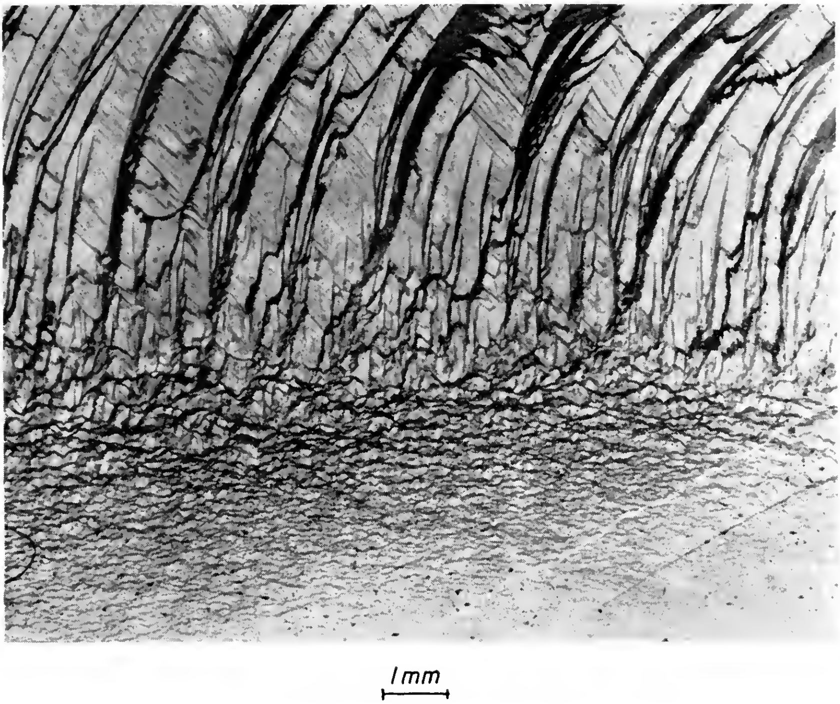

FIG. 66. Vertical thin section of coned concretion; non-coned central zone at bottom of photograph; coarser and purer calcite separates partially conical layers. Near Smithville, Oklahoma (G-3610).

contain more carbonate, and are full of tiny inclusions. In the coned zone the shale layers are thicker (0.02 to 0.6 mm.), more widely separated, and all inclined steeply in one direction relative to the shale lenses of the interior zone, although across the whole width of the concretion the partially conical layers have symmetrical arrangements similar to that of specimen G-638. Between the shale layers are crystalline carbonate conic scales. The shale layers bear the characteristic "teeth" on the surfaces facing the center of the concretion. From the "teeth" fine shale trails pass into the carbonate layers, forming an acute angle with the shale layer and pointing away from the interior of the specimen. The particles comprising the shale have a high birefringence and are probably illite or sericite; they are preferentially arranged parallel to the length of the shale lens. Some of the lenses have an outer darker and denser band 0.016 to 0.024 mm. wide and more rarely an inner band 0.008 to 0.024 mm. thick. Occasionally on the inner side of a shale lens there is a band of carbonate 0.039 mm. wide that contains fewer inclusions than the normal carbonate. The carbonate conic scales are composed of "dirty" grains, which have the typical spindle shape on extinction, 0.06 to 0.33 mm. long; the long dimension is oriented approximately parallel to the shale trails described above. In places there are microcones, 0.19 mm. high, of fine shale layers with an apical angle of about 40°. They are particularly well developed in the region where the shale layers and conic scales are bent around to a small angle with the external surface of the concretion. The calcite spindles are oriented parallel to the microcone axes and normal to the outer surface. Irregular opaque grains, up to 0.08 mm. in width and silvery gray in reflected light, occur sparsely throughout the section but are more common in the interior than in the coned layer.

16. Calcite Lenses, Big Pond Creek, Parke County, Indiana (Slide Nos. 260–261)

Lensoid fillings of white calcite follow the outline of shells of *Dunbarella* and bear the impression of the external ornament of the shell. They occur in the Logan Quarry shale, Staunton formation. Their thickness far exceeds that of the original shell; the maximum thickness of the lens in the thin section is 2.61 mm. The calcite is fibrous, with a central parting where there is evidence of crushing into small grains. Cleavages are prominent at the distal ends of the fibres and the length of the fibres is nearly parallel to the crystallographic "c" axis. Thin dense shale partings interrupt the fibres in places and a parting is present in the calcite on each side of such shale layers. There is no evidence of cone structure.

17. Calcite Vein, Trumpet Valley, Parke County, Indiana

A calcite vein (G-3564) from Logan Quarry shale, Staunton formation, 10 mm. thick and unrelated to shells, has a similar structure to the above except that near one boundary there are lenses of black shale inclusions that have the form of small arcs in section. When a vertical polished surface through the vein is etched with dilute hydrochloric acid, the shale lenses are seen to be saucer-shaped, thus appearing as incipient cone forms. They originated obviously from the disruption of shale laminae; their incorporation into the growing calcite and their distortion are both due to growth of the fibres.

18. Calcite Lens with Trilobite *Elrathia kingii*, Deseret, Utah

Specimens of trilobites occurring as concretionary bodies in Middle Cambrian shale are well known and have been described by Bright (1959). They are remarkable in that they are relatively thick objects. One example in the Museum's collection (PE-554) is over 8 mm. thick, and possesses a well-preserved form of the upper surface of the carapace on one surface and a poorer form of the lower surface of the carapace on the other. According to Bright (1959) the majority of the specimens occur the right way up.

VERTICAL LONGITUDINAL SECTION DOWN THE AXIS OF THE TRILOBITE (SLIDE NO. 263)

The maximum thickness of the specimen is 4.0 mm. and the calcite fibres comprising it vary in length up to 2.32 mm. and up to 0.18 mm. in diameter. There is a considerable amount of dust inclusions and in part this is aggregated into cone-shaped lines that point toward the dorsal surface (fig. 67); the cones also show up as relatively dust-free areas in the more dusty surrounding calcite. These cones normally extend throughout the thickness of the lens but some of them terminate before reaching the dorsal surface. The apical angles are about 26°.

Under crossed nicols the calcite fibres are seen to be arranged generally with their length perpendicular to the dorsal-ventral surfaces, but in the cones there is a divergence that parallels the lines of dust inclusions marking the cones (fig. 67, *b*). In addition, the areas between the apices of the cones are infilled with fibres arranged in small bundles pointing toward the ventral surface (fig. 67, *b*). The dust inclusions appear to be present both as inter- and intra-granular particles. In some areas there is a more than usual accumulation of dust; the calcite in such areas is not fibrous but is highly irregular (fig. 67). The crystallographic "c" axis of the calcite is essentially parallel to the length of the fibres.

TRANSVERSE VERTICAL SECTIONS OF THE TRILOBITE (SLIDE NO. 264)

Three sections taken across the cephalon and thorax show microscopic structures similar to those in the longitudinal section. Some idiomorphic pyrite occurs within the calcite without disturbance to the fibres. In places the fibres are curved toward the dorsal surface, particularly where there is a change in contour of the surface, e.g.,

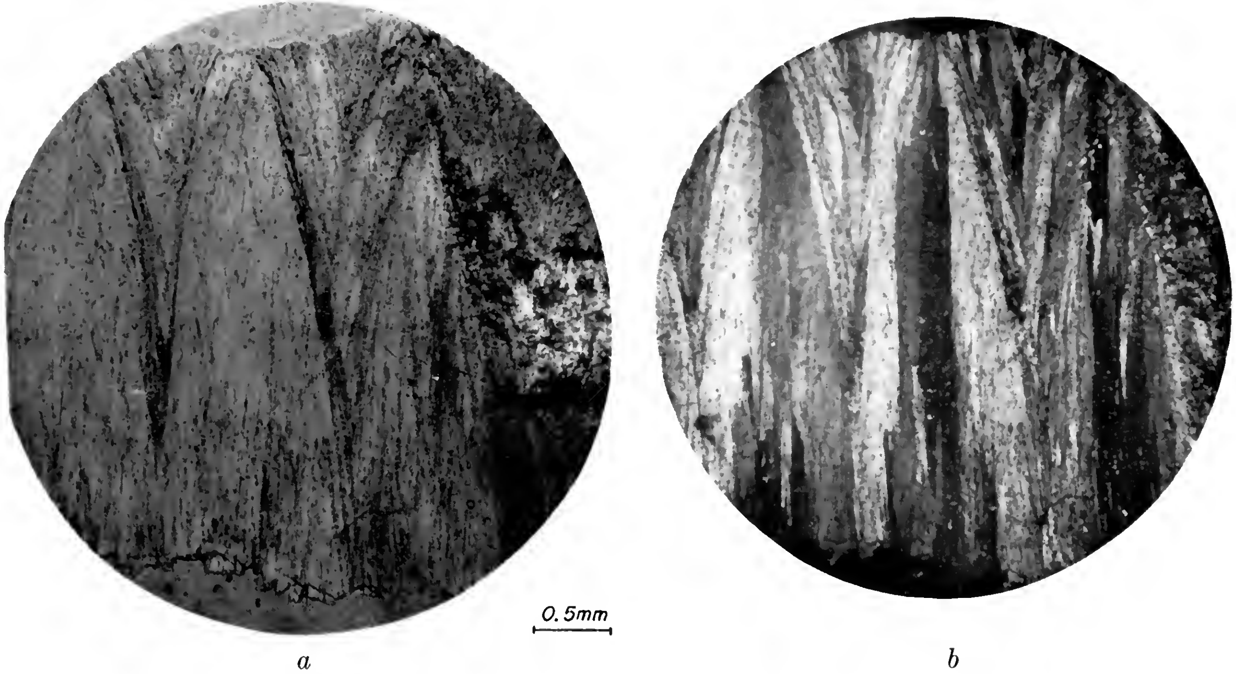

FIG. 67. Vertical longitudinal thin section along axis of a trilobite (*Elrathia kingii*) and associated coned concretion (dorsal image of trilobite uppermost): *a*, ordinary light; *b*, crossed nicols. Deseret, Utah (slide no. 263).

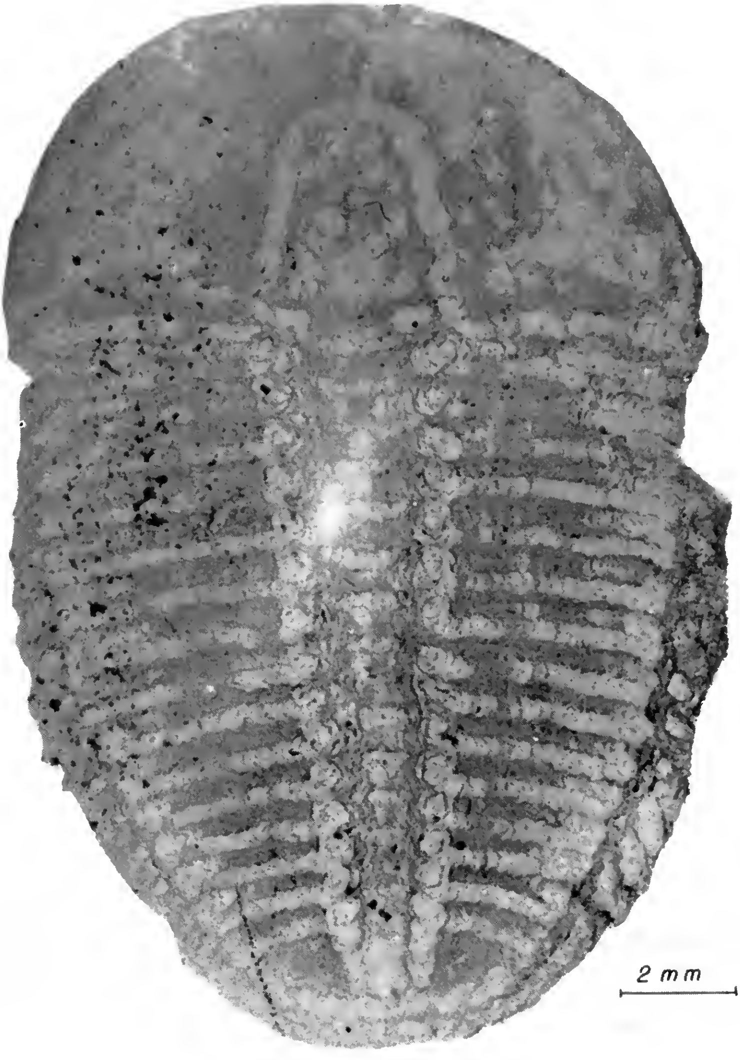

FIG. 68. Horizontal thin section through coned concretion that bears replica of *Elrathia kingii* on dorsal and ventral surfaces, showing image of trilobite. Deseret, Utah (slide no. 262).

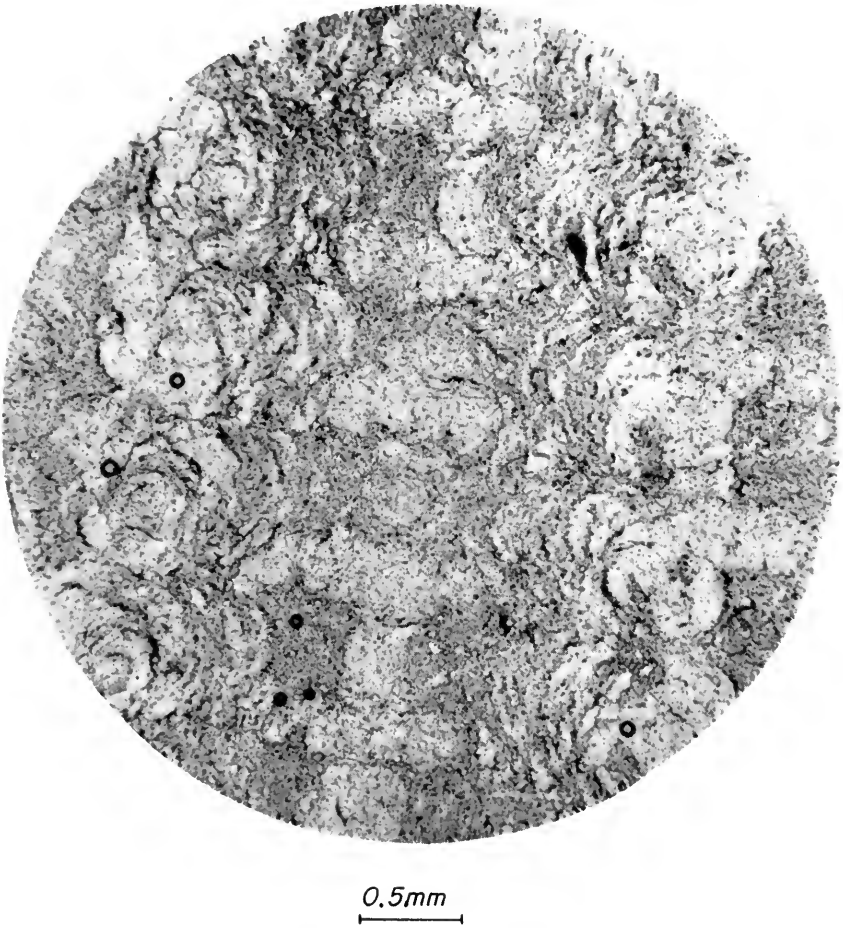

FIG. 69. Horizontal thin section showing enlarged view of part of axial region of image shown in figure 68 (slide no. 262).

at the dorsal furrows, which mark the junction of the axis and the pleura.

HORIZONTAL SECTION (SLIDE NO. 262)

A horizontal section was made approximately through the middle of one calcite-thickened trilobite specimen. The astonishing result is that an excellent image of a trilobite is preserved in the calcite; the axis, segments, and glabella, for example, are clearly discernible because of the dust accumulations (fig. 68). The calcite is fine-grained (ca. 0.1 mm. across). The "c" axes of the grains are mainly nearly perpendicular to the section. Along each side of the axis are incomplete concentric arcs of dust (fig. 69) in a relatively dust-free zone. Other poorly developed arcs of dust occur in the glabella region and in the relatively dust-free zones that alternate with dust-rich zones in the pleural region. The dust-free zones appear to be related to the relief of the original carapace, e.g., between the segments and at the dorsal furrows between the axis and pleura. The dust is composed of minute wispy particles that are concentrated into thin irregular aggregates in the arcs (fig. 69); some particles are 0.012 mm. across. The incomplete arcs result from the intersections with cones, which are seen in the vertical sections. The dorsal surface of most of the specimens available has a thin adhering shiny black crust that can easily be flaked off the underlying calcite. In one specimen it is largely calcareous, with some insoluble mineral particles and brownish-colored aggregates; in another it is composed of birefringent crystals up to 0.25 mm. across, insoluble in hydrochloric and hydrofluoric acids, with fine opaque matter and brownish birefringent needles up to 0.2 mm. long. This thin layer may represent the mineralized carapace or perhaps only the upper layer of the carapace. Bright (1959) says that the carapace is usually replaced completely with cryptocrystalline calcite and rarely replaced by iron oxide or silica. He considers that ". . . combination of the uneven carapace and pressure was probably a factor in the development of the cone-in-cone." He also suggests that ammonia produced by decay of the soft parts of the trilobite was instrumental in the precipitation of the carbonate and the development of the concretion.

The presence of an image of the fossil within the calcite vein is highly revealing. The dust particles are presumably fine-grained clay material that originally lay beneath the carapace. Growth of the calcite fibres downward from the ventral surface of the carapace has caused the loose clay particles to be dispersed in essentially a vertical direction. Conical growth and displacement of the dust into the conical surfaces have been concentrated along originally reflexed or thickened portions of the carapace (e.g., at the apodemes, the thickened ventral knobs for muscle attachment), with the development of relatively dust-free zones and thus an outline of the form of the carapace and production of the image.

Loose clay in the concavities of the ventral surface may have been displaced downward, forming "dirty" zones, while opposite the apodemes and reflexed zones there would have been fewer loose particles available and calcite growth would have been cleaner. The restriction of the prominent coning to the reflexed and thickened portions of the carapace suggests a physical control. Initiation of the crystallization at these points and its conical increase downward ahead of the crystallization below the concave portions would have given rise to relatively dust-free conical zones. The replica of the ventral surface on the lower surface of the concretion may have been caused by the presence of a compacted impression in the clay layers immediately beneath the carapace. The impression controlled the thickness of the calcite and was pushed away from the carapace by the downward growth.

19. Trilobite, Argentina (PE-6164)

MACROSCOPIC STRUCTURE

A large *Thysanopyge argentina* from the Middle Ordovician of Argentina shows a structure similar to the above. Harrington and Leanza (1957) describe the occurrence in Arenig shales of northern Argentina of clay discs bearing crusts, 10 to 20 mm. thick, of cone-in-cone in which the cones point to the interior. Cone-in-cone also is present as laminae 20 to 30 mm. thick with the cones pointing toward the center. Further, they say (p. 52): "Many of these cone-in-cone crusts contain beautifully preserved remains of complete trilobites including huge specimens of *Thysanopyge argentina* up to 40 cm. in length. The blurred shape of the trilobite is always detected on the outer surfaces of the cone-in-cone layers, and parting the laminae along the mesial plane where the cone points end, excellently preserved specimens are always found."

The trilobite specimen is about 225 mm. long and has a maximum breadth of 177 mm.; it is 16 to 17 mm. thick. The sides have a fibrous structure. A small vertical cut at the margin shows a cone structure formed of brown layers in a dense hard brown matrix that gives a slight effervescence in dilute acid when scratched. The ventral surface, a replica of the ventral surface of the carapace, has a number of cone cups, the bases of which are 6 to 7 mm. across.

MICROSCOPIC STRUCTURE

A thin section (slide no. 265) from the marginal area shows a dense brown, very fine grained matrix with partially conical lines of opaque blebs, which are red-brown in reflected light (?iron oxide-stained). The matrix is peppered with minute grains (ca. 2 to 3 microns), which have a higher birefringence than the rest; the grains appear to be of calcite set in silica. Throughout the slide there are numerous small brownish aggregates about 0.015 mm. across, which are made up of very minute particles; in addition, there are minute flakes, presumably clay minerals or micas.

It is considered probable that the material between the dorsal and ventral surfaces was originally composed entirely of calcite, the growth of which occurred on the ventral surface of the carapace and caused the cones. Subsequently, this calcite was largely replaced by silica so that only minute blebs now remain, and the crystal structure was destroyed. The fibrous nature is preserved on the marginal surface, although no remnant of this is visible in thin section. The cones, formed of the opaque materials, are also preserved in the replacing matrix.

20. Ptychoparid Trilobite in Calcite Concretion, Gibson Lake, Teton County, Montana (G-3569)

Two specimens were kindly made available to me by Dr. A. R. Palmer of the United States Geological Survey. They are from the Middle Cambrian Switchback shale. These are relatively thick (one 13 mm.) concretions with a poor trilobite image on one surface and a barely discernible image on the other. In vertical thin section (slide no. 287) one concretion (9.3 mm. thick) is seen to be composed of fibrous calcite. The replaced and fractured carapace, approximately in the center (fig. 70), is present as a cryptocrystalline calcite layer 0.015 to 0.018 mm. thick with a discontinuous opaque layer 0.005 mm. thick; in part, however, it appears as a double layer 0.06 mm. thick with included opaque streaks. The fibrous calcite of both the upper and lower layers of the concretion has a complex series of cones formed from fine included material, presumably clay. The cones, in contrast to those of the *Elrathia* specimen (fig. 67), are of varying heights and their apices occur at different levels within the layers. There are relatively dust-free, inwardly pointing, conical areas in which the calcite is coarsely fibrous (up to 2.1 mm. thick) and darker areas with considerable clay inclusions where the calcite is more irregular. These "dirty" areas tend to have an outwardly pointing conical form. There are some thicker lenses of clay, particularly in the ventral layer, and one bears a few corrugations on the surface facing toward the trilobite. It is not easy to determine the direction in which the cones point, because in each layer they appear to be directed both toward the carapace and away from it.

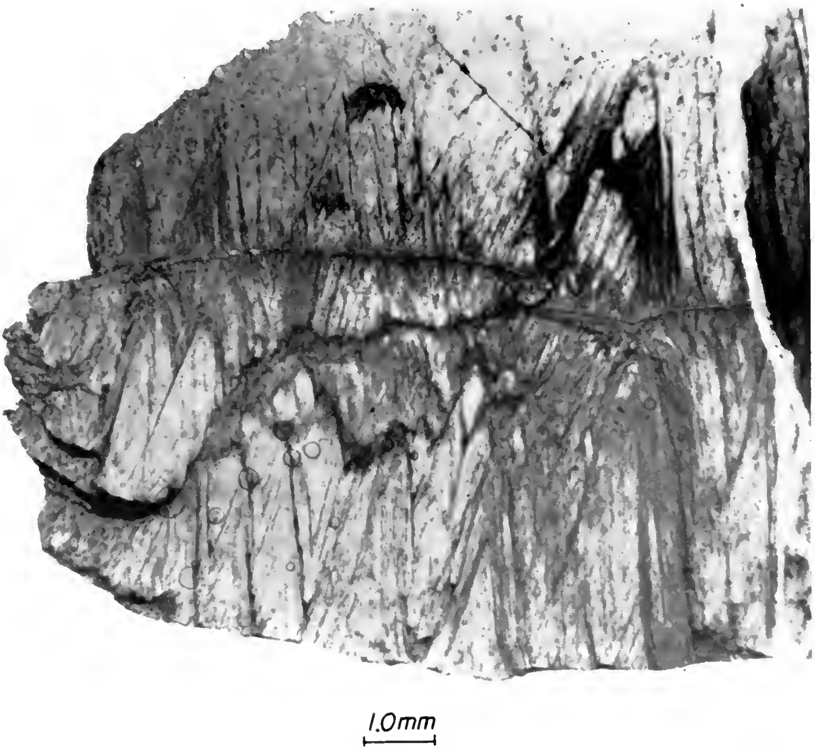

FIG. 70. Vertical transverse section of coned concretion with trilobite image on dorsal and ventral surfaces; trilobite lies in median parting of concretion. Gibson Lake, Teton County, Montana (slide no. 287).

However, in the ventral layer the true direction certainly seems to be toward the fossil, while in the dorsal layer it also is probably toward the trilobite.

There is no clear relationship of the clay-rich and clay-poor zones to the contours of the carapace. However, the breaks in the latter and the reflexed zone beneath dorsal furrows do influence the calcite structure and the cone forms. The calcite commenced to crystallize after the fracture of the carapace but while the enclosing clay was still soft and unconsolidated.

21. CALCITE LENS, CEDAR BLUFF, ALABAMA (G-3570)

Dr. A. R. Palmer of the United States Geological Survey has kindly supplied a specimen of fibrous calcite from the Conasauga shale (Cambrian). He informs me that trilobites occur on a thin parting between two layers of fibrous calcite. The specimen consists of one of these layers, some 17 to 18 mm. thick, together with the fossil-bearing parting.

In thin section (slide no. 280) the calcite is coarsely fibrous with fibres up to nearly 10 mm. in length but only up to about 0.28 mm. in width. There are numerous fine inclusions mainly disposed in streaks parallel to the fibres, but toward the parting there are very acute conical forms in the dust directed toward the parting. The shape of the calcite fibres is here related to the cone forms. Near the parting there are some small clay lenses, one of which has a partially conical form with corrugations on the surface facing the parting toward which the apex points.

22. CONCRETION WITH TRILOBITES, CABRIÈRES, HÉRAULT, FRANCE (P-196, P-200)

MACROSCOPIC DESCRIPTION

These specimens, up to 29 mm. thick, are parts of siliceous concretions of Ordovician age. They bear on one surface fragments of replaced dorsal tests of asaphid trilobites. The other surface is rounded and has concentric markings that are the bases of cones, as well as some corrugated cone cups up to 10 mm. in diameter. Polished vertical surfaces exhibit many buff-colored partially conical shale laminae, some of which bear the stepped or corrugated structure on the outer surface. The cone apices point toward the trilobite-bearing surface; near the surface the conical layers are more numerous but less regularly formed. The matrix is dense, fine-grained silica similar to that of the Argentine trilobite (PE-6164) and the siliceous concretion (G-638). These concretions have been described in detail by Cayeux (1935), Bonte (1945a), Thoral (1946), and Denaeyer (1947). Bonte reports that the nodules, called "gâteaux," occur generally as very flattened ellipsoids and frequently contain in the equatorial plane entire or fragmentary fossils, mainly trilobites. The shape of the "gâteaux" is governed by the shape of the fossils they contain and the cones of the two halves point toward the center of the nodules. Bonte also shows that the position of the conspicuous cone bases, called "mamelons," on the nodule surfaces is influenced by the relief of the trilobite carapace.

MICROSCOPIC STRUCTURE (SLIDE NO. 621)

In thin section the partially conical shale layers are seen to occur in a very fine grained chert-like matrix composed mainly of quartz

FIG. 71. Vertical thin section of calcite vein in calcareous siltstone. Fleurant Point, Quebec (slide no. 269).

or chalcedony grains about 3 to 15 microns in diameter. The matrix grains are stained, presumably by iron oxides. Tiny micaceous grains and opaque specks also occur among the silica. In places there is micaceous material in very thin lines that suggest weakly developed microcones, the "structure entrecroisée" of Bonte (1945a).

It is considered that, like the other siliceous specimens, these from Hérault represent silica replacement of originally calcareous concretions. The macrocones are preserved as well as a trace of the microcones, but the characteristic microstructure of typical cone-in-cone has been destroyed by the replacement of the calcite by silica.

23. CALCITE VEINS, ESCUMINAC FORMATION (LATE DEVONIAN), FLEURANT POINT, QUEBEC (G-3562–64; SLIDE NOS. 268–269)

Calcite veins 0.14 to 3.0 mm. thick occur intercalated with thin greenish-gray shale (up to 0.05 mm. thick) and calcareous silty shale (up to 0.12 mm. thick). The specimens were collected by Dr. R. Denison for the *Bothriolepis* specimens they contain.

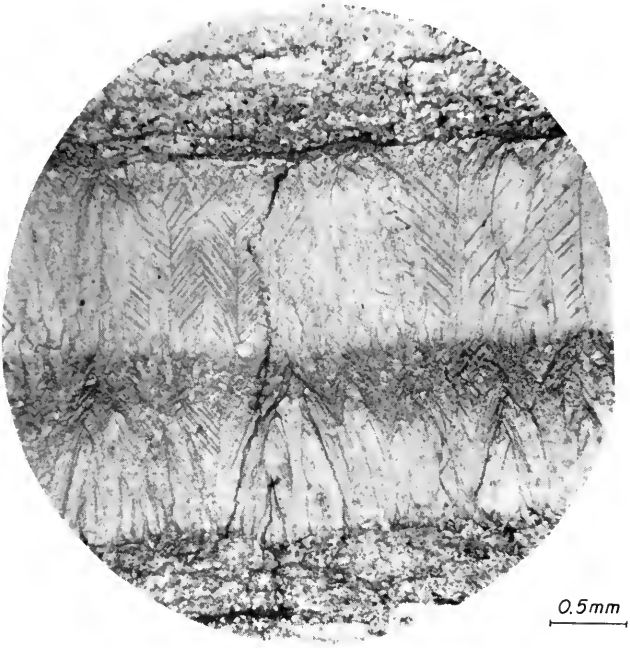

FIG. 72. Vertical thin section of double calcite vein in calcareous siltstone. Fleurant Point, Quebec (slide no. 269).

The calcite is fibrous, with its long direction perpendicular to the contacts; the "c" axes of the grains lie parallel to the long direction or nearly so (grains often extinguish at a small angle to the length). The fibres are up to 0.7 mm. across and may extend nearly the full thickness of the vein. The thicker veins have a distinct comb structure and the calcite grains, although their long directions are parallel, are angular in shape and termination (figs. 71 and 72). Many of the grains have twin lamellae in one or two directions. Both margins have fine-grained calcite although it is more prevalent at one margin, possibly the lower one, based on the orientation of a fossil fish contained in the specimen. A conical structure formed by lines of minute inclusions is present (fig. 71); these lines of inclusions are inter- and intra-granular and may run the entire thickness of the vein. The cones appear to point mainly in one direction (?downward) but the structure is not always clear and some cones may have the reverse orientation.

A double vein (fig. 72) has an upper(?) layer of needle calcite 1.25 mm. thick and an intermediate zone, about 0.42 mm. thick, of small grains of calcite with much fine dust, which merges into a lower(?) zone of needle calcite 0.74 mm. thick. Conical lines are readily discernible, particularly in the lower(?) zone, where they appear to point mainly upward, although it is difficult to be sure of their true orientation. The lower(?) border of the central dusty zone has conical projections of dust aggregations directed mainly downward. The dust cones are partly related to the shape of the calcite grains. The cones of the upper(?) zone are poorly developed but seem to point mainly upward as in the case of the lower(?) zone. Well-developed stylolite sutures cross the veins at intervals running in a more or less vertical direction (figs. 71 and 72). Thinner veins of calcite are often lens-like (fig. 73), associated with a thin clay lens either above or below the vein. In some cases a clay layer has been disrupted by calcite growth at places above the clay layer and in adjacent areas below it; the opposite direction of calcite growth has broken up the clay layer

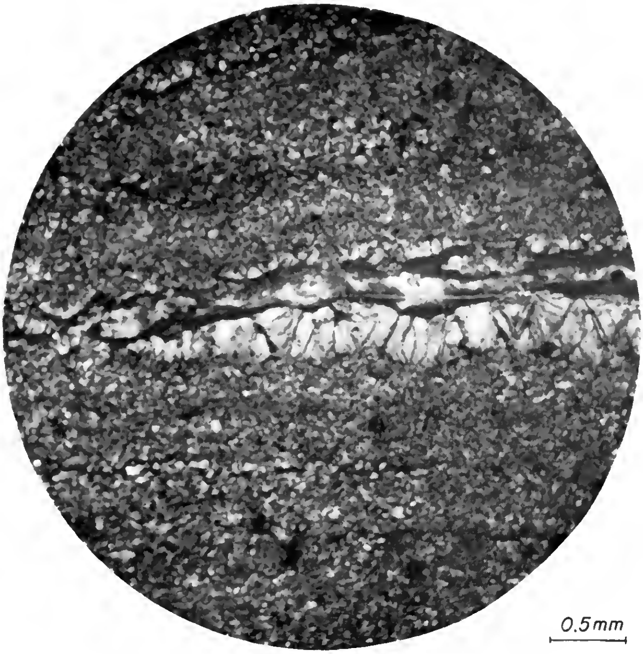

FIG. 73. Vertical thin section of calcite lens in calcareous siltstone. Fleurant Point, Quebec (slide no. 268).

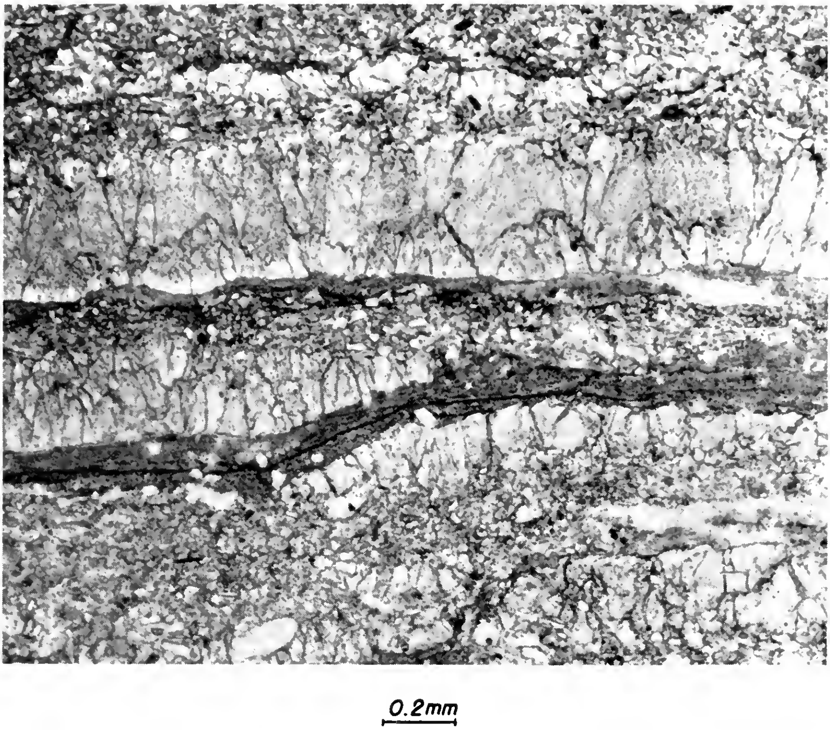

FIG. 74. Vertical thin section of calcite veins and clay laminae in calcareous siltstone. Fleurant Point, Quebec (slide no. 269).

and moved the parts differentially upward or downward (fig. 74). If the clay lens lies below the calcite, the latter has cone forms pointing upward, and the reverse is true in cases where the clay lies above. The calcite immediately adjacent to the clay layer appears less charged with dust and thus seems to be the latest part added. In cases where calcite has crystallized on both sides of a clay lens the cones appear to point away from each other.

The calcite veins formed after deposition but probably early in the diagenesis before there had been much induration of the sediment, so that some of the sediment could be incorporated and distributed as individual particles in the growing calcite. The cone forms are a direct result of the growth of the calcite and are not related to the twin lamellae or the stylolites, both of which cut the cone structure and were probably caused by the Shickshokian (Acadian) deformation that affected the region (Alcock, 1935). The carbonate of the veins possibly resulted from the redistribution of the calcite in the sediment.

24. Coned Calcite Veins in Black Shale, Cunningham Brook, New Brunswick (G-3640–42)

These specimens were collected by Dr. R. Denison for the fossil fish remains they contain. The shales belong to the Jones Creek formation of Silurian age.

MACROSCOPIC STRUCTURE

The concretions are contained in a dense, finely laminated black shale. There are two types: (1) a fine-grained, dense, homogeneous, calcareous claystone type, which may contain a layer of fish scales; and (2) a coarse-grained, relatively pure calcite with wisps and laminae of shale. The latter type is more irregularly developed than the former and has the appearance of vein calcite except for the irregular shape of the masses. A layer of fish scales is present in one example. Cone forms are visible in the second type, which apparently often, but not invariably, occurs in close juxtaposition with the fine-grained homogeneous type. The structure of these coned calcite masses can best be investigated in thin section, although the conical clay layers and undulating clay and silt layers that can be traced from the shale into the veins are clearly seen on polished vertical surfaces under the binocular, particularly if etched with dilute acid.

MICROSCOPIC STRUCTURE (SLIDE NOS. 281–282, 288–289)

The shale is composed of light buff-colored, homogeneous clay layers up to about 2 mm. thick, and thinner, dark brown, more irregular clay layers up to about 0.25 mm. thick, alternating with calcareous silty layers up to about 0.5 mm. thick. The calcite veins vary in thickness, the thickest in the collection being 20 mm. Some veins are evenly developed and parallel to the bedding but most of them are more irregular in shape and terminate laterally at an abrupt high angle against the shale; occasionally they are notably rounded, bulbous, or saucer-shaped (fig. 75). The veins contain bands of shale and silt that are deformed into open folds and into conical forms (figs. 75–77). The conical forms have well-defined corrugations on the outer surface. These bands can be traced across the vein into the shale and clearly indicate the expansion of the shale caused by development of the calcite (fig. 75). Pyrite is of common occurrence

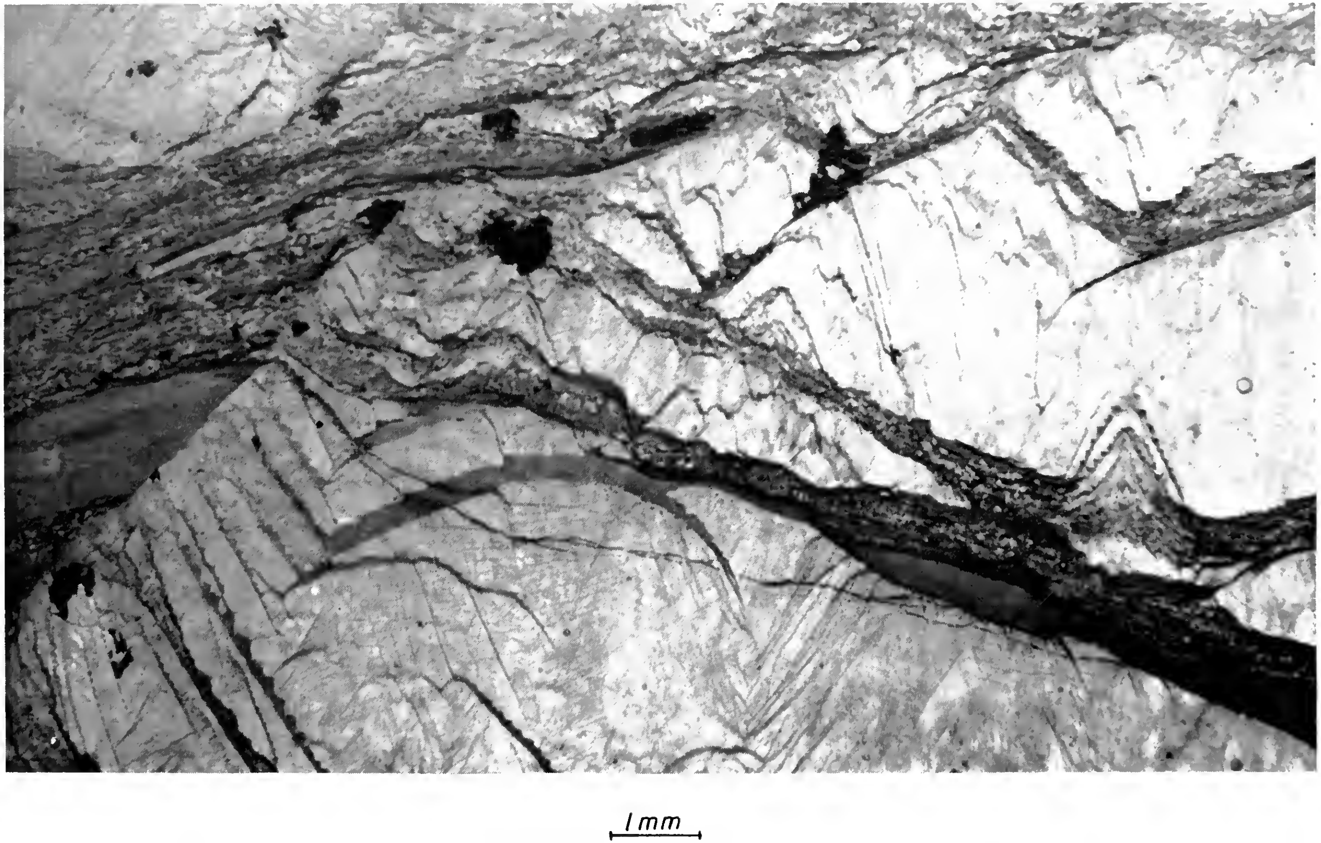

FIG. 75. Vertical thin section of coned calcite vein showing silt and clay laminae; opaque areas are pyrite. Cunningham Brook, New Brunswick (slide no. 289).

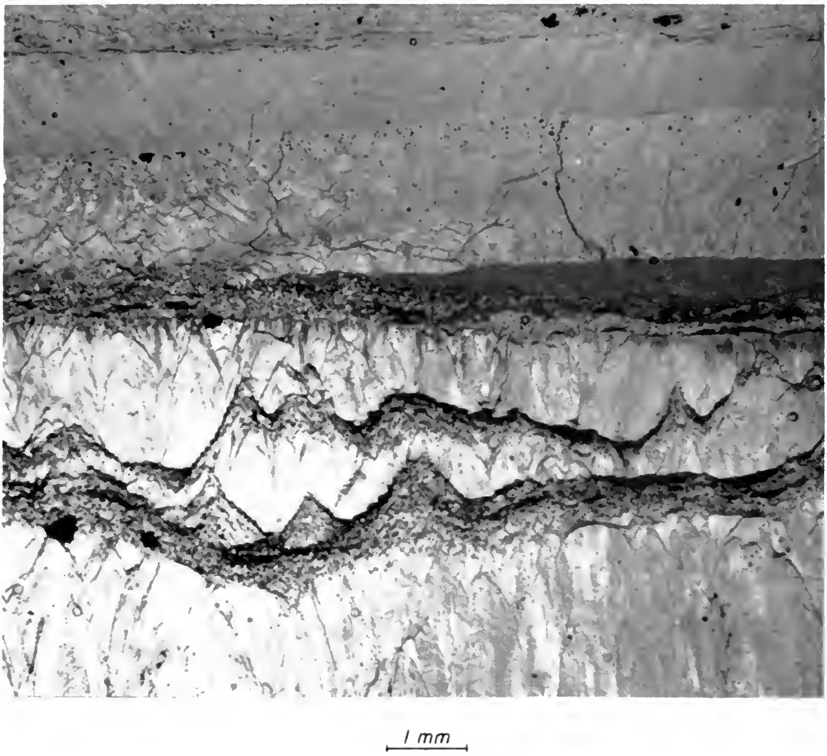

FIG. 76. Vertical thin section of coned calcite veins showing variable position of a vein with respect to a clay lamina shown at top of photograph. Cunningham Brook, New Brunswick (slide no. 288).

in the shale, in the vein calcite, and in the shale and silt bands within the veins. Throughout the veins there are many inclusions, frequently in fine lines and cones, that are both inter- and intra-granular. The calcite is usually coarse-grained, up to about 4 mm. long and 0.37 mm. wide; the long dimensions are generally more or less vertical and the grains do not extend the full height of the vein. Many do not extinguish between nicols parallel to their length. In places the calcite fibres are gently inclined to the horizontal, more or less parallel to clay layers. The calcite grains have irregular shapes, often wedge- or spindle-shaped, presumably caused by crowding. Some of the veins have a considerable clay content which "chokes" the calcite; the latter is consequently much more irregular and finer-grained, about 0.04 to 0.06 mm. across. The clay in such veins is present as spongy aggregates rather than well-defined layers, but partially con-

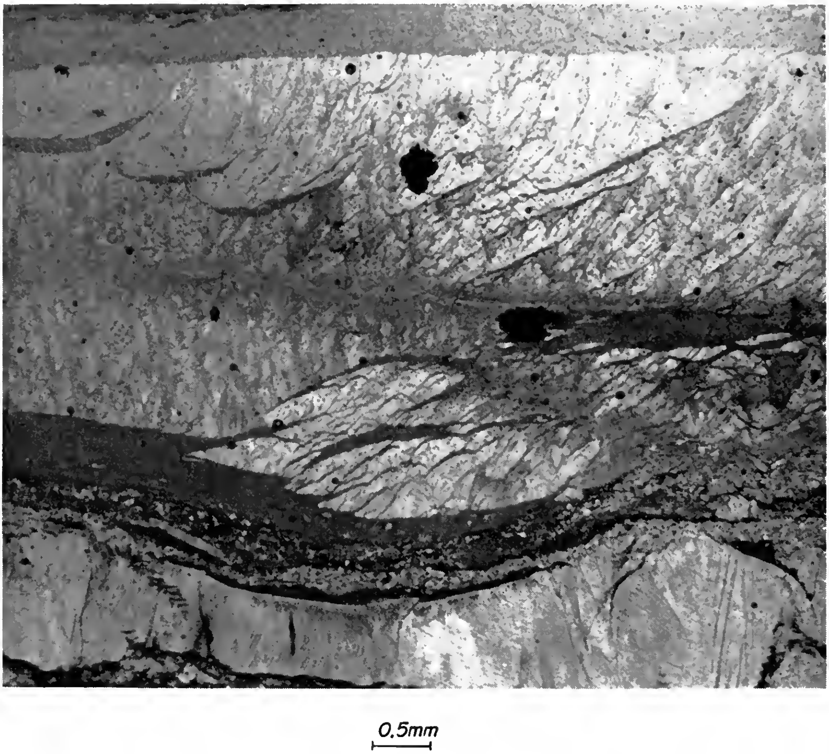

FIG. 77. Vertical thin section of coned calcite veins showing clay arcs derived from a clay lamina within which a calcite vein had formed; opaque areas are pyrite. Cunningham Brook, New Brunswick (slide no. 288).

ical forms can be discerned (fig. 78). The locus of development of the calcite may vary within a clay layer so that at one point a thicker amount of clay lies above the vein than below but this passes to a zone showing the reverse situation (fig. 76). One particular vein has in part a central line which appears to be a zone of very fine calcite and clay which extinguishes parallel to its long direction; it passes along the vein to a position near one bounding surface, apparently indicating a difference in the relative amount and direction of growth of the calcite fibres (fig. 77). Micro-shears disrupt this central line in places with thrust-like displacements, the vertical movements on which range from 0.05 to 0.14 mm. Twin lamellae in one or two directions occur in many of the calcite grains. One specimen (slide no. 289) has a layer of fish scales and interstitial calcite occurring within the coarse fibrous calcite of a vein. In another (slide no. 281) a layer of fish scales with calcite between the individual scales occurs

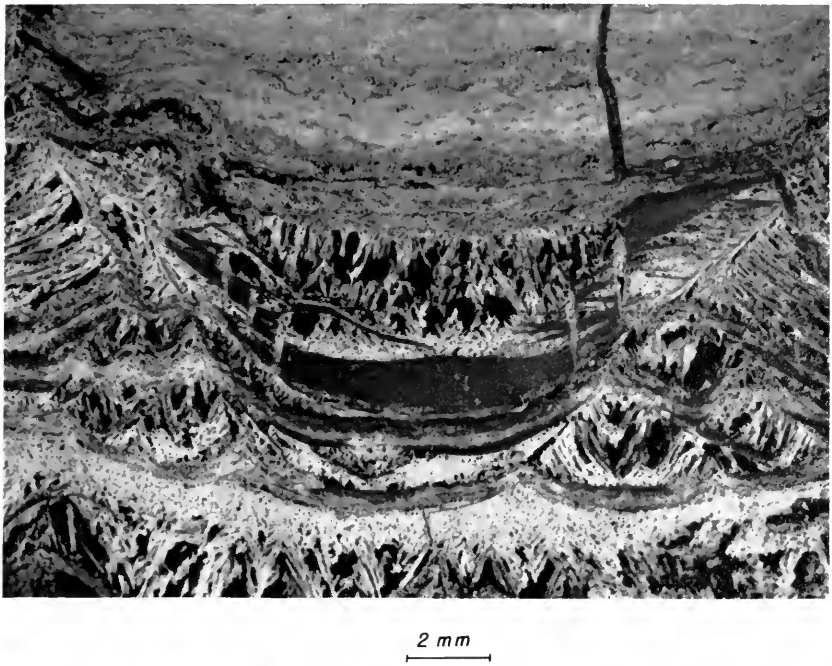

FIG. 78. Vertical polished and etched surface of calcite veins showing delicate clay films with conical form. Cunningham Brook, New Brunswick (G-3641).

in a fine-grained, homogeneous, calcareous mudstone that appears to have been thickened by concretionary addition of the calcite (fig. 79). A silty layer, 1.07 mm. thick within this concretion, can be traced into a coarse calcite vein (fig. 79); the calcite above and below this layer contains clay cones that point toward the layer. One border is the boundary of the vein but the other is an undulating and coned shale layer within the vein. The former border is a plane surface except for a series of cones that disrupt the bounding clay, which rises in a series of small corrugated cones into the vein.

It is difficult to determine the absolute movement of the clay bands in the veins, although the relative movement is obvious. If trails of clay which rise from the corrugations of many of the clay bands (figs. 80, 81) indicate the direction of movement, then this movement is toward the bases of the cones and thus the same as the probable direction of growth of the calcite grains. The outer surface of the partially conical clay layers is consistently the one that is corrugated (figs. 75, 81). The origin of this corrugation suggests a direct relationship to the mode of origin of the conical clay bands.

Fig. 79. Vertical thin section of double-coned calcite vein with silt parting and showing part of layer of fish scales enclosed in fine-grained structureless carbonate concretion. Cunningham Brook, New Brunswick (slide no. 281).

The corrugations are on the side from which the clay bands have been moved and disrupted by the growth of the calcite. The inner surface of the conical clay layer always appears as a smooth line in the sections. It presumably represents the originally horizontal clay surface, on or under which calcite was crystallizing simultaneously with the growth on other surfaces that resulted in the displacement of the layer.

The clay structures in the calcite veins are vividly displayed when a polished surface cut perpendicular to the bedding is etched with dilute hydrochloric acid. The calcite is removed and the remaining insoluble matter largely retains its original orientations. The partial cones with their corrugations are visible as exceedingly fine films (fig. 78). I am grateful to Dr. E. Olsen for an X-ray analysis of one of these films, which indicates the presence of illite, quartz, sericite, and carbon. This is consistent with its origin as a clay probably

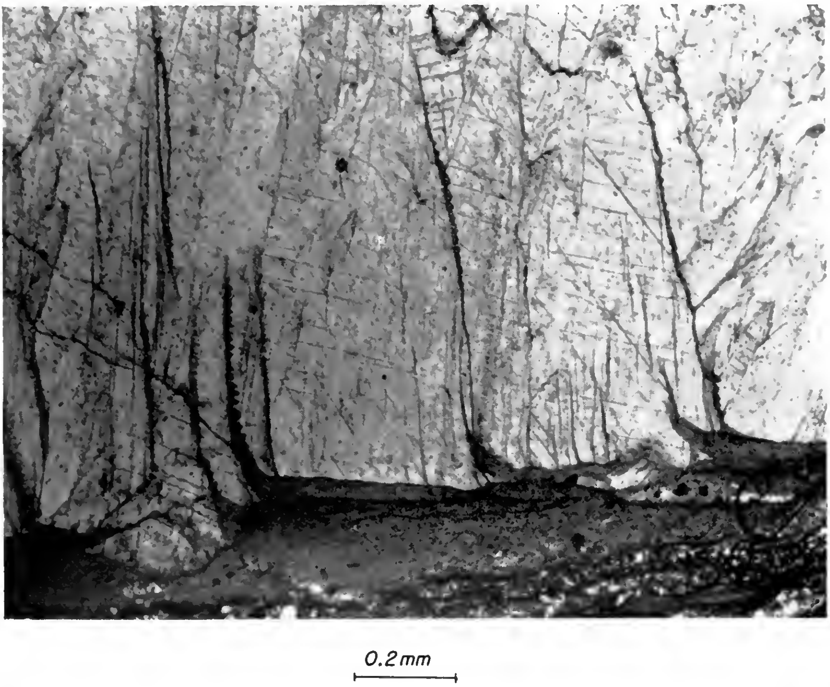

Fig. 80. Vertical thin section of calcite vein with corrugated clay layers (vertical) derived from clay lamina. Cunningham Brook, New Brunswick (slide no. 282).

deposited in a marine environment. Some of the veins after etching show such a considerable quantity of inclusions that a dense gray mass remains. This, however, has a very light and porous texture, resulting from the expansion of the original clay produced by the growth of the fine-grained concretionary calcite; partial cone forms can be discerned but they are not so well developed as in the coarser veins.

The twin lamellae and micro-shears do not appear to be related in any way to the development of the veins or to the conical clay layers. They are probably later structures, formed during the Acadian orogeny that affected the rocks of this area (MacKenzie, 1951).

25. Calcite Veins, One Mile Northwest of Myton, Duchesne County, Utah (G-3694)

These specimens were collected by Dr. John Clark from the upper part of the Myton member (Uinta C), Uinta formation, of Late

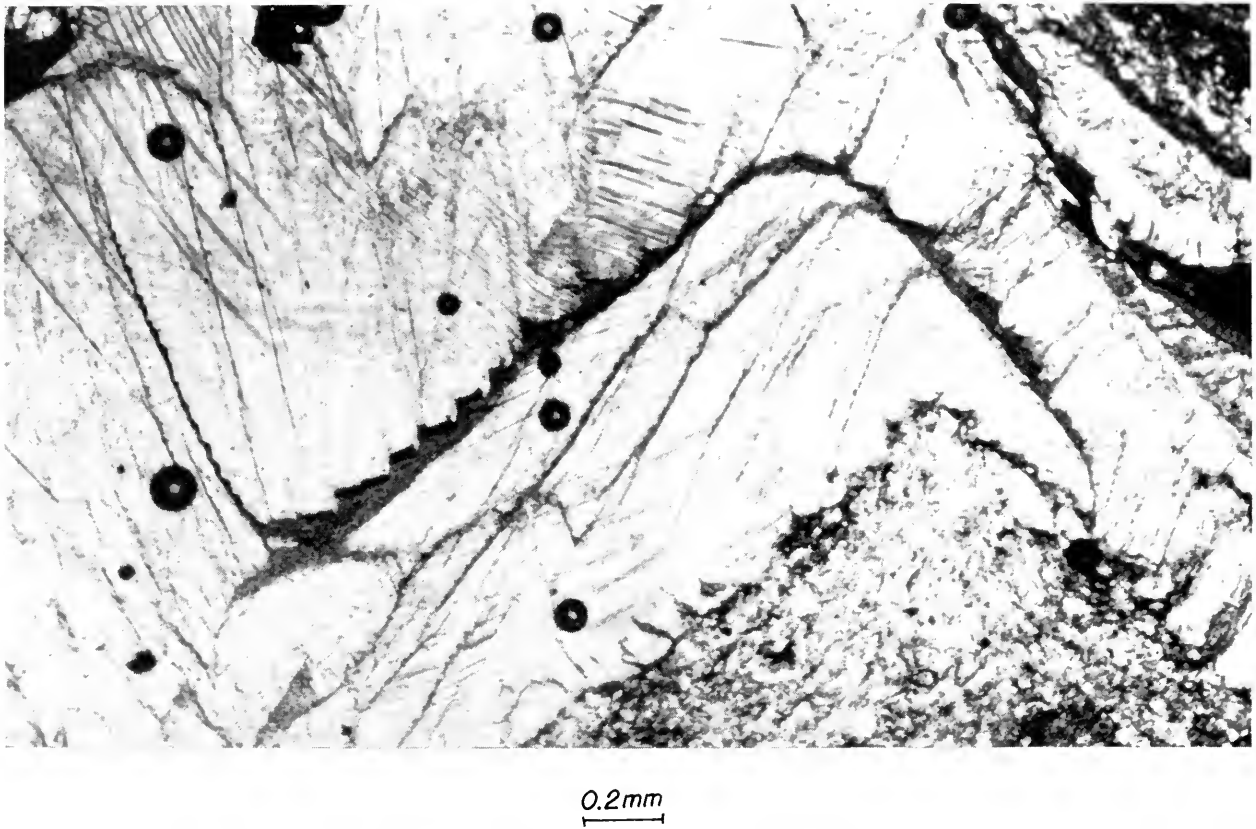

FIG. 81. Vertical thin section of calcite vein showing conical corrugated clay laminae bearing corrugated trails from toothed segments. Cunningham Brook, New Brunswick (slide no. 281).

Eocene age. The veins occur parallel to the stratification in thinly bedded, greenish-gray, sandy siltstones that contain abundant carbonized plant remains and gypsum laminae. Dr. Clark interprets the beds as non-marine near-shore deposits of a lacustrine environment.

MACROSCOPIC STRUCTURE

One specimen of a vein is divided into two layers, 5.5 and 13.5 mm. thick, of pure, white, fibrous calcite. A vertical fracture surface exhibits finely corrugated partial cone-cups, the apices of which point toward the interior of the vein.

MICROSCOPIC STRUCTURE (SLIDE NO. 824)

The calcite fibres are from about 0.09 mm. to, rarely, 0.42 mm. across and up to 2.3 mm. long. The junction of the two layers is marked by a zone, 0.1 to 0.2 mm. wide, of fine-grained calcite. Intercalated inter-granularly and perhaps, in part, intra-granularly are clay films 0.028 mm. to 0.038 mm. thick that transgress the general trend of the fibres to form acutely pointed cones. The apices are formed mainly at the wedge-shaped terminations of the fibres. An occasional clay layer has a step-like form.

These veins thus show an incipient cone structure that is better developed than in the veins from Fleurant Point, Quebec, is quite similar to the lens from Cedar Bluff, Alabama, but is not so well developed as in the veins from Cunningham Brook, New Brunswick.

26. TRACY, IOWA (G-3561)

These specimens were collected from a spoil heap of a surface working of Pennsylvanian coal and were donated to the Museum by Mr. J. Wollin, who reports that they occur as concretions.

MACROSCOPIC STRUCTURE

The maximum thickness is 205 mm. Fibrous structure is very evident and relatively pure calcite needles are readily seen under 30 × magnification. Cones are poorly formed and packed so closely together that they interfere with one another. Individual partial cones attain a height of about 68.3 mm. but are often smaller; some are curved and the calcite needles are also curved. Shaly lenses are irregular; some are thin and lie between the calcitic cones, and others occur as horizontal wedges. The cone angle is generally very acute and varies from 14° in small cones to 50° in larger ones, averaging perhaps between 20° and 25°. Inner cone-cup surfaces are very corrugated and the vertical step portion is up to 2.76 mm. in depth. The steps of the corrugations are clearly composed of fibrous calcite. In some parts of the specimens the calcite is not fibrous but apparently structureless, with penetrations of thin "curtains" of inclined fibrous calcite.

FIG. 82. Vertical thin section of cone-in-cone specimen. Tracy, Iowa (slide no. 258).

MICROSCOPIC STRUCTURE

Vertical section (slide no. 258).—The vertical calcite fibres are large, up to 2.8 mm. long and about 0.09 to 0.20 mm. wide, although between crossed nicols they appear as aggregates of narrower parallel fibres. Conical lines are formed by clay inclusions within and between the fibres (fig. 82). The calcite within the cones extinguishes parallel to the cone walls so that the conical structure seems to be controlled by the crystallization of the calcite fibres. Cleavages are prominent in some of the fibres and bear no relationship to the cones.

In places there are denser patches of clay inclusions where the calcite is more irregular and finer in grain.

Horizontal section (slide no. 255).—The clay is aggregated into many incomplete interfering arcs up to about 0.12 mm. across. Pyrite and fossil fragments occur sparsely. The calcite grains vary from about 0.015 to 0.06 mm. in diameter.

27. KENTUCKY (G-1357)

No information on the locality or stratigraphical occurrence is available for this specimen.

MACROSCOPIC STRUCTURE

The cones are extremely well developed and individualized, and they extend throughout the whole thickness (22.52 mm.) of the layer. Between the cones are partial cones of fibrous calcite but in some cases the material appears to be a structureless calcilutite. The cone surfaces have both longitudinal and concentric striations. The cones flare out at the base so that the cone angle varies from about 24° at the top to 40° about a third of the way down and 76° near the base. Some cones extend upward from the base for 12.22 mm., at which point there is a suggestion of a horizontal parting.

MICROSCOPIC STRUCTURE

Vertical section (slide no. 271).—The calcite appears to be very fine grained (0.02 mm.) but between crossed nicols spindle-shaped areas extinguish as units up to ca. 1.85 mm. long, possibly because incipient recrystallization tends to form larger individuals. The spindles are more or less parallel to the cone axes but they do not extinguish together. There are considerable inclusions of clay particles and these are, in part, aggregated into indistinct conical lines. Toward the base of the cones there are numerous faint bands similar to those previously described in the Dotson's Branch specimen (p. 207). One corrugated clay layer, 0.04 to 0.16 mm. thick, occurs within the cone and is parallel to one side of it.

Horizontal section (slide no. 270).—This shows a dense meshwork of incomplete clay arcs 0.03 to 0.04 mm. across. The calcite is fine-grained (up to 0.03 mm.) but aggregated into irregular patches up to about 0.28 mm. across, which almost extinguish as a unit between crossed nicols. This patchy extinction may be the result of incipient recrystallization.

28. OHIO SHALE (DEVONIAN), COOPER'S HOLLOW, OHIO (G-3607)

These specimens were collected and donated to the Museum by Miss Carole Stentz. They occur in the Upper Devonian Ohio shale. One specimen is described both macroscopically and microscopically.

MACROSCOPIC STRUCTURE

The specimen is about 36 mm. thick with the weathered vertical surface showing partially cone-shaped lines, some of which are arranged in a cone within a cone series, pointing toward the upper surface. A freshly broken vertical surface bears both cone and cone-cup surfaces. The cone surfaces are formed of partially conic scales and bear longitudinal striations as well as—to a lesser degree—incomplete horizontal concentric ribs. The cone-cup surfaces have the characteristic corrugated or step-like structure formed by clay layers and lenses. The cone angle is small (about 20–25°) but flares toward the base. The bottom surface of the specimen has incomplete arcs marking the intersections of partially conical clay surfaces. These are commonly arranged in more or less complete concentric circles outlining the bases of macroscopic cones up to 19 mm. across. As the fine-grained gray carbonate is homogeneous and shows no fibrous structure, the cone surfaces have the appearance of being superimposed on a structureless matrix.

MICROSCOPIC STRUCTURE, VERTICAL SECTION (SLIDE NO. 294)

The clay layers of the macrocones are from about 0.016 mm. to 0.12 mm. thick. In most cases the clay is diffuse and intermixed with calcite and not so well defined as in most other specimens. The corrugated surface is also not well marked except in a few of the layers. Microcones of very fine clay layers occur throughout, the individual cones ranging from about 0.2 to 1 mm. in height. The calcite is fibrous, with fibres up to about 1.4 mm. long by 0.1 mm. broad, in the uppermost portion of the specimen. The calcite passes downward into more spindle- or fan-shaped grains, which are about 0.23 to 0.32 mm. long and 0.02 mm. to 0.06 mm. broad near the base. The fibres and spindles are oriented with their length normal to the top and bottom surfaces of the coned layer; their shape and orientation are related to both the micro- and macrocones. The clay particles of the microcones appear to be present within as well as between the grains. Throughout the slide are scattered many minute (0.004

to 0.007 mm.) granules and cubes of pyrite. These are more numerous in some zones and especially in some of the thicker clay layers.

The microscopic structure is thus similar to that of all cone-in-cone specimens and proves that the macrocones are related to the microcones and to the calcite fabric throughout the matrix and are not merely superimposed structures.

29. CONE-IN-CONE, NORTH OF GREYBULL, T53N, R94W, WYOMING (G-3572–74)

Three specimens collected from the Upper Cretaceous and given to the Museum by Mr. Neal Brown contain cone-in-cone calcite layers associated with sandstone. The top of only one specimen was identified.

MACROSCOPIC STRUCTURE

In one specimen (G-3572) the cone-in-cone layer is approximately 20 mm. thick and is composed of brown fibrous calcite; corrugated cone-cup surfaces are developed and to a lesser degree cone surfaces are visible. In many places individual partial cones extend the full thickness of the layer. Coarse friable calcareous sandstone lies on the apical surface of the cone layer. The oriented specimen (G-3573) has a basal layer of cone-in-cone approximately 10 mm. thick, separated by about 45 mm. of coarse friable calcareous sandstone from a thin fibrous calcite layer 3 to 6 mm. thick, similar to the lower layer. The third specimen (G-3574) has a more irregular development of brown fibrous calcite up to about 10 mm. thick on one surface. Some small ellipsoidal masses a few millimeters long, of fibrous calcite, are present in the calcareous sandstone immediately adjacent to the fibrous calcite layer.

MICROSCOPIC STRUCTURE, VERTICAL SECTIONS

G-3572 (slide no. 284).—This specimen, which contains relatively well-developed macrocones with corrugated cone cups, has coarse fibrous calcite up to 2.9 mm. long by 0.14 mm. in diameter. Cone surfaces of clay inclusions are well developed; the terminations of the fibres and the shape of the calcite aggregates also form the cones. The thicker conical clay layers are corrugated. Twin lamellae, oriented in one or two directions, occur sparsely but bear no relationship to the cones. Some grains of quartz and plagioclase occur among the calcite and, rarely, have a clay concentration shaped like a dunce's cap on the side facing the bases of the cones (fig. 83).

FIG. 83. Vertical thin section of coned calcite veins in sandstone showing quartz grains and associated clay "caps." Near Greybull, Wyoming (slide no. 284)

G-3573 (slide no. 285).—Microcones pointing upward are only rarely discernible in the fibrous calcite, and the clay inclusions are mainly in the form of inter- and intra-granular streaks. The upper surface of the vein is in contact with sandstone, which has considerable granular calcite cement. The contact is sharp and there is no fibrous calcite in the sandstone, although there are some sand grains dispersed in the fibrous calcite, particularly near the junction. Some of the calcite—both the interstitial calcite of the sandstone and the fibrous calcite of the vein—has twin lamellae.

G-3574 (slide no. 283).—Like the above specimen the sandstone contains considerable granular calcite cement. Fibrous vein calcite occurs along one margin and, although the actual contact is sharp, there are lenses of vein material 4 to 5 mm. thick in the sandstone near the more continuous vein. The fibrous calcite of the lenses has cones of clay inclusions and a few sand grains. The contacts of the lenses with the sandstone are sharp.

It is considered that the coned fibrous calcite of these three specimens crystallized in thin laminae or lenses of clay intercalated among the sand. The latter is not involved in the calcite vein except for a very small number of dispersed grains. These grains were caught up passively in the growing calcite. The fact that some loose grains were available suggests that the veins developed *pari passu* with the cementation of the sand.

30. NEEDLES PEAK, BIG BEND REGION, TEXAS (G-3609)

This specimen was kindly supplied by Mrs. June Zeitner of Mission, South Dakota.

MACROSCOPIC STRUCTURE

This specimen is composed of cream-colored, coarse, fibrous calcite; macroscopic clay lenses are absent. Corrugated partial cone-cup surfaces are well developed in one vertical fracture surface and some poor partial cones are present on another. The coned calcite is about 25 mm. thick but on one surface is a layer, about 3 mm. thick, of coarse calcite fibres oriented normal to the fibers of the main portion. The fibers of the thin layer have a radial arrangement and in places they bend at a right angle and pass continuously into the fibres of the coned portion.

MICROSCOPIC STRUCTURE

In thin section (slide no. 286) the main coned layer of the specimen is seen to be composed of long calcite fibres up to about 0.23 mm. in diameter. The fibres do not extend the entire thickness of the layer. Fine clay inclusions form dense lines that essentially parallel the fibres but have very acute conical forms. The thin layer (3.25 mm.) is made up of calcite fibres up to 0.42 mm. in diameter and at least 9 mm. long, oriented nearly at right angles to the fibres of the rest of the specimen. Lines of fine, mainly intergranular, clay inclusions parallel the fibres and possess only a slight suggestion of very acute conical form. At some points along the contact between the two layers the fibres of one bend continuously into parallelism with the fibres of the other, whereas at other places the contact is discordant and sharp. There is a little increase in the amount of included clay along the discordant contact. Neither the direction of growth of the fibres nor the cause of the change in direction of their growth is known. That it is a growth phenomenon is supported by the absence of twinning and granulation along the contact, even in the fibres which can be traced from one layer into the other.

31. POTTERY HILL, OTTAWA, ILLINOIS (G-1824)

MACROSCOPIC STRUCTURE

The maximum thickness (33.60 mm.) of this Pennsylvanian specimen is the total of a number of layers varying in thickness from 2.00 mm. to 7.9 mm. The cones are very irregular and distorted and pass into corrugated surfaces lacking a cone form, similar to those in specimen G-3843, described above (p. 213). Fibrous structure is plainly to be seen, especially on weathered surfaces. The fibres appear to be vertical to bedding even in coned portions. Horizontal partings are very irregular and contain thin layers of micaceous clay; on the better defined coned forms the surfaces are corrugated. Cone cups are variable in size; one is about 13 mm. deep with vertical corrugations about 0.5 mm. high and a "tread" that is inclined toward the axis (cone apex down). The total impression of the specimen is that each layer has been pressed down into the one beneath with a smear of clay between.

MICROSCOPIC STRUCTURE (G-1822)

Vertical section (slide no. 259).—This section is of interest because it shows features intermediate between those of the coned calcite vein from Cunningham Brook and the Woodland Valley and Dotson's Branch specimens. There are several distinct coned layers separated by non-coned layers (fig. 84). The coned layers are composed of typical spindle-shaped calcite and contain both microcones of clay and well-developed, thicker, conical, corrugated clay lenses that tend to be continuous across the slide. Two such layers are separated by a wavy clay layer 0.23 mm. thick; the cones on each side of this clay point in the same direction. The clay is believed to represent an original layer that has been deformed and separated from other clay layers by the growth of calcite and is thus similar in origin to the clay and silt layers included within the calcite veins of the Jones Creek formation described above (p. 251). Although solution of calcite might have been responsible for the origin of the clay, there is no evidence for this; the clay is probably an original layer.

One other separating layer, 0.9 mm. thick, is composed of fine-grained calcite (0.005–0.015 mm.), clay, and pyrite particles. The cones on either side point toward the layer and the junctions between the coned and non-coned sections are gradational. The relationships are thus identical to those described for specimen G-3568 (p. 221) and concretion G-151 (p. 224).

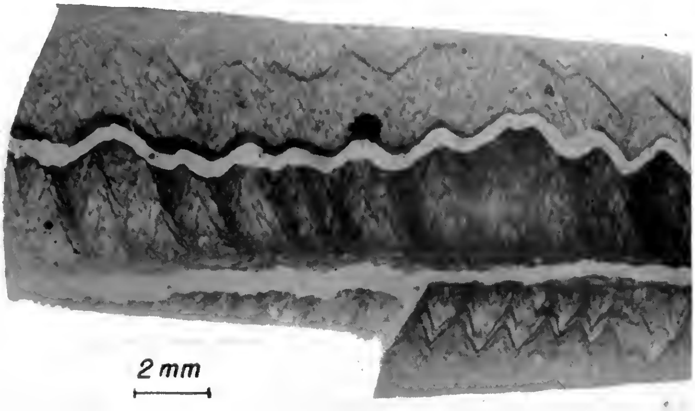

FIG. 84. Vertical thin section of cone-in-cone layers. Ottawa, Illinois (slide no. 259).

32. POTTERY HILL, OTTAWA, ILLINOIS (G-1826A)

MACROSCOPIC STRUCTURE

This specimen has two distinct layers, a laminated dark gray calcareous shale about 30 mm. thick and a buff crystalline carbonate layer about 80 mm. thick. The sharp contact is generally a slightly undulating plane presumably parallel to the original bedding. In places, however, it abruptly steepens to a near vertical position for some 10 or more millimeters before resuming its more normal, nearly horizontal course. Under the binocular microscope the contact is seen to be minutely irregular.

The carbonate layer appears to be coarsely fibrous and to have a cone-in-cone structure; the cones and conic scales have a very acute apical angle. Cone cups with corrugated surface occur rarely. The shale layer is dense but exhibits a fine parallel banding, with laminae from a fraction of a millimeter to 3 millimeters thick. Irregularly shaped dark zones of material connected to the shale layer penetrate and anastomose into the coned carbonate layer.

Etching with dilute acid emphasizes the structures. The bands of the shale layer stand out as alternating laminae of greater and lesser carbonate content. The laminae richer in carbonate have an incipient microcone structure and also possess small lenses of compact clay. The laminae terminate at an oblique boundary between the shale and carbonate layers, although they are bent into partial conformity. The carbonate layer shows considerable clay inclusions disposed in innumerable, very fine, acutely conical planes. An occasional corrugated conical layer, the apex of which points toward the shale layer, is present. Some clay lenses several millimeters long interrupt the conical structure.

MICROSCOPIC STRUCTURE (SLIDE NOS. 563–565)

The carbonate layer is dense with fine clay inclusions; at the thin edges of the section the carbonate is seen to have a very fine grained (mainly up to about 0.06 mm.) fibrous texture but it extinguishes as units over larger zones. Clay lenses up to 2.3 mm. long and 0.23 mm. thick are present. On their upper and lower surfaces they have fibrous calcite fringes up to 0.33 mm. thick, which are less dense with inclusions than the surrounding carbonate. The irregular zones that are in contact with the shale layer are darkened by much intergranular clay, and the carbonate grains (ca. 0.04 mm. across) are equigranular instead of being fibrous.

The shale layer is very fine grained and made up of thin laminae of different compositions. Bands of relatively pure, fibrous calcite, 0.23 mm. thick, occur among clay-rich bands. Some of the latter have dense, saucer-shaped, clay lenses, each of which has fringes of fibrous calcite. A microcone structure is discernible in some of these fringes. Other bands are more homogeneous, but interstitial calcite and small wisps of dense clay, 0.028 to 0.1 mm. thick, are present. Lenses of coned fibrous calcite, 3 to 4 mm. thick, are inserted between the bands in places. Finely divided pyrite is disseminated throughout the shale and also occurs in sparse aggregations.

The shale layer appears in many respects to be similar to the interior portion of the coned concretion G-151 (p. 222), and the carbonate layer apparently is similar to the coned external layers. The contact of the two layers is, however, much sharper than in the concretion. Presumably the conditions of carbonate crystallization changed abruptly. The boundaries between the coned carbonate and shale layer that are oblique to the presumed bedding are analogous to those oblique boundaries in the coned veins from Cunningham Brook (fig. 75).

33. Jubilee Creek, Peoria County, Illinois (G-2065)

The total thickness of the specimen is some 135 mm., but cone-in-cone is restricted to about 105 mm. The cones are not well formed but they show both external cone and internal cup surfaces. The cone surfaces are strongly corrugated (vertical portions up to 2.42 mm. and shorter, slightly inclined portions ca. 1 mm.). The cup surfaces are coated by a buff residue in some cases and by a gray-green clay in others. The coned portion, which has a fibrous structure, passes into a greenish-gray calcareous layer that appears, in part, to be recrystallized calcite with lenses of gray clay. The cone angle is near 32° with a slight flaring toward the base.

34. Specimen of Unknown Origin (G-3593)

The total thickness of the specimen is about 150 mm. The cones and cups are very well developed but interfere greatly with one another. Cone-in-cone developed along a common axis is particularly well seen (fig. 85). Clay lenses between conic scales are prominent and the cone cups have a marked corrugation. The cones all point toward one surface that has a few scattered fossils similar to the Woodland Valley and Dotson's Branch occurrences. Fibrous structure is evident. A remarkable feature is the development of certain "master" cone surfaces with clay layers that cut across other cone surfaces.

35. South of Lovell, Wyoming (G-3578–84)

This material was collected from the Thermopolis shale, Upper Cretaceous, by Dr. E. S. Richardson, Jr., and myself at a locality found by Mr. Neal Brown. The cone-in-cone layers were exposed by digging into weathered shale that dips 30°. It was not possible to obtain unweathered material; much gypsum and limonite were associated with the shale. The lower cone-in-cone layer is about 230 mm. thick, with gray shale below and a hard band, 140 mm. thick, above, with gypsum seams and limonite. The upper cone-in-cone layer, a lens-shaped body some 450 mm. across, is broken into two parts, a lower one 45 mm. thick and an upper one 0 to 90 mm.

FIG. 85. Large cone-in-cone specimen showing "nested" cones. Locality unknown (G-3593).

thick. The lower cone-in-cone layer fractures easily along vertical surfaces. Acute cones point upward and coarse clay corrugations are present on the cone cups. The ferruginous calcite has a fine fibrous structure on weathered surfaces but otherwise appears dense and dark brown in color. The upper cone-in-cone layers are similar to the lower one but thinner, and the cones point downward. In part the cone structure is not evident macroscopically. The tendency for vertical fracture of the cone-in-cone layers produces many pointed splinters that can commonly be seen lying in patches along the strike of the weathered shale outcrop. The patchy occurrence represents the frequency of the lenses characterizing certain stratigraphic horizons.

The arrangement of the cones in the upper and lower layers is identical to that of the cones in the concretion specimens at Elk Creek (p. 225).

36. FAIRBURN, SOUTH DAKOTA (G-3588–92)

From the Sharon Springs member, Pierre shale, Upper Cretaceous, Dr. E. S. Richardson, Jr., collected specimens of cone-in-cone lenses which laterally appear to be replaced by dense carbonate concretions without cones at the same level. One specimen (G-3588) is of typical complex cone-in-cone some 80 mm. thick and composed of fine fibrous calcite. The partial cones point upward, but are not well individualized as they greatly interfere with one another.

37. CONCRETIONS, NEAR MYTON, DUCHESNE COUNTY, UTAH (G-3844–47)

A number of concretions were collected by Dr. John Clark from the upper part of the Myton member (Uinta C), Uinta formation, Upper Eocene, and about a mile south of the locality of the calcite veins (G-3694) described on page 257, but approximately 200 feet lower in the section.

The enclosing rock is a gray-green mudstone, believed by Dr. Clark to belong to a sequence of near-shore deposits of a lacustrine environment.

MACROSCOPIC DESCRIPTION

G-3844 is a pink, fine-grained calcareous concretion with irregular green zones. Lenses of red and green mudstone occur in the similarly colored portions of the specimen. These lenses are generally just a few millimeters across but some are larger; one is 18 mm. and extends, appropriately colored, from the pink across a green zone and back into the pink-colored portion of the concretion. The clay lenses are arranged in a step-like echelon series similar to the corrugated clay lenses of the typical cone-in-cone structure.

Another concretion (G-3845) is highly irregular in shape and is composed of a gray-green, fine-grained, impure, calcareous material enclosing irregular lumps of gray mudstone. The surface of the specimen is knobbly and ridged, indicating the irregular way the carbonate was deposited as the concretion grew.

A similar concretion (G-3846), but with a silty base, in section has a series of radiating, branching lines of lighter-colored material originating at a point nearer the margin than the center. These sheets, of finer grain and more calcite-rich, are continuous into the ribs on the surface and are presumably related to zones of initial deposition of carbonate.

G-3847 has a rough, globular shape but its surface is also ribbed. A polished section, however, shows it to be composed of relatively pure, coarsely fibrous calcite. The fibres are radially arranged, originating from a zone at the margin of the concretion. In this latter zone the calcite is partly non-fibrous and partly fibrous, the fibres being much smaller than in the main part of the specimen. Small lenses of gray clay also occur in the marginal zone, and, where they separate thin laminae of fibrous calcite, the structure is analogous to cone-in-cone structure with its corrugated clay layers separating conic scales.

MICROSCOPIC STRUCTURE

The thin section of G-3844 (slide no. 823) is mainly composed of fine-grained homogeneous calcite with disseminated clay. In places this passes into fibrous calcite only some 0.03 to 0.04 mm. long, in which there are lenses of light brown clay up to 0.14 mm. thick (the section did not cut any green-colored zone of the concretion). Although the fibrous calcite and clay lenses are features possessed by cone-in-cone structure, the latter is not recognizable as such in the thin section.

Slide no. 819 (specimen G-3845) shows homogeneous calcite (ca. 0.06 mm. across) with disseminated clay, which passes into zones of fibrous calcite with clay lenses. The fibres, up to 0.23 mm. long, have varying orientations in different parts of the section but are invariably normal to the surface of associated clay lenses, some of which are up to 8 mm. in diameter. In places the fibrous calcite occurs in small conical tuft-like aggregates resembling the microcones of typical cone-in-cone specimens. The association of fibrous calcite with discrete clay lenses is again a feature reminiscent of cone-in-cone structure.

The thin section (slide no. 820) of the radially fibrous concretion G-3847 shows very dusty, spindle- or wedge-shaped, fibrous calcite up to 6.5 mm. long and 0.7 mm. across. Many fine lines of dusty inclusions enhance the radial structure. The radial structure is not entirely regular, as conical tuft-like groups outlined by fine lines of inclusions occur with their apices located at an inclusion of clay; the tufts point toward the interior in many cases and toward the exterior in others. In places, possibly where there are more impurities concentrated, the fibrous calcite is finer-grained and the wedge-shaped grains form smaller tufted aggregates similar to the microcone structure of typical cone-in-cone. The zone from which the overall radial structure originates is composed of more or less equant calcite, ranging in size from about 0.02 mm. to 0.1 mm. across. Although these concretions do not possess good cone-in-cone structures, the above descriptions clearly show that they do have both macro- and micro-structures similar to those present in cone-in-cone specimens. The presence of this incipient cone structure in these concretions, together with the coned calcite vein from the same formation nearby (p. 257) is very interesting, as they are the only examples of cone structure known to me from undoubted non-marine sediments and also the only ones of Tertiary age.

The fibrous calcite in the concretions is closely related to the discrete lenses of clay or silt enclosed within the concretions. In the non-fibrous portions the clay is present throughout as finely divided particles. The development of incipient cone structure thus seems to depend on the physical state of the sediment in which the carbonate is crystallizing at the time of crystallization.

38. SALINA, KANSAS (G-3566)

This characteristic development of cone-in-cone, about 27 mm. thick, shows the fibrous character of relatively pure calcite. Cone-cup surfaces are more evident than cone surfaces, and the former have strong tooth-like corrugations, with steps near to vertical and up to 2.2 mm. high. Cone angles are about 20 to 25°.

39. MILAN, OHIO (G-1540)

This is typical cone-in-cone. Some cones extend the entire thickness of the specimen (53.9 mm.); others are shorter. The cone angle appears to be very constant at about 26°. The fibrous calcite appears to be oriented parallel with the cone walls.

40. DUDLEY, ENGLAND (G-118)

This specimen is a very large cone ca. 185 mm. in height, made up of a series of superimposed conic scales bearing strong concentric calcitic clay corrugations which can be flaked off, and in places bearing longitudinal striations. The corrugations increase in size toward the base, where they are up to 4 mm. in breadth. In the lower part of the specimen there is a complex of smaller (some about 48 mm. high) interfering cones, which exhibit corrugated cone-cup surfaces as well as cone surfaces. The base shows the arc structures of the smaller cone bases. The main cone angle is 50°. Fibrous structure is not evident, and fractured surfaces appear as structureless, fine-grained calcilutite. Thin section study (slide no. 279), however, indicates that the fine calcite possesses a texture and orientation similar to other cone-in-cone examples. Shaly material coats the corrugated cone and cone-cup surfaces.

A partial chemical analysis is given in Table I.

41. BLACK HILLS, SOUTH DAKOTA (G-783)

Although both cone and cone-cup surfaces are present, the cones are only partially developed because of mutual interference. The cone angle is 40 to 45°. The cone-cup surfaces are strongly corrugated and the cone surfaces also have an occasional transverse ridge. The fibrous character of the cones is very evident; it produces the longitudinal striations on the cone surfaces and on portions of the cone-cup surfaces.

A partial chemical analysis is given in Table I.

42. RATON, NEW MEXICO (G-2094)

The cones are well formed and cone-cup surfaces are corrugated. The conic scales are clearly shown and thin to the apex of the cone. The corrugations show more or less vertical surfaces that are striated and suggest slip surfaces disposed in concentric arcs. The thickening of the conic scales toward the base of the cones might account for the often-observed flaring of the basal portions of the cones. In addition to the thickening of the overlapping conic scales their increase in number away from the apex of the cone would also develop a conic form.

43. Specimen of Unknown Origin (G-3567)

MACROSCOPIC STRUCTURE

The fine, fibrous structure of the layer (34.82 mm. thick) is very evident. Cones are few and dispersed and show as individualized cone-cups only; no actual cones are visible. The sides of the cups flare toward their bases and have well-marked corrugations. The calcite fibres of the wall lie parallel to the cup and at an angle to the apparently vertical fibres in the surrounding matrix. The largest cone-cup measures 32.62 mm. in depth with a base diameter of 19.90 mm. and a fibrous corrugation 1.64 mm. thick. The cone angle varies from 12° near the apex to 52° in the central region.

MICROSCOPIC STRUCTURE, VERTICAL SECTION

The specimen shows a fine grain, which extinguishes in larger ill-defined spindle-shaped areas between crossed nicols. In addition to the microcones of clay there are conspicuous, corrugated, partially coned layers of clay up to 0.23 mm. thick. A thin layer at the surface toward which the cones point is a transition zone where the calcite spindles are more irregular and where there is more clay.

44. Specimens of Unknown Origin (G-707A and B)

G-707A has a height of 53 mm., a base 33 to 35 mm. in diameter, and a cone angle of about 35°. The base shows small cone-cups. Annular rings are present on the surface of the cones; where the rings are absent a longitudinally striated surface is evident.

G-707B is a large incomplete cone ca. 64 mm. high, which would be about 103 mm. high by projection of the cone walls; its cone angle is about 26°. The structure of composite conic scales is evident.

IV. CHEMICAL COMPOSITION

Harnly (1898) records several analyses of cone-in-cone specimens from Kansas as follows (in percentages): SiO_2=1.46 to 5.84; Fe_2O_3+

$Al_2O_3=1.2$ to 2.62; $CaO=54.13$ to 54.64; $CO_2=33.07$ to 42.06; $MgO=0.0$ to 2.76.

Hendricks (1937) reports cone-in-cone from the Missouri Mountain slate (Silurian), Arkansas, as being composed of a relatively pure manganiferous siderite containing only small quantities of calcium and magnesium.

Reis (1903, p. 214) quotes a number of analyses of cone-in-cone specimens, with their carbonate content ranging from 70 to 90 per cent. He also presents detailed analyses of a number of others, one of which, from Staffordshire, England, is quoted in Table I. Three specimens in the Museum's collection have been partially analyzed by the late Mr. H. W. Nichols; these results are also given in Table I.

TABLE I

	G-93 North East, Pennsylvania	G-783 Black Hills, South Dakota	G-118 Dudley, England	Staffordshire, England (Reis, 1903)
$CaCO_3$	67.89	75.61	49.67	52.28
$MgCO_3$	tr	1.68	17.27	27.12
$FeCO_3$	17.27	11.40	17.53	10.58
$MnCO_3$	+	+	+	2.59
Residue	+	+	+	8.44

+ = not reported.

G-93 and G-783 are composed of calcite with some substitution of Ca by Fe and Mg. The other two examples would appear to be composed of a mixture of carbonates or a carbonate approaching an ankerite, with substantial substitutions of (Fe, Mn) for Mg and with Ca in excess of the 1:1 ratio for Ca: (Mg, Fe, Mn).

Some approximate determinations of carbonate content were made by weighing the residues after treatment of several specimens in warm hydrochloric acid (1:1). A bulk sample (G-3547) from Woodland Valley, Indiana, has a residue of 24 per cent and thus an approximate carbonate content of 76 per cent. The residue in the non-coned central portion of the concretion (G-3586) from near Judique Village, Cape Breton Island, Nova Scotia, is 28.4 per cent, while that from the coned portion in the upper part of the same specimen is 17.4 per cent.

In two other specimens the clay in the lenses forming the macroscopic cones was separated from the fibrous carbonate. Determinations of residues made on each fraction were as follows:

TABLE II

	Dotson's Branch, Indiana (G-3554)		Tracy, Iowa (G-3561)	
	Clay	Fibrous carbonate	Clay	Fibrous carbonate
	%	%	%	%
Soluble	52	85	7	96
Residue	48	15	93	4

A complete separation was not achieved. The Dotson clay fraction contains considerable carbonate, but this may have been caused mainly by contamination with fibrous carbonate rather than by carbonate content within the clay lens. The Tracy clay fraction contains but little carbonate. The fibrous carbonate fractions both have very high soluble proportions, the Tracy specimen being the purer carbonate. This is in agreement with the microscopic examination in which the Dotson's Branch specimen is seen to have abundant microcones of fine clay within the macrocones (see p. 206).

The carbonate content of the cone-in-cone specimens is quite similar to that of non-coned carbonate concretions; for example, the residue of a sample of a large concretion (Li-4703) occurring within gray shale at the Mecca Quarry, Indiana, and stratigraphically close to the Woodland Valley cone-in-cone horizon is 12 per cent, while that of a concretion (Li-4706) from black sheety shale also from Mecca Quarry is 14 per cent. The bulk carbonate content of cone-in-cone specimens is thus similar to that of calcareous concretions commonly found in shales.

V. GRAIN ORIENTATION

A number of grain orientation studies were made from thin sections cut normal to the cone axes. "C" crystallographic axes were determined on a universal stage by means of the conoscopic method. These axes were plotted on a Schmidt net and contoured; the resultant stereograms are shown in figure 86.

The grain size is so small in the Kentucky (slide no. 270) and Woodland Valley, Indiana (slide no. 254), specimens that the centered conoscopic figure at each interval of the traverse is usually poorly defined and is probably the result of an aggregate of grains. However, the scatters obtained are believed to reproduce the scatter of the "c" axes.

The "c" axes are by no means vertical; the angular spread, corresponding to a conical angle, varies from 16° to 20° in the Tracy,

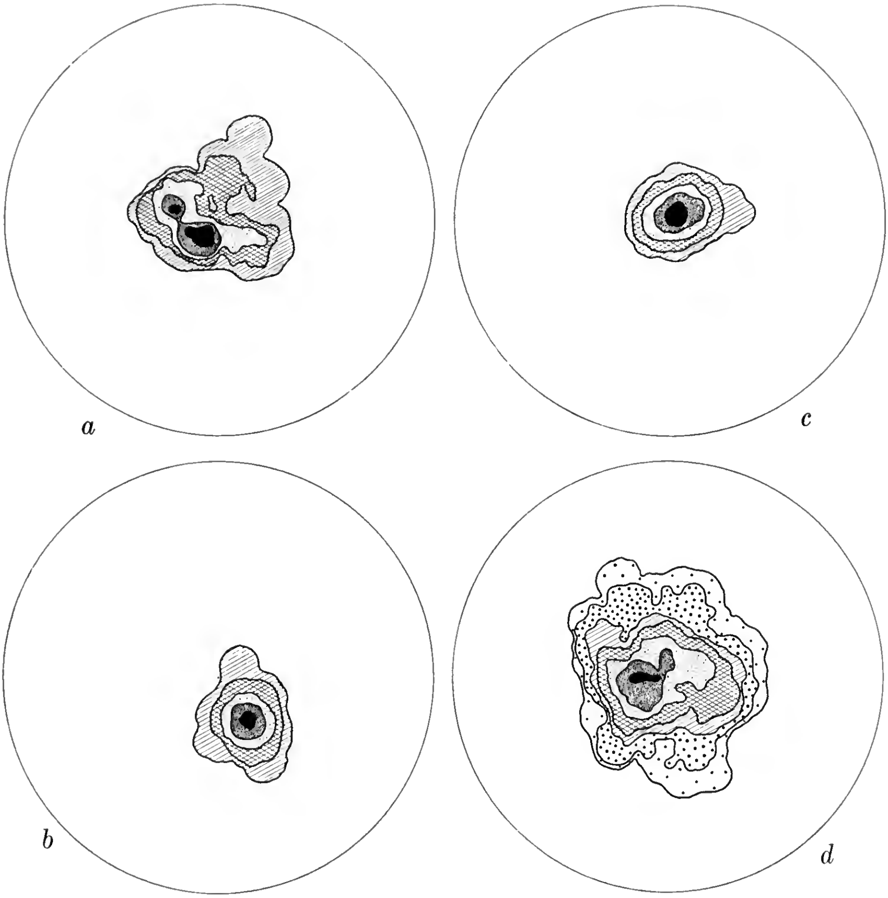

FIG. 86. Petrofabric diagrams of cone-in-cone; "c" axes of calcite plotted on the lower hemisphere of a Schmidt stereonet and contoured: *a*, 30 axes, Woodland Valley, Parke County, Indiana (contours: 3 %, 7 %, 13 %, 20 %, 27 %); *b*, 100 axes, Tracy, Iowa (contours: 1 %, 5 %, 25 %, 50 %, 75 %); *c*, 102 axes, single cone, Kentucky (contours: 1 %, 5 %, 20 %, 46 %, 60 %); *d*, 248 axes, concretion with trilobite, Deseret, Utah (contours: ½ %, 1 %, 3 %, 5 %, 9 %, 13 %, 17 %).

Iowa, specimen (slide no. 255) to a surprising 60° for the trilobite from Utah (slide no. 262). The axes also do not fall on a small circle centered around the cone-in-cone axes as they would if the grains were oriented parallel to the conical surfaces. Rather, the orientations have a brush-like pattern or an incomplete radial structure. The angle of maximum spread of "c" axes agrees well with the measured cone angles of the Iowa and Indiana specimens and with the cone angle near the apex of the Kentucky specimens. The spread of

60° in the trilobite is, however, much greater than the cone angle of 26° measured in the vertical thin sections. The grains with the largest angle to the cone-in-cone axis may represent the less regular grains of the very "dusty" areas, particularly around the cones marking the margins of the trilobite axis.

VI. PREVIOUS VIEWS ON CONE-IN-CONE STRUCTURE

Cone-in-cone structure has certainly been known and described for over a century and there have been many attempts to explain its origin. In 1859 Sorby (1860) gave an excellent brief description of its microscopic structure and suggested that it is a concretionary structure, formed after the deposition of the rocks in which it occurs by the crystallization of calcium carbonate and other isomorphic bases, the crystals forming almost entirely on one side along an axis in a fan-shaped manner to produce a conical shape.

Tarr (*in* Twenhofel, 1932) and Cayeux (1935) review at some length the work previous to their own publications and include good bibliographies. Mention might be made here of the following few papers. Cole (1893) holds that the structure is produced when crystallization starts at a number of points on the surface of a bed or in the interior of a concretion and growth radiates out and tends to form a cone from each point. The serrated clay between the cones is the residue forced aside during the crystallization. He further states that it is highly probable that the "c" axes of the calcite are parallel to the axes of the cones. Gresley (1894) gives good descriptions and figures of specimens from the Devonian near Erie, Pennsylvania, and these are identical to some available to myself. He attributes the structure to concretionary concentration of calcium carbonate, which induces pressure among the particles so as to form cones and also involves the partial expulsion of the contained clay, which, owing to the radial pressure, forms horizontal rings or ridges.

Reis (1903) describes and figures the structure in great detail and has a long and very involved discussion of its origin. Briefly, he holds that it is caused, over a long period of time, by the enrichment of carbonate by concretionary action often accompanied by the decomposition of organic residue. The accretion begins soon after the laying down of the beds under some superimposed pressure and is related to the diagenesis of clay-rich, carbonate solution-bearing layers. The crystallization tends to form aggregates approximating the crystal form. Contraction tensions produce polygonal pyramidal surfaces of "splitting." Entry of water causes solution, which in turn forms the clay residues, producing the stepped conical clay layers. He holds that the vertical surfaces of the "steps" are slide surfaces, and that movements of portions of the mass are also indicated by dislocations of fine horizontal bands. Later Reis (1914) abandons solution as playing a part in the origin of the clay layers and considers that they are formed by the growth of the calcite, which pushes the clay into the conical layers. Fine bands which cross the cones approximately parallel to the bedding he likens to rhythmic deposits in gelatin produced by Liesegang. He explains the interruptions and displacements in the bands as due to different rates of crystallization.

Keyes (1896) considers the crystallizing force of calcite as responsible for the production of cones and states ". . . that even the clay is pressed into the form assumed under normal conditions by the calcite." Richardson (*in* Lang, Spath, and Richardson, 1923) has studied the fibrous calcite veins, known as "beef," which occur in the Lower Lias of the Dorset coast, England. The "beef" shows cone-in-cone structure, which is more complex the greater the thickness of the vein and is frequently associated with calcareous concretionary nodules. He suggests that rapid crystallization of the calcite fibres on each side of the central parting takes place under a vertical principal stress caused by the weight of the superincumbent strata and under lateral stresses caused by resistance to lateral growth of the fibres. The state of stress produces inclined planes of maximum shear (conical in three dimensions), which act to inhibit crystal growth in such a way that the fibre cannot cross such a plane. In support of this, he states that the cones penetrate the total thickness of the "beef" vein without interference by the central parting as shown in his figure 5. However, his figure 6 does not support this, for the cones on either side of the parting appear to be independent, and Lang (op. cit., p. 52) states that "All seams are double, and the cones of each layer interpenetrate at the junction." Tarr (1932, p. 726) also states that ". . . the cones were on both sides of the parting but did not cross it."

Linck (1930) suggests that cone-in-cone structure forms as the result of the crystallization of a gel-type sediment in which calcium carbonate has been maintained in a colloidal state by the action of protective colloids, with loss of water and decrease in volume. It is difficult to see how the crystallization of a pre-existing gel could form a trilobite image in the coned calcite as in the case of the *Elrathia* concretion (p. 241). The Cunningham Brook specimens (p. 251) clearly prove that the formation of the coned calcite veins resulted in expansion and separation of pre-existing sedimentary layers. This occurred after sedimentation and thus the coned calcite could not be formed by the crystallization of a pre-existing sedimentary colloidal gel.

Herrmann (1930) also considers that fibrous crystallization takes place but under the influence of pressure directed from all sides. The pressure is a result of swelling of the surrounding clay. Conical slip surfaces, along which clay layers arise, are also produced in the carbonate-rich concretionary body and there are differential movements of the cones.

Tarr (1932) holds that cone-in-cone occurs in massive material as well as in the more usual fibrous calcite. However, this appears to be a mistaken view. A specimen he describes from Dudley, England, is almost certainly composed of fibrous calcite as is also the specimen (G-118) from Dudley in the Museum's collection and described above (p. 274). He also mentions specimens from Kansas and Kentucky as being massive. I cannot comment about these, although specimens from these two states in the Museum collection are, again, of fibrous calcite. The cone structure in coal, a fine example of which is in the collection (G-450), is an entirely different structure and should not be confused with true cone-in-cone (see p. 190). Likewise, the percussion cones in quartzite that Tarr mentions should not be considered as belonging to true cone-in-cone but to pressure-induced structures, such as those induced by striking homogeneous material (fig. 26) and shatter cones (fig. 25).

Tarr also states that the cones are later than the fibrous layer in which they occur, although his "proofs" are far from convincing (1932, p. 727). Tarr invokes pressure as the main agent, accompanied by solution which gives rise to the annular rings of clay and clay films as insoluble residues. In the cases of coal and quartzite he excepts solution as playing a role. He originally (1922) held that a fibrous character was essential, but later (1932) refuted this on the erroneous basis of the cones in massive material, although he still considered a fibrous nature very important (1932, p. 733) when present. The cleavage angle of calcite Tarr also thinks important in spite of the fact that he establishes (1932, p. 719) that the conical angles in "beef" depart widely from the rhombohedral cleavage angle of calcite. He even states that the reason why the cones have their bases at the surface of a layer instead of their apices, as in the case of percussion cones, is because of the cleavage in calcite. As to the source of pressure, Tarr discards the pressure caused by the volume increase when aragonite changes to calcite, the pressure produced by growing concretions, the pressure of diastrophic disturbances, and the pressure of crystallization forces. The weight of overlying beds is his remaining source, and he details (1932, p. 729) his reasons for believing in a differential vertical pressure. Tarr's point 2, ". . . the cones are dominantly on the upper side of a layer with their bases upward, though smaller ones occur also on the lower side, with their bases downward," is by no means universal. Likewise, his point 3, ". . . the most perfect cones have apical angles that approach those of the ideal cones developed in testing the crushing strength of materials, that is, angles of 70 to 110°," and point 4, ". . . the apical angles in cone-in-cone are nearly that of the rhombohedral cleavage of calcite (the cleavage of calcite would give an apical angle of 106°)," are also dubious in view of the great departures of conical angles from these values. With respect to Tarr's point 8, ". . . the surface of a layer of fibrous calcite containing cone-in-cone commonly shows concentrically curved fracture lines that are the result of pressure," the curved lines are more than mere fracture surfaces; in all of the specimens that I have examined the curved lines represent intersections of partially conical layers of clay.

Tarr's claim that solvent action along the shear planes removes carbonate, leaving behind an insoluble clay residue, is open to doubt. He postulates that the annular rings of clay are produced when solutions move down the shear planes and attack the upper edges of the calcite fibers first, thus producing greater solution at these points and resulting in the stepped character of the clay (see Tarr, 1932, fig. 107). However, this applies only to cones with their apices pointing downward. In the case of those with their apices pointing upward, downward-moving solutions would produce clay steps on the inner surface of the conical clay layer—a position I did not find in a single specimen. Both types of cones are identical in structure and are mirror images. Following Tarr's explanation, the solvent must thus move up the conical shears of all cones pointing upward and, of course, down the shears of cones in the reverse position. This seems most unlikely. Solvent action thus does not appear to be adequate to explain these characteristic stepped clay structures.

Cayeux (1935) attaches importance to the occurrence of cone-in-cone in materials other than calcite. It should be noted in this respect that he quotes Gresley (1894) for many of the diverse media. Actually, Gresley clearly considers cone-in-cone structure to have been originally formed of calcite in all cases. In a footnote Gresley states that his specimens of other mineralogical composition "... are unquestionably what may be called re-altered products, that is, 'tertiary' formations . . .," in other words, replacements of calcite. Cayeux also mentions gypsum and coal. The former is also recorded by Tarr (1932), who considers it a replacement of calcite. As far as the cone structure in coal is concerned, I have already stated (p. 190) that it is an entirely separate structure and should not be considered along with true cone-in-cone.

In the case of specimens composed of carbonate Cayeux argues that if only clay impurities were concerned in the conical surfaces the structure could be explained solely by the forces of crystallization of calcium carbonate. Because quartz grains showing important displacements from their original positions occur in the carbonate of one specimen, he considers that external mechanical forces, such as lateral compression, must be involved. An impure mass of carbonate held between resistant planes which resist vertical displacement of the material has suffered a lateral compression. The latter has caused a large-scale recrystallization of the carbonate along with the elimination of impurities of small dimensions. Thus, siliceous specimens from Hérault he considers to be composed of normal micro-quartzite and the cone-in-cone structure to have been formed exclusively by dynamic means, causing a more or less geometric arrangement of micaceous material (but see p. 246).

Denaeyer (1939, 1940b) claims to have reproduced cone structures by tensional forces applied to a flattened ball of plastic clay and suggests that even gentle warping of beds would suffice to cause local zones of tension. Recrystallization under the influence of the directed tension results in the preferred orientation of the fibrous calcite of calcareous cone-in-cone (1940b, p. 318). He describes many occurrences of cone-in-cone (1940a, c, 1947) and elaborates his idea (1945) that penecontemporaneous tectonic deformation causes traction forces in muddy plastic rocks. He suggests (1946), however, that the traction forces that form cone-in-cone on septarian nodules are not due to tectonics but to variation in the volume of the nodules during concretion formation and to the adherence of the nodules to the enclosing strata.

Bonte (1942) considers cone-in-cone to be the result of concretionary action caused by directed diffusion phenomena around decaying organic matter, and Gay (1942) outlines a theoretical model of diffusion and crystallization to explain the conical forms. This model is, however, too simplified to explain the complexities of structures actually found in cone-in-cone specimens. Thoral (1942) also believes that the structure is due to early concretionary activity connected with decomposition of organic matter and that the diffusion and thickness of the concretion are related to the grain size of the enclosing sediment.

Bonte (1945a), while adhering to his original views on the origin of the conical structure, considers that the concentric rings or steps that characterize cones are formed by a mechanical process. Compression causes part of the coned mass to separate by slipping along the length of the calcite fibres and by transverse tearing of the fibres; then foreign amorphous or crystalline material is interposed to form the normal rings. In some cases the steps are deformed or partially flattened to permit the dislocation of the cones. Similarly, Bonte (1952) explains the coned calcite veins or "beef," the fibrous calcite of which crystallized rapidly and concurrently with the opening of the walls of the vein.

For a number of years Bonte and Denaeyer held opposing views on the origin of cone-in-cone, but in 1947, in collaboration with J. Goguel, they produced a mutually agreed theory which combined portions of each of their earlier ideas. This mutual theory (Bonte, *et al.*, 1947) may be summarized as follows: The volume of a nodule or a bed increases during recrystallization or concretionary growth, but the horizontal dimension is prevented from increasing by the opposition of the neighboring sediments. This results in an augmentation of horizontal pressure, although the vertical pressure remains essentially constant. In the case of cone-in-cone layers on septarian nodules the authors suggest that tangential pressure exceeds the radial pressure, so that there is traction in the radial sense (presumably in the directions of minimum stress). Denaeyer (1952) interprets cone-in-cone in calcite veins, oblique or vertical to the bedding, as a consequence of tension forces exerted on the calcite during crystallization as the fissure opened. Further, he suggests (1954) that reduction in volume of sediments by dehydration causes separation of the strata. Simultaneous lateral secretion results in the formation of double or multiple layers of calcite with "beef" structure ("fibro-conique") and occasionally with cone-in-cone. The transport or separation of argillaceous impurities during the lateral secretion assists in the production of the stepped films. The latter show the small internal slides or tears that follow a conical form and are produced by the parting of the walls of the fissure. The oriented crystallization of calcite is due to the action of a directed traction (tension). This explanation may be extended to thick lenticular beds of cone-in-cone. In the case of isolated nodules Denaeyer still considers that the lateral opposition of the sediments should not be forgotten (presumably for the production of radial traction forces).

The concept that a tractional force causes the orientation of fibrous calcite and the conical toothed or stepped clay layers has been the consistent mechanical explanation of Denaeyer. Bonte, Denaeyer, and Goguel (1947) hold that the concretionary growth itself is responsible for the orientation of the calcite and the cone-in-cone structure, albeit by the production of traction forces. Denaeyer (1954) considers the traction forces, at least in the case of veins and beds of cone-in-cone, to be externally produced, causing the fissuring, lateral secretion, and then the displacements in the fibrous calcite that form the steps in the clay layers.

I, too, believe that the cone-in-cone lenses and layers had a concretionary origin, and consider that the concretionary growth itself is responsible for the structure. But the operation of tractional forces to form the cones seems unlikely. One may ask why cone-in-cone is not present on all concretions or veins where similar forces should be operating during formation. Growth of a concretion is an expansion process. It is likely that the direction of maximum stress in and around such a growing body is radial in a spheroidal or lensoid concretion and vertical in a horizontal vein or layer. The minimum stress directions would then lie parallel to the surface of the growing body. The veins on the Cunningham Brook specimens (described on pp. 251–257) strongly indicate that the force of crystallization of the calcite pushed the sedimentary layers apart and not that the latter were dilated by some external process (dehydration or tectonics). According to Denaeyer (1954) the traction forces can only displace the clay layers after they have formed. They would then be embedded in the crystalline calcite. There is no evidence that tensional forces have operated to produce the steps in the clay by a series of displacements, or that these displacements are greater in the earlier-formed part (the inner zone in the case of coned layers or lensoid concretions) of the structure. In fact, the reverse is true, for the displacements are greater toward the latest formed zone.

Twenhofel (1950, pp. 605–611) follows Tarr in ascribing pressure from the load of overlying sediments and solution as the agencies that cause cone-in-cone structure. Pettijohn (1957) considers pressure instrumental in forming cone-in-cone, not by the weight of overlying beds but by the forces produced by concretionary growth acting on earlier-formed layers. Solution is then responsible for forming the conical clay layers. Weller (1960) holds that cone-in-cone is a shear structure produced by the weight of overburden acting on calcite fibres, which are secondary material formed before much consolidation has taken place. Concentric shears are formed around fairly evenly spaced centers and are accompanied by solution along the principal shear planes.

Morawietz (1961), in an interesting description, suggests that cone-in-cone limestone layers develop very early in diagenesis in water-rich, hydrogen sulfide- and hydrocarbon-bearing, partly calcareous muds with about 70 per cent pore volume. Superposed pressures are unnecessary; the carbonate crystallizes as a result of lowering of solubility as the sediment dries out, due to temporary uplift above sea level. The resultant heating, degassing, and evaporation cause crystallization to start suddenly, to be rapid at first and then slow down. Morawietz figures (op. cit., p. 239) double cone-in-cone layers, with their apices directed away from the center and with a central clay parting. This is the only case of such an arrangement known to me either from the literature or in the Museum's collection. In all the latter the cones of a double layer point toward the center. Morawietz states that the upper and lower cone-in-cone layers grew toward each other and finally compressed and imprisoned the central clay layer between them. The proximal (apical) portion of each layer is, however, finer-grained and more clay-rich than the distal. He believes that there was some expansion, particularly of the upper layer of the double cone-in-cone, over the thickness of original sediment. The reason for the cone-in-cone structure is not explicitly discussed, but Morawietz considers it (op. cit., p. 246) to result from rapid crystallization of calcium carbonate in radiating tuft- and cone-like needle aggregates.

Müller (1962) considers cone-in-cone structure in a concretion from the Muschelkalk to have been the result of recrystallization of a colloidal concretion under the influence of confining pressure.

VII. DISCUSSION OF LITERATURE

The above survey of the literature shows that some confusion has attended the description of the occurrence of cone-in-cone; arising from this confusion conflicting theories have been proposed. In my opinion the term "true cone-in-cone structure" should be restricted to occurrences composed essentially of carbonate. Specimens having the characteristic structure of these types but now composed of other minerals, such as the siliceous examples in the Museum's collection, must be regarded as replacements, as indeed Gresley (1894) recognized long ago. Fibrous texture of the calcite is also a constant feature and must be regarded as an essential factor in the origin of the structure.

Pressure both from external forces and from crystallization of calcite has been invoked as imposing cone-in-cone structure on already crystalline material (Tarr, 1932; Cayeux, 1935; Pettijohn, 1957; Weller, 1960). The complex character of cone-in-cone, as revealed in most of the specimens described above, particularly the microscopic structure and the relationship between the microcones, the impurities, and the fibrous calcite, indicate that the cones cannot be explained simply as late shear structures. Stress resulting from volume increase caused by inversion of aragonite to calcite has also been suggested as an agent (Tarr, 1922). It is difficult, however, to envisage how the intricate micro- and macrocone forms of the clay could result from such a force. If aragonite was the first to form, then the cones must have been formed at that time, and the later change to calcite was inconsequential. Moreover, there is no evidence that the carbonate initially crystallized as aragonite. Tractional forces have been invoked by Denaeyer (1939, 1940b, 1954), Bonte, *et al.* (1947), and Bonte (1952) to orient the calcite, form the conical structure, and produce the stepped nature of the clay layers. The operation of such forces seems inadequate to explain the structure and is unlikely to have operated, at least in nodular concretions, for the reasons explained (p. 285). A mechanism that may appear to explain satisfactorily some types of occurrences is, nevertheless, deficient if it is not able to account for other occurrences possessing the same essential characteristics.

Action of solution has been called upon to help explain the conical corrugated clay layers (Reis, 1903; Tarr, 1932; Pettijohn, 1957; Weller, 1960). Certainly the complex micro-fabric cannot be explained in this way. The evidence of the specimens from New Brunswick (p. 251) clearly shows that solution was not involved in the production of the clay layers and that the latter represent original sedimentary laminae.

W. A. Richardson (1923) considers that a stress field caused by superposed beds and the force of crystallization of the calcite set up conical shear stresses that controlled the course of crystallization of the calcite so that the growth of individual fibres stopped at the conical shear surfaces. While this suggestion of the simultaneous operation of external stress and force of crystallization has merit, it is incomplete in that it does not explain the conical clay layers and fails to explain why cone-in-cone does not occur in all cases of the crystallization of calcite in a sediment or rock; for example, in all calcareous concretions and in all fibrous calcite veins. Both Dawson (1868) and Marsh (1868) interpret cone-in-cone as the effect of pressure on concretionary action, although Dawson does not specifically say whether the compression acted at the time of the crystallization or later, while Marsh considers that compression and crystallization were contemporaneous.

Crystallization of calcite has been held by many geologists to be the essential cause of cone-in-cone. Sorby (1860), Cole (1893), Gresley (1894), Keyes (1896), and Reis (1914) consider that the way the fibrous calcite crystallized is responsible for the cone structure. The latter four authors explicitly state that the crystallizing force of calcite pushed the clay into conical layers. Recently Morawietz (1961) considers that rapid crystallization in radial conical forms produces the structure, but his only reference to clay is to that compressed between the two layers of a double cone-in-cone seam.

VIII. RESULTS OF THIS STUDY: THE ORIGIN OF CONE-IN-CONE AND DISCUSSION OF REQUISITE CONDITIONS FOR ITS FORMATION

The specimens described in this paper provide clear evidence that cone-in-cone structure is essentially produced by crystallization and fibrous growth of calcium carbonate and is concretionary in origin. The following questions consequently arise as to the particular conditions controlling its appearance:

1. What causes the initial deposit of calcium carbonate?

2. Where does the calcium carbonate come from?

3. At what stage does the concretionary action take place relative to the deposition and consolidation of the enclosing sediment, and what is the condition of the sediment?

4. What controls the type of fabric, that is, the fibrous habit as compared with the non-fibrous habit of non-coned concretions or as compared with the non-coned layers of concretions associated with coned layers?

5. How much expansion over the original thickness of sediment is involved?

6. What, if any, is the influence of the vertical pressure of overlying beds and what is the influence of the crystallizing force of calcite?

7. What controls the size of cones, the size of the conical angles, and the individualization of the cones?

8. What causes the cessation of growth?

These questions will now be discussed in turn.

1. *What causes the initial deposit of carbonate?* The deposition of calcium carbonate in cone-in-cone may be controlled entirely by physico-chemical conditions, such as the available supply of calcium, activity of CO_2, or pH of the environment. However, the decay of organic matter has been cited by many as a possible initiator of the deposition at localized centers. Lalou (1957) reports on the experimental crystallization of carbonates by bacterial action on organic matter and suggests that, in addition to the release of CO_2, the reduction of sulfates and production of H_2S with concomitant increase in pH is essential to the deposition. A relationship between the decay of organic matter and the occurrence of cone-in-cone has been noted by Reis (1903), Bonte (1942), Gay (1942), Thoral (1942), Brown (1954), Harrington and Leanza (1957), Bright (1959), and Morawietz (1961). Stubblefield (1930) reports Upper Cambrian cone-in-cone concretions containing trilobites. Lang (*in* Lang, *et al.*, 1923) describes ammonite shells that occur in the center parting of cone-in-cone layers ("beef") and also cone-in-cone one-fourth inch thick with ammonite ornamentation on both upper and lower surfaces. David (1952) also describes fossils that occur in the middle of coned "beef" layers, the outside surfaces of which have more or less faithful images of the contained organisms. Steinmann and Hock (1912, p. 190) mention orthoceratids that occur within cone-in-cone concretions. Fossils are closely associated with many of the cone-in-cone specimens described in this paper. In addition, the activity of H_2S is shown in many specimens by the very common occurrence of pyrite and, in a few cases, of sphalerite. The decay of organic matter may thus have been the initial cause for the precipitation of the carbonate by establishing favorable physico-chemical conditions.

2. *Where does the calcium carbonate come from?* The source of the carbonate is a difficult question. Undoubtedly in some cases

the environment of deposition was poorly supplied with carbonates; the concretionary cone-in-cone represents a concentration by diffusion from the enclosing sediments, with perhaps some carbonate coming from the original content of the circulating interstitial water. Pantin (1958) suggests that the carbonate of the concretion he describes was derived from a clastic source and was concentrated by recrystallization. In other cases the environment of deposition was or soon became enriched in carbonate, possibly by the activity of organisms, and the cone-in-cone layer represents a relatively widespread limy horizon. In some examples—Woodland Valley, Dotson's Branch, Barren Creek, and Montgomery Creek, Indiana—there has been replacement of shell by pyrite in the sediment above or adjacent to the cone-in-cone; this replacement may have released some carbonate to the growing cones.

3. *At what stage does the concretionary action take place relative to the deposition and consolidation of the enclosing sediment, and what is the condition of the sediment?* The microscopic structure of the cone-in-cone and in particular the displacement of the clay particles to the microcone surfaces suggest that the sediment was by no means consolidated at the time of cone formation. Probably it still had a high water content, and the crystallizing calcite was easily able to insinuate itself among the particles and move them. The disposition of the clay as fine particulate matter and its distribution pattern in the case of the *Elrathia* specimen (p. 238) support this view. On the other hand, the Cunningham Brook specimens (G-3640–42, p. 251) show that the growth of the calcite not only displaced clay particles into very fine conical films but also displaced layers of clay into conical or saucer-shaped forms. Presumably these layers were sufficiently compacted to behave as coherent lenses, although there probably was further compaction caused by the calcite crystallization and perhaps subsequently by loading. The corrugated clay lenses of complex cone-in-cone are considered analogous to those of Cunningham Brook.

However, if the sediment is compacted beyond a certain degree, the calcite growth then takes place along a bedding contact and the resulting fibrous but unconed vein grows by separating the two opposing surfaces by the force of crystallization. The calcite is very pure and there are no finely divided clay particles present to form microcones and no clay lenses to form the thicker corrugated clay layers outlining macrocones. Specimen G-3564 (described, p. 237) conforms to this origin except that along one boundary there are small saucer-shaped clay lenses that have been detached by the calcite growth. This vein is typical of epigenetic veins, which may be formed at any time after consolidation and diagenesis of the enclosing sediment, depending on the supply of material and perhaps depth of burial. The veins in the specimens from Quebec (G-3562–64, p. 247) probably represent an intermediate type in that they contain very little included material; there is minor coning outlined by fine clay immediately adjacent to the initial growth plane, where the calcite is fine-grained.

4. *What controls the type of fabric, that is, the fibrous habit as compared with the non-fibrous habit of non-coned concretions or as compared with the non-coned layers of concretions associated with coned layers?* The fabric of post-consolidation calcite veins is commonly fibrous, with the long dimension of the fibres normal to the walls of the veins (Grout, 1946). This is also a crystallographic preferment, as the "c" axes are virtually parallel to the long dimension of the fibres. The reasons for this particular fabric habit are complex but presumably include the anisotropic properties of the crystal lattice and physical and chemical properties of the environment. Turner (1949) notes that in the growth fabric of calcite the "c" axes are perpendicular to the longest grain dimension, which is parallel to the direction of greatest ease of growth. This is contrary, however, to the fabric of cross-fibre veins. Griggs, *et al.* (1960) have shown experimentally that calcite recrystallized under non-hydrostatic stress tends to show the "c" axes parallel to the maximum principal stress (see also Kamb, 1959, p. 160) and, further, that the "c" axes of new grains tend to be at an angle of 25° to 30° to those of the host grain. The pressure-temperature conditions of the experiments certainly were far from those that exist during the growth of cone-in-cone, which must take place at near-surface temperature and pressure. However, the factors controlling the calcite orientation (p. 277) in cone-in-cone may be similar.

In the case of a watery mud with an exceedingly fine meshwork of water-filled spaces between the clay particles, precipitation of calcium carbonate (initiated by the development of the right conditions) may begin at numerous randomly distributed nucleation points. As a consequence the grain size will remain tiny. The clay particles will act to shield the small crystals against much increase in size, so that the interstices are soon filled by a multitude of tiny grains; a compact structureless concretion results. Growth of such a mass will continue peripherally as long as the supply of carbonate and the other physico-chemical conditions permit. In the case of the coned concretion G-151 (see p. 222) the form of the crystallized calcite varies from the non-coned center to the coned exterior. This difference appears to result from the physical condition of the clay at the time of crystallization. In the coned region the clay had been somewhat compacted (so that more or less compacted layers or lenses were present) at the time calcite crystallization commenced. Nucleation was concentrated on the surfaces of these lenses and ensuing growth forced the lenses apart. The separation between clay and calcite, however, was by no means perfect, as there was still considerable "looseness" to the clay; much of the clay was incorporated into the calcite mostly inter-granularly and perhaps intra-granularly when grain size increased. The small calcite grains were less crowded by clay particles than were the grains in the non-coned zone, and consequently continued growth was possible through a supply of ions to the free surface. Growth on the crystal surface away from the clay lens probably would have been favored, particularly as there would have been competition laterally and interference by neighboring nuclei. Thus could have arisen a fibrous growth normal to the surfaces of the clay lenses, and this would have been directed outward from the central non-coned concretion.

The lattice orientation is more difficult to explain. It possibly arises because of a tendency of calcite to crystallize with the "c" axis lying in the direction of maximum principal stress and, therefore, normal to the clay lenses, which are approximately parallel with the bedding. Kamb (1959, p. 156) on theoretical grounds states that the stable orientation of calcite growth is for the "c" axis to be perpendicular to the interface between crystal and fluid and to parallel the unique stress axis. Nucleation on the surface of clay lenses thus results in the "c" axes being oriented normal to the lenses.

Growth of certain grains may be favored over their neighbors, with the result that they grow larger and their free surface is able to expand normal to the "c" axis more readily and to take on a flamboyant pattern of growth. A further influence on growth may be surface effects that cause new grains to grow with their "c" axes at an angle to that of the flamboyant grain (Griggs, *et al.*, 1960). Thus would arise a multitude of tuft-like aggregates such as characterize the complex cone-in-cone and give rise to the orientations seen in the fabric stereograms (fig. 86). Subtle variations in the factors that control nucleation and growth rate lead to variations of grain size.

The establishment of more or less coherent clay lenses is thus necessary for the development of complex cone-in-cone. It is likely that this very early diagenetic effect arises in a number of ways. First, there may be original variations in the nature of the layers of sediment such that some layers develop more compact lenses than others (fig. 87, *a, b*). This may explain the examples in which good cone-in-cone structure grades laterally into less well-defined zones (Woodland Valley, p. 197) or in which small patches of microcones grade into a more homogeneous concretionary structure (Velpen limestone, p. 218). Secondly, compaction of the sediment by the overburden during crystallization of the carbonate may explain the passage of a non-coned concretion through a fine-grained transition zone to a well-developed cone-in-cone layer (fig. 88, *a, b*). Thirdly, the growth of a non-coned concretion may cause compaction of the peripheral sediment layers until a stage is reached which favors the development of fibrous calcite and thus of a coned layer (fig. 89, *a–c*). This assumes that an expansion of volume attends the concretionary growth and that the force of crystallization causes the compaction. Force of crystallization is a well-known phenomenon; evidence of its action in sediments is clearly shown by Folk (1962), who figures shells forced apart by the growth of fibrous calcite.

Variations in the physical conditions of the sediment, such as the degree of compaction, thickness, and number of discrete laminae, at the time of crystallization, coupled with the physico-chemical factors of nucleation and growth, control the particular fabric, structure, and complexity of each cone-in-cone occurrence. Nucleation occurred on the ventral surface of the *Elrathia* (fig. 67) and growth proceeded downward, either by lifting the carapace or by compacting the sediment beneath or both. Fine dust was incorporated into the vein and influenced the growth so that relatively dust-free cones with marginal conical dust surfaces and intervening zones highly charged with dust resulted. In other cases nucleation occurred not only on the carapace surface but on a number of thin semi-discrete clay lenses, and growth proceeded from each, separating and forcing them into a complex cone-in-cone structure (Bright, 1959, pl. 18, fig. 2). In this way the complex cone-in-cone was produced on both the dorsal and ventral surfaces of the specimen from Montana (G-3569, fig. 70). The relatively complex coned veins from Cun-

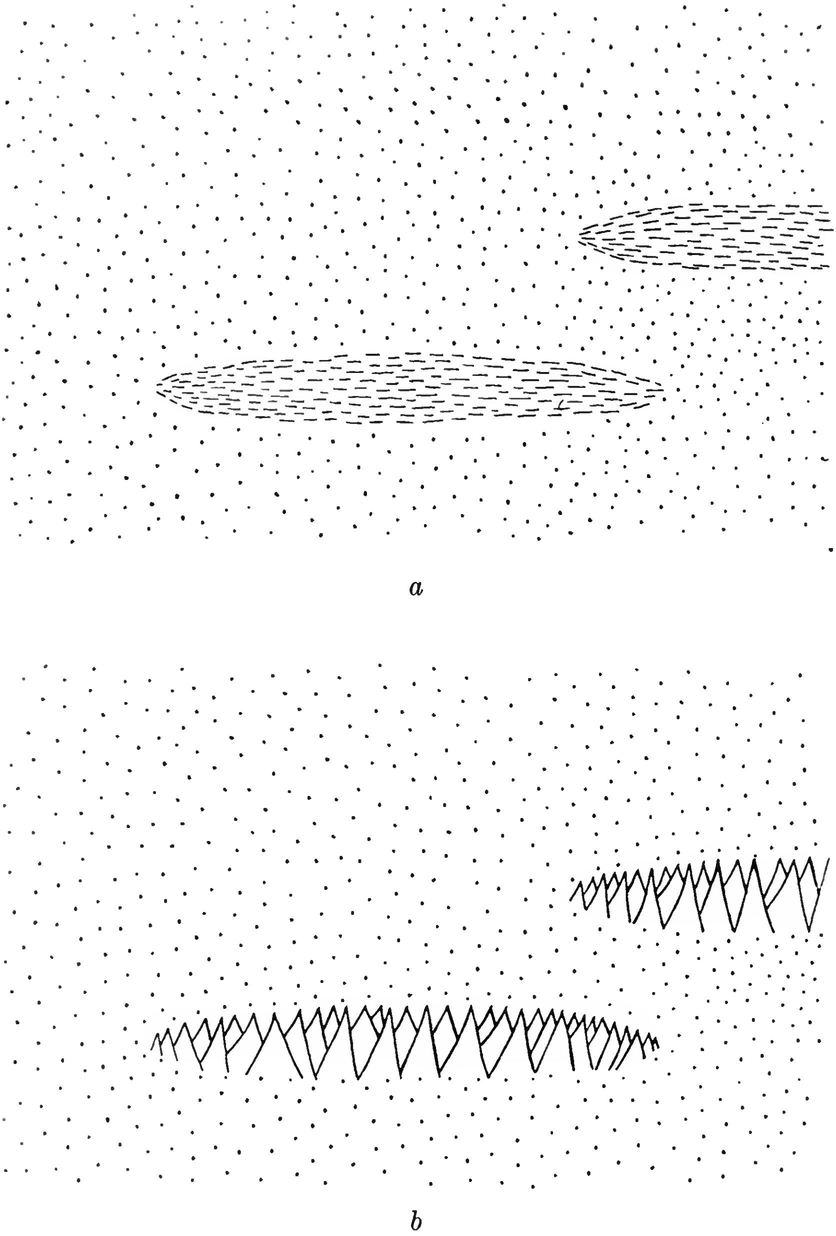

FIG. 87. Diagrams illustrating origin of cone-in-cone lens related to original sediment differences: *a*, initial conditions showing lenses of clay; *b*, cone-in-cone formed during early diagenesis in clay lens.

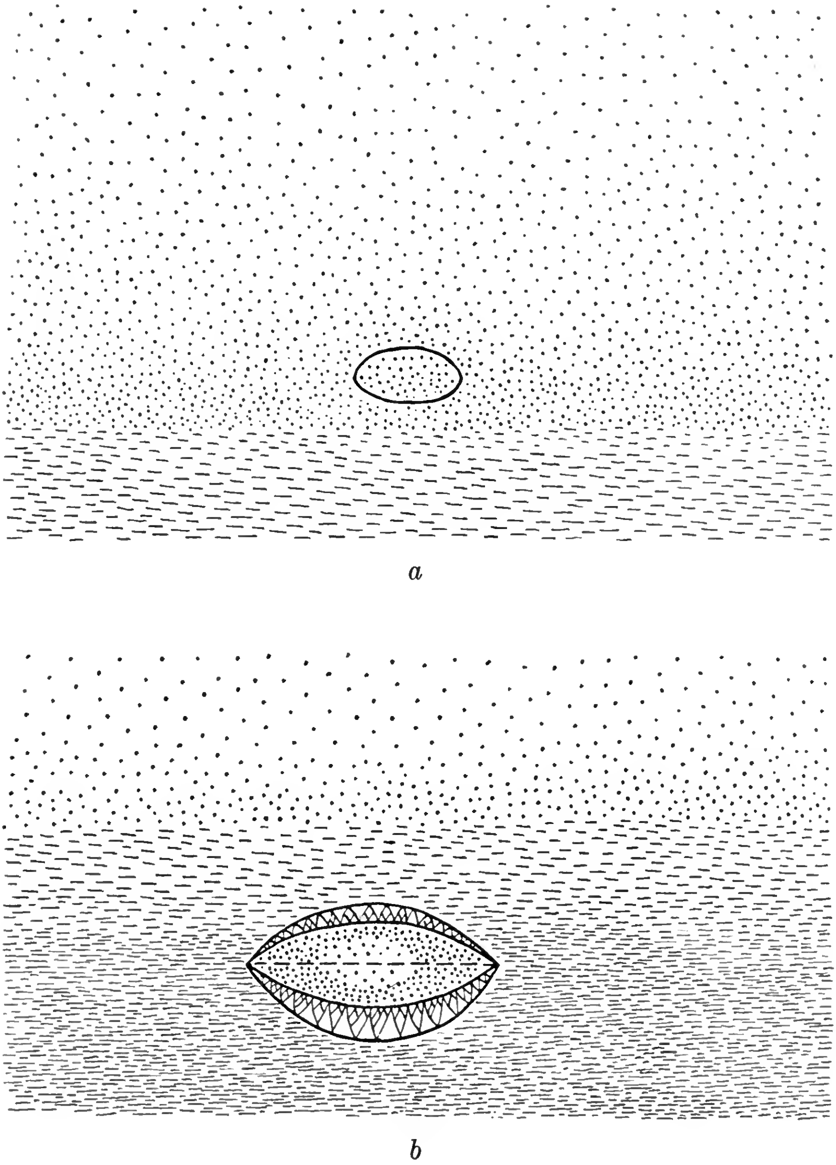

FIG. 88. Diagrams illustrating origin of cone-in-cone in clay layers as a result of compaction by overlying sediment during early diagenesis: *a*, initial development of structureless concretion; *b*, development of cone-in-cone layers around structureless core due to compaction of the clay. (Only one coned layer may develop.)

ningham Brook, New Brunswick, indicate more or less simultaneous nucleation on discrete clay lenses; in some cases this occurred on the lower, sometimes on the upper, and sometimes on both surfaces, producing cones with their apices directed both upward and downward. In the complex but typical cone-in-cone specimens such as those from Woodland Valley and Dotson's Branch, Indiana, the same principles apply, but the cones in such layers all point in the same direction (upward in these examples) save for a rare exception (fig. 35). Why the growth should be consistently in one direction is difficult to say unless it is related to the direction and mode of supply of the ions, particularly in the very early stage of nucleation.

The cone-in-cone lenses in the sandstone specimens (G-3572–74, p. 263) represent a special case. The growth of calcite in the interstices of a relatively coarse sediment such as sand is not able to produce the cone-in-cone structure, as the fundamental conditions are absent; a calcareous, cemented sandstone results, which is analogous to a non-coned claystone concretion. But crystallization in clay lenses (and possibly in fine silt lenses) within a sandstone will result in cone-in-cone lenses identical to normal cone-in-cone except that sparse sand grains are included within the crystalline structure.

5. *How much expansion over the original thickness of sediment is involved?* Estimation of the amount of expansion involved in the development of cone-in-cone structure is fraught with difficulties because the volume of the sediment at the commencement of crystallization is not known nor is the effect of subsequent compaction by the overlying beds. This latter effect must be slight in the case of the cone-in-cone layer because of its crystalline nature. Morawietz (1961) considers that there is little increase, and that this is restricted to the upper layer of the double cone-in-cone layers. However, the coned veins from Cunningham Brook, New Brunswick, the coned concretions associated with trilobites and with the fossil fish, described by Brown (1954), and the cone-in-cone separating the ammonite impressions, described by Lang (Lang, *et al.*, 1923), all point decisively to a substantial increase of volume produced by the growth

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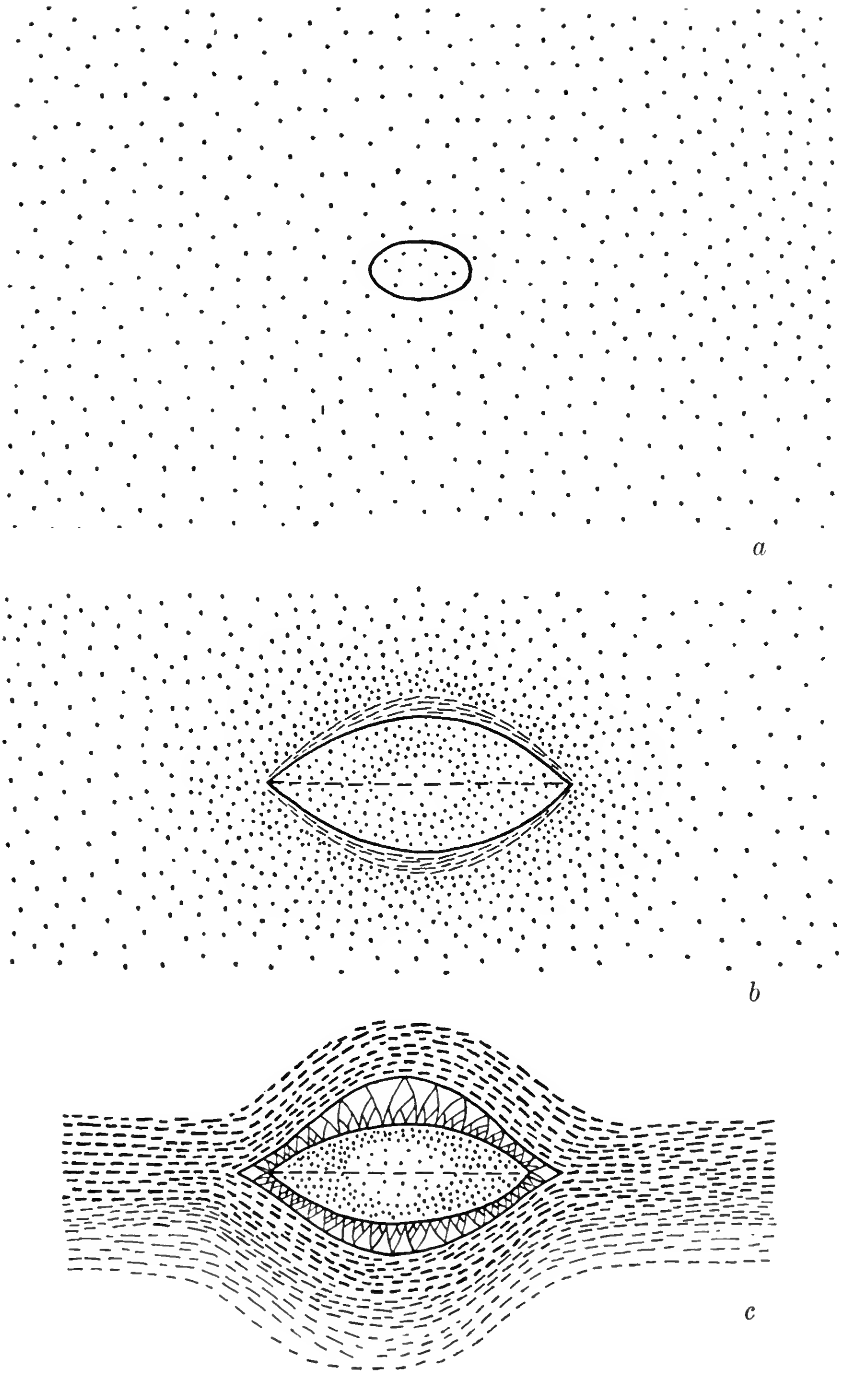
FIG. 89. Diagrams illustrating origin of cone-in-cone in clay layers as a result of compaction by growing concretion during early diagenesis: *a*, initial development of structureless concretion; *b*, growth of concretion showing clay layers compacted around it; *c*, further calcite deposited as fibrous coned layers around structureless core.


a
b
c

of calcite. With regard to the typical complex cone-in-cone no good direct evidence is available. If the view is valid that the mud had already been somewhat compacted at the time of crystallization, then there must have been expansion, since it is unlikely that there could have been zones of watery mud existing among layers and lenses of partly compacted mud. Likewise, the lenses of cone-in-cone occurring within the calcareous sandstone must represent considerable expansion, as a lens of watery mud could not have existed within sand. On the other hand, the presence of the brachiopod spine descending along a macrocone clay layer (fig. 45) would suggest that virtually no movement took place, although this is by no means certain, since the growth of the fine-grained calcite could have produced a movement so delicate as not to disrupt the spine.

The structureless non-coned central portion of coned concretions contains a notable proportion of clay; e.g., the insoluble residue of a sample from the central zone of the Cape Breton Island specimen (G-3586) is 28.4 per cent in comparison with 17.4 per cent of a sample from the upper coned layer. This indicates a greater addition of calcite in the latter zone, where the calcite is coarser-grained and most of the clay is separated into the conical layers. It is possible that expansion is slight during the formation of early diagenetic non-coned concretions. But, if the conditions pass transitionally into those favoring the fibrous crystallization and development of microcones, relative expansion increases and continues to do so as the calcite coarsens and macrocones are formed; that is, the calcite crystallization sets up increasing compaction in the sediment surrounding the growing concretion. It is also likely that the clay layers suffer further compaction as they become imprisoned between the crystallized calcite of the conic scales.

6. *What, if any, is the influence of the vertical pressure of overlying beds and what is the influence of the crystallizing force of calcite?* Neither the force of crystallization nor the weight of overlying beds is responsible for inducing the cone structure in an already existing material. The crystallization force probably is partly responsible for producing the physical state in the clay favorable for the development of cone-in-cone. Similarly, the weight of overlying sediment may operate in the same way and, although this differential pressure is slight, it may be sufficient to influence the growth orientation of the calcite, producing fibers elongated parallel to the "c" axes and more or less parallel to this force.

7. *What controls the size of cones, the size of the conical angles, and the individualization of the cones?* The cone angle and the size of the cones are controlled by the physical properties of the sediment—e.g., the degree of compaction and lamination of the clay—and by the density of nucleation and rate of growth of the calcite which control the grain size. The microcones arise directly from the mode of growth of individual fibre groups, which develop as tuft-like aggregates from a nucleation point, the microcone apex. These groups grow together and form the micro-fabric which, because of the fine clay particles trapped between the grains and tufts, shows the characteristic interfering microcones. Macrocones are established by layers or lenses of clay that remain coherent and are forcibly deformed by the crystallizing calcite. The layers are forced into partially conical surfaces by the differential development of the relatively pure calcite of the microcones crystallizing between the layers. The calcite forms the conic scales, which are separated by the corrugated or step-like clay layers. The number, degree of perfection, and size of the conic scales are thus determined by the number and thickness of the coherent clay lenses. Conic scales commonly thicken toward the base of the cones and this may account, in part, for the flaring of the cone angle toward the distal end. Coarsening of grain toward the cone bases may be one cause of the increase in thickness of conic scales. The apical angle of the macroscopic cones would seem to be controlled by the cone-angle of the microcones. Random packing of the similarly oriented microcones could result in partial macrocones, the individualization of which is a function of the spacing and number of the clay lenses. It may be, however, that the stress state existing in the environment of crystallization controls not only the lattice orientation of the fibrous calcite but also the differential growth of the calcite that produces the macrocones; for example, the growth may be influenced by cylindrical zones of varying rates of calcite deposition concentric to random axes which become the eventual macrocone axes. (Concentric cylindrical zones which increase in length toward the exterior produce an internal cone-cup surface.) If the cone axes are parallel to the direction of maximum stress, cylindrical zones around the axes will parallel potential tensional surfaces. Orientation of macrocones around a common axis, as in specimens G-3586 and G-3587, arises from a control of the axial position determined by original differences in the clay medium at the time of initiation of crystallization (p. 233). The clay lenses are commonly thicker toward the surface of the cone-in-cone marked

by the cone bases; this is possibly a result of a greater degree of compaction.

8. *What causes the cessation of growth?* Growth of the cone-in-cone layer naturally would cease if the supply of carbonate should fail or if the physico-chemical conditions should become unfavorable for continued deposition. Cone-in-cone development would also come to an end if the correct physical clay environment were no longer available. Deposition of calcite could continue but no cones would result. An example of such a case is the cone-in-cone lenses in sandstone, G-3572–74. The basal surface of a cone-in-cone layer is generally an even one except for the irregularities formed by the arcs of partial clay cones. Such evenness of development is also characteristic of the coned trilobite concretions. This suggests that the differential growth which produces the macroconing in complex cone-in-cone layers is a relative effect; the overall thickness remains remarkably constant (or diminishes in a regular way in the case of the coned concretions whose coned layers taper out laterally), but what has varied is the amount of nucleation and growth between the various clay lenses and layers making up the total thickness.

Although cone-in-cone structure is widely distributed geographically in many formations of different ages, it is not of universal occurrence nor is it present in all argillaceous limestones by any means. The reason for its restricted appearance is the necessity for a combination of special circumstances, particularly the physical state of the clay at the time concretionary action is taking place.

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