

EXHIBIT M

Titanium Minerals*

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Elemental titanium has become famous as a space age metal, because of its high strength/weight ratio and resistance to corrosion. However, the major use is in the form of titanium dioxide pigment, which because of its whiteness, high refractive index, and resulting light-scattering ability, is unequaled for whitening paints, paper, rubber, plastics, and other materials. A relatively minor use is in welding rod coatings, in the form of the mineral rutile. United States consumption of titanium dioxide in concentrates for these applications in 1982 was as follows: pigments, 630,000 st; titanium metal, 31,000 st; and welding rod coatings, 5,000 st. The only commercially important titanium ore minerals at the present time are ilmenite and its alteration products, and rutile.

Titanium was discovered by Gregor in 1790, as a white oxide which he recovered from menaccanite, a variety of ilmenite occurring as a black sand near Falmouth, Cornwall. Barksdale (1966) stated that the fundamental chemi-

cal reactions on which the present day titanium industry is based were known before 1800, although it was not until 1918 that these pigments were available commercially on the American market.

Pings (1972) outlined the early history of the titanium industry in the United States, referring to the work of Guise (1964) and others:

Mining of titanium minerals in the United States began sometime between 1880 and 1900, in Chester County, Pennsylvania. Small quantities of rutile were also produced during that time in North Carolina and Georgia. In 1901 rutile was mined from a deposit near Roseland, VA, and was used in making titanium chemicals and for coloring ceramics. Ilmenite in the deposit was produced as a separate item in 1913, and rutile and ilmenite were obtained from this deposit through 1921.

The mining of titanium bearing beach sands began in 1916 near Mineral City and Pablo Beach, FL, for the purpose of making titanium tetrachloride to be used in tracer bullets, flares, and smokescreens. The titanium pigment industry was founded in 1918. By 1928 a large part of the domestic production of rutile, ilmenite, and zircon came from Florida. However production ceased in 1929 in Florida with the mining of newly discovered deposits in Virginia which were mined until 1968. The discovery of new deposits in Florida, and the development of better mining and concentrating methods for low-grade sands, led to a return of activities in this area. The large deposits near Tahawus, NY, were brought into production in 1942 by National Lead Co. (now NL Industries, Inc.), and by 1949 this company was the leading producer of ilmenite in the world. In 1948 the extensive deposits of ilmenite and ilmenite-bearing iron ores were discovered in eastern Quebec.

The large Trail Ridge sand deposit in Florida was discovered by E. I. du Pont de Nemours & Co., Inc. geologists in cooperation with the US

* The writers are indebted to many sources of information for material used in this chapter. We especially wish to thank Stanford O. Gross for geological, mining, milling, and production information on the MacIntyre Development, and H. Leroy Scharon for his contribution on methods of exploration for hard-rock ilmenite deposits. Special thanks are also due the US Bureau of Mines; NL Industries, Inc.; W. P. Dyrenforth of Colorado School of Mines Research Institute, Golden, CO; A. G. Naguib, Vice President, Mineral Development International, Orange Park, FL; and Thomas E. Garnar, Jr., E. I. du Pont de Nemours & Co., Inc., for their cooperation and valuable assistance in preparing the manuscript.

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Bureau of Mines and the Florida Geological Survey, and was developed by Du Pont in the late 1940s (Garnar, 1980).

The beginning of the modern titanium metal industry was in 1948, when Du Pont produced the first metal. US Bureau of Mines reports, which gave details of the Kroll process, together with the attractive properties of the metal for military aircraft, led to a concerted effort by industry and government to develop a large-scale titanium metal industry, which reached a peak capacity of over 36,000 stpy from six producers by 1958 (Pings, 1972a).

The major developments affecting the titanium metal industry since the late 1950s have been fluctuations in the production rate of military aircraft, and the increasing use of the metal in commercial aircraft and for industrial applications. A major change in the titanium dioxide pigment industry starting in 1957 was the development and expansion of the chloride process, which generally uses higher grade TiO_2 raw materials such as rutile in contrast to the relatively low TiO_2 ilmenite feed used in the

older sulfate process. The resulting increased demand for rutile led to higher prices, which in turn stimulated the development of processes for making rutile substitutes by beneficiation of ilmenite.

Since 1960, new deposits of sand ilmenite were developed in New Jersey, Georgia, and Florida. Annual domestic titanium dioxide pigment production was 635,000 st in 1982, 19% below the peak of 787,000 st reached in 1974.

Production and Consumption of Titanium Concentrates and Products

United States production and consumption of ilmenite plus slag in 1982 were down appreciably from 1978 levels. Consumption of rutile also decreased, resulting in a 9% drop in United States pigment production from 1978 through 1982. World production of ilmenite plus slag has declined since 1978, and rutile production has increased (Table 1).

TABLE 1—Salient Titanium Statistics

	1978	1979	1980	1981	1982
United States:					
Ilmenite concentrate:					
Mine shipments, st	580,878	646,399	593,704	523,681	233,063
Value, 1000 \$	\$25,628	\$32,965	\$32,041	\$37,013	\$19,093
Imports for consumption, st	308,671	184,478	357,488	236,217	348,366
Consumption, st	792,289	791,063	848,607	856,116	583,250
Titanium slag:					
Imports for consumption, st	149,172	111,210	194,994	268,825	247,845
Consumption, st	128,826	144,708	181,582	252,826	225,541
Rutile concentrate, natural and synthetic:					
Imports for consumption, st	289,617	283,479	281,605	202,373	163,325
Consumption, st	263,184	313,761	297,582	285,371	238,937
Sponge metal:					
Imports for consumption, st	1,476	2,488	4,777	6,490	1,354
Consumption, st	19,854	23,937	26,943	31,599	17,328
Price, Dec. 31, per lb	\$3.28	\$3.98	\$7.02	\$7.65	\$5.55
Titanium dioxide pigments:					
Production, st	700,755	742,081	727,245	761,190	635,061
Imports for consumption, st	117,708	104,968	97,590	124,906	138,922
Apparent consumption, st	801,728	837,042	753,480	806,040	722,362
Price, Dec. 31, cents per lb:					
Anatase	46.0	53.0	57.0	69.0	69.0
Rutile	51.0	59.0	63.0	75.0	75.0
World production:					
Ilmenite concentrate, st	*3,874,661	*3,874,586	4,015,772	*4,009,737	*3,371,090
Titaniferous slag, st	1,037,193	*842,038	1,343,200	*1,245,000	*1,170,000
Rutile concentrate, natural, st	*332,690	*393,807	*459,634	**409,220	**381,253

Source: US Bureau of Mines.

*Estimated, *Preliminary, *Revised.

* Excludes US production data to avoid disclosing company proprietary data.

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TABLE 2—Consumption of Titanium Concentrates in the United States, by Products
Short Tons

Year and Product	Ilmenite*		Titanium slag		Rutile (natural and synthetic)	
	Gross weight	TiO ₂ content*	Gross weight	TiO ₂ content*	Gross weight	TiO ₂ content*
1978	792,289	475,448	128,826	91,490	263,184	245,184
1979	791,063	487,228	144,708	106,346	313,761	292,912
1980	848,607	513,315	181,582	133,933	297,582	277,882
1981:						
Alloys and carbide	\$	\$	#	#	—	—
Pigments	843,055	501,301	252,826	186,020	1206,257	1192,779
Welding-rod coatings and fluxes	\$	\$	—	—	7,389	6,944
Miscellaneous	13,061	9,721	—	—	71,725	66,873
Total	856,116	511,022	252,826	186,020	1285,371	1266,596
1982:						
Alloys and carbide	\$	\$	#	#	—	—
Pigments	574,634	345,618	225,541	168,433	1194,994	1184,403
Welding-rod coatings and fluxes	\$	\$	—	—	5,607	5,275
Miscellaneous	8,616	6,775	—	—	38,336	35,435
Total	583,250	352,393	225,541	168,433	1238,937	1225,113

Source: US Bureau of Mines.

* Estimated. † Revised.

* Includes a mixed product containing rutile, leucoxene, and altered ilmenite.

† Includes estimate of imported ilmenite used to make synthetic rutile in the United States.

‡ Includes imported synthetic rutile, but excludes synthetic rutile made in the United States from imported ilmenite.

§ Included with "Miscellaneous" to avoid disclosing company proprietary data.

Included with "Pigments" to avoid disclosing company proprietary data.

|| Includes ceramics, chemicals, glass fibers, and titanium metal.

†† Includes synthetic rutile made in the United States.

Table 2 shows that about 94% of total United States TiO₂ consumption in 1982 was used in titanium dioxide pigment manufacture. Table 3 shows that paper and plastics are the fastest growing uses for titanium pigments. As shown in Table 4, the major imports of titanium concentrates are ilmenite and rutile from Australia, and titanium slag from Canada.

World production of titanium concentrates, shown in Table 5, comes mainly from four major producing countries, Australia, Norway, the United States, and the USSR, with about 230,000 to 1,300,000 stpy each, and from Finland, India, and Malaysia, each producing 120,000 to 200,000 stpy. Australia is by far the largest producer of rutile, while Canada and the Republic of South Africa produce nearly all of the world's titaniferous slag.

Prices of titanium concentrates and products (Table 6) generally increased significantly in the years 1978–1981, due to increased production costs and to development of a tight

metal supply in 1979–1980 caused mainly by sharply increased demand for commercial aircraft. The prices of rutile and titanium sponge metal dropped in 1982 because of the economic recession, and collapse of the commercial aircraft market.

Titanium Dioxide Pigments

Titanium dioxide pigments are made by two basic processes. In the older sulfate process, ilmenite (43 to 65% TiO₂) or slag (70 to 74% TiO₂ or 85% TiO₂) is converted to water-soluble sulfates, and the TiO₂ is recovered by hydrolysis of high-TiO₂ solutions. In the chloride process, rutile (95% TiO₂), high-TiO₂ ilmenite (60 to 70% TiO₂), or rutile substitutes (85 to 95% TiO₂, including 85% TiO₂ slag), are converted to volatile chlorides, and the TiO₂ is recovered by vapor phase oxidation of titanium tetrachloride.

Until the early 1950s, titanium dioxide pigments were produced entirely by the sulfate

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TABLE 3—Distribution of US Titanium-Pigment Shipments, by Industry, TIO₂ Content Percent

Industry	1978	1979	1980	1981	1982
Paints, varnishes, lacquers	47.9	47.4	44.1	43.4	43.3
Paper	20.8	21.8	24.3	23.8	24.6
Plastics (except floor covering and vinyl-coated fabrics and textiles)	11.6	11.8	10.6	11.4	11.4
Rubber	2.8	2.9	2.1	2.2	2.3
Printing ink	2.0	1.9	2.8	1.3	0.9
Ceramics	2.1	1.9	1.7	1.4	1.1
Other	6.7	7.1	8.2	8.6	6.4
Exports	6.1	5.2	6.2	7.9	10.0
Total	100.0	100.0	100.0	100.0	100.0

Source: US Bureau of Mines.

TABLE 4—US Imports for Consumption of Titanium Concentrates by Countries Short Tons

Country	1978	1979	1980	1981	1982
Ilmenite:					
Australia	308,649	184,478	338,676	234,562	342,279
Finland	—	—	27	—	—
Germany, Federal Republic of	—	—	—	—	24
India	—	—	18,739	—	—
Netherlands*	—	—	46	—	—
Norway	22	—	—	1,656	—
Sri Lanka	—	—	—	—	6,063
Total [†]	308,671	184,478	357,488	236,217	348,366
Titanium slag:					
Canada	149,172	81,289	145,475	246,137	201,168
South Africa, Republic of	—	29,921	49,519	22,685	45,685
Other	—	—	—	3	992
Total	149,172	111,210	194,994	268,825	247,845
Rutile, natural:					
Australia	242,505	140,291	143,038	88,345	74,501
Malaysia	—	—	267	11	—
Sierra Leone	—	7,980	40,900	25,236	53,308
South Africa, Republic of	5,453	10,819	18,907	47,406	11,320
Sri Lanka	6,063	6,305	—	—	—
Thailand	—	—	197	—	—
Other	8	18	33	25	2
Total	254,029	165,413	203,342	161,022	139,131
Rutile, synthetic:					
Australia	23,546	72,218	60,962	39,708	22,744
Germany, Federal Republic of*	—	—	2	—	—
India	11,011	22,134	10,471	440	—
Japan	675	1,243	6,590	1,200	1,450
Taiwan	356	22,471	238	—	—
Other	—	—	—	3	—
Total [†]	35,588	118,066	78,263	41,351	24,194
Titaniferous iron ore[‡]:					
Canada	51,640	153,714	10,185	12,271	6,996

* Country of transshipment rather than country of production.

† Data may not add to totals shown because of independent rounding.

‡ Includes materials consumed for purposes other than production of titanium commodities, principally heavy aggregate and steel furnace flux.

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TABLE 5—World Production of Titanium Concentrates—Ilmenite, Leucoxene, Rutile, and Slag, by Country,* St

Concentrate type and country	1978	1979	1980	1981 ^a	1982 ^a
Ilmenite and leucoxene^f					
Australia:					
Ilmenite	1,383,400	^r 1,267,656	1,442,924	1,452,033	[#] 1,276,463
Leucoxene	^r 17,752	^r 24,001	26,393	21,657	[#] 22,198
Brazil	22,131	^r 14,541	18,562	16,631	17,000
China	NA	NA	NA	150,000	150,000
Finland	145,395	131,947	175,267	178,023	176,000
India ^g	178,063	161,867	185,078	208,147	209,000
Malaysia ^h	205,929	220,262	208,470	190,432	121,000
Norway	845,461	903,690	912,608	724,907	[#] 608,215
Portugal	358	295	258	368	370
Sri Lanka	36,421	61,035	37,430	88,197	88,000
USSR ⁱ	450,000	450,000	460,000	470,000	475,000
United States ^l	589,751	639,292	548,882	509,342	[#] 227,844
Total	^r 3,874,661	^r 3,874,586	4,015,772	4,009,737	3,371,090
Rutile:					
Australia	283,376	^r 307,435	323,801	263,729	[#] 243,343
Brazil	402	484	472	190	220
India ^g	6,239	5,445	5,908	9,647	8,800
Sierra Leone	—	^r 8,267	52,356	55,992	[#] 52,590
South Africa, Republic of ^m	20,000	46,000	53,000	55,000	52,000
Sri Lanka	12,673	16,176	14,097	14,662	14,300
USSR ⁱ	10,000	10,000	10,000	10,000	10,000
United States	W	W	W	W	W
Total	332,690	^r 393,807	459,634	409,220	381,253
Titaniferous slag:					
Canada ⁿ	937,000	^r 525,840	964,200	837,000	750,000
Japan ^o	193	198	—	—	—
South Africa, Republic of ^m	100,000	316,000	379,000	408,000	420,000
Total	1,037,193	^r 842,038	1,343,200	1,245,000	1,170,000

Source: US Bureau of Mines.

^aEstimated. ^pPreliminary. ^rRevised. NA Not available. W Withheld to avoid disclosing company proprietary data.^{*}Table excludes production of anatase ore in Brazil (4,298,731 tons produced prior to 1979 and apparently largely mined in 1978; 7,373,074 tons mined during 1979; and unreported quantities mined in 1980 and 1981), all of which was stockpiled without beneficiation. This material reportedly contains 20% TiO₂. The table includes data available through June 15, 1983.[†]Ilmenite is also produced in Canada and in the Republic of South Africa, but this output is not included here because an estimated 90% of it is duplicative of output reported under titaniferous slag and the rest is used for purposes other than production of titanium commodities, principally as steel furnace flux and heavy aggregate.[‡]Reported figure.[§]Data are for fiscal year beginning Apr. 1 of year stated.[#]Exports.^{||}Includes a mixed product containing ilmenite, leucoxene, and rutile.[¶]Contains 70% to 72% TiO₂.^{**}Contains 85% TiO₂.

process. However, by 1981, as shown by the listings of US and world production capacities in Tables 7 and 8, the proportion of pigment produced by the chloride process was about 78% in the United States, and was substantial in the rest of the world as well. Total world production capacity in 1982 was about 1,900,

000 stpy chloride process pigment and 900,000 stpy sulfate process pigment. Future annual growth in consumption of TiO₂ pigments has been estimated at 2 to 3% in the United States, and at 3 to 4% in the rest of the world.

The chloride and sulfate process TiO₂ pigments have each demonstrated superior prop-

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TABLE 6.—US Prices of Titanium Concentrates and Products

	Yearend prices				
	1978	1979	1980	1981	1982
Concentrates: \$ per st:					
Domestic ilmenite, 64% TiO ₂	—	—	35*	35*	40*
Imported ilmenite, 54% TiO ₂ f.o.b. Atlantic ports	45	50	50	65	65
Imported rutile, 95% TiO ₂ f.o.b. Atlantic ports:					
Small lots	325-350	425-450	425-450	450-475	450-475
Large lots, long term, estimate	250-275	350-375	350-375	325-350	275-300
Titanium slag:					
70-72% TiO ₂ , f.o.b. Quebec	100	100	104	121	134
85% TiO ₂ , f.o.b. Republic of South Africa	—	120	124	156	156
Synthetic rutile, f.o.b. Mobile, AL	—	—	310	340	350
Products: \$ per lb					
TiO ₂ pigments, regular grade:					
Rutile, carlots, f.o.b. plant	0.51	0.59	0.63	0.75	0.75
Anatase, carlots, f.o.b. plant	0.46	0.53	0.57	0.69	0.69
Titanium sponge metal:					
Domestic, f.o.b. plant	3.28	3.98	7.02	7.65	5.55
Imported, Japanese, c.i.f. US ports, not including import duty	3.20	3.60	7.50-8.70	7.50-8.50	No quotation

* Bulk, large lots, f.o.b. Green Cove Springs, FL.
Open market price not available in previous years.

erties over the other in various applications. The chloride process, being a continuous process is inherently simpler, consisting of fewer steps, and has less waste material to dispose of, as it uses feed materials with higher TiO₂ content and lower iron content than the sulfate process. Chloride process manu-

facturers are increasing their ability to use lower grade feed materials, at the expense of having to dispose of more iron chloride or iron oxide. The sulfate process has the advantage of lower cost raw materials, but has the greater quantity of waste material for disposal.

TABLE 7.—United States Titanium Dioxide Pigment Producers in 1982.

Company and plant location	Estimated Dec. 31, 1982 Annual Capacity, st	
	Sulfate process	Chloride process
American Cyanamid Co., Savannah, GA	64,000	46,000
E. I. du Pont de Nemours & Co., Inc.:		
Antioch, CA	—	35,000
De Lisle, MS	—	150,000
Edge Moor, DE	—	110,000
New Johnsonville, TN	—	228,000
Gulf + Western Natural Resources Group, Chemicals Div.:		
Ashtabula, OH	—	35,000
Gloucester City, NJ	44,000	—
Keri-McGee Chemical Corp., Hamilton, MS	—	56,000
NL Industries, Inc., Sayreville, NJ*	—	—
SCM Corp., Glidden Pigments Group, Chemical/Metallurgical Div.:		
Ashtabula, OH	—	42,000
Baltimore, MD	66,000	42,000
Total	174,000	744,000

* Closed 100,000 stpy sulfate process plant in September 1982.

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TABLE 8—World Titanium Dioxide Pigment Production Capacity, Dec. 31, 1982

Country	Producing Companies	Estimated Annual Capacity, st	
		Sulfate	Chloride
North America:			
Canada	Canadian Titanium Pigments, Tioxide Canada	76,000	—
Mexico	Pigmentos y Productos Quimicos	33,000	—
United States	American Cyanamid, Du Pont, Gulf & Western, Kerr-McGee, NL Industries, SCM	174,000	744,000
South America:			
Brazil	Titanio do Brasil (Tibras)	33,000	—
Europe, Western:			
Belgium	Kronos SA-NV, Bayer SA	72,000	—
Finland	Kemira Oy	88,000	—
France	Thann et Mulhouse, Tioxide SA	182,000	—
Germany, Federal Republic of	Bayer, AG, Kronos Titan GmbH, Sachtleben Chemie	298,000	66,000
Italy	Montedison	44,000	—
Netherlands	Tiofine	39,000	—
Norway	Kronos Titan A/S	28,000	—
Spain	Dow-Uniquinosa, Titanio SA	77,000	—
United Kingdom	BTP Tioxide, Laporte Industries	143,000	100,000
Europe, Eastern:			
Czechoslovakia	Prerovske Chemiske	22,000	—
Poland	ZPN	40,000	—
USSR	State Authority	137,000	—
Yugoslavia	Cinkarna Celje	22,000	—
Asia:			
China, Mainland State	Authority	20,000	—
Taiwan	ISK Taiwan	10,000	—
India	Travancore Titanium Products	15,000	—
Japan	Fuji Titanium, Furukawa Mining, Sakai Chemical, Teikoku Kaku, Titan Kogyo, Tohoku Chemical, Titanium Industries	224,000	26,000
Korea, Republic of	Hankuk Titanium, Donhwa Titanium	10,000	—
Africa:			
South Africa, Republic of	South African Titan Products	35,000	—
Australia	Tioxide Australia, Laporte Titanium (Australia)	75,000	—
Totals		1,897,000	936,000
Total, chloride plus sulfate		2,833,000	

Source: Modified from Coope, 1982.

Sulfate Process

Specifications for Sulfate Plant Feed: There are no rigid specifications for feed material to be used in the sulfate process, but certain impurities such as chromium, vanadium, columbium, manganese, and phosphorus are known

to seriously impair pigment properties, so the degree of freedom from these elements is an important factor in selection of concentrates for this process. The TiO_2 content must be high enough to be recovered economically, and capable of dissolution in sulfuric acid at practical temperatures. Some typical commercial concentrates with their chemical and mineralog-

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TABLE 9—Composition of Typical Commercial Ilmenite Concentrates and Titaniferous Slag
Weight Percent

	United States		Australia		Norway	India		Malayala	Canada	Republic of
	New York	Florida	Cable Bunbury	Western Titanium		Cullon	MK	Amang	QIT Slag	South Africa RB Slag
TiO ₂ (total)	48.1	84.00	54.4	55.4	45.0	60.6	54.2	53.1	70-74	85.0 (min)
TiO ₂									10-15	25.0*
Fe ₂ O ₃	8.7	28.48	19.0	11.1	12.5	24.2	14.2	8.7		
FeO	39.3	1.33	19.8	22.5	34.0	9.3	26.6	33.6	12-16	
Al ₂ O ₃	1.4	1.23	1.5		0.6	1.0	1.3		4-6	
SiO ₂	1.5	0.28	0.7	1.4	2.8	0.7			3.5-5	
CaO	0.5	0.007	0.04		0.25				1.2*	0.15*
MgO	1.9	0.20	0.45		5.0	0.9	1.0		4.5-5.5	1.3*
Cr ₂ O ₃	0.009		0.2	0.03	<0.076	0.12	0.07	0.005	0.25	0.3*
V ₂ O ₅	0.05		0.12	0.13	0.16	0.15	0.16	0.02	0.5-0.6	0.6*
ZrO ₂	0.01					0.9	0.8			
S	0.6		<0.01		<0.05	0.21	0.12		0.03-0.10	
P ₂ O ₅	0.008	0.12	0.02		<0.04			0.065	0.025*	
MnO	0.5		1.4		0.25	0.4	0.4	4.0	0.2-0.3	2.5*
H ₂ O (loss on ignition)	1.3		0.4			2.0	0.3			
Rare earths						trace	0.12			
C	0.22				<0.055				0.03-0.10	
Reference	(1)	(2)	(3)	(3)	(4)	(3)	(3)	(3)	(5)	(6)

References: (1) NL Industries; (2) DuPont; (3) Anon., 1971c; (4) Anon., 1973c; (5) Guilmond, 1964; (6) Anon., 1977, chloride grade.
* Maximum

ical compositions are listed in Table 9. It will be noted that the TiO₂ contents range from about 45% for unaltered ilmenite concentrates to 85% for slag.

Processing to Pigment: In the sulfate process finely ground ilmenite or high-TiO₂ slag is digested with strong sulfuric acid, forming a solid, porous cake which is dissolved in dilute acid and water to yield a solution of titanyl sulfate (TiOSO₄) and iron sulfate. Any ferric iron present is reduced to the ferrous state by adding scrap iron. This is done to avoid precipitation of ferric iron later in the process and to facilitate washing the precipitated titania, since ferrous iron is less strongly adsorbed. After reduction, the solution is clarified by settling and filtration. With ilmenite solutions, some of the iron is usually crystallized out as ferrous sulfate heptahydrate (copperas). The solution is then concentrated, and the titania is precipitated by hydrolysis, filtered, washed, calcined at 900° to 1000°C to the oxide, and further treated prior to the finished pigment stage. The nature of the various special treatments determines the grade and type of the finished pigment, i.e., whether it is anatase or rutile, chalking or nonchalking, oil or water dispersible, etc.

The estimated tons of raw material required to produce one ton of TiO₂ are as follows:

Ilmenite or titanium slag	1.5-2.8
Sulfuric acid	3.0-4.0
Iron scrap	0.1-0.2

Chloride Process

In the chloride process, titanium tetrachloride (TiCl₄) is produced by chlorinating titaniferous, higher-grade materials at about 850° to 900°C in the presence of petroleum coke. The estimated tons of raw materials required to produce one ton of TiO₂ are as follows:

Rutile	1.1-1.2
Chlorine	0.1-0.2
Petroleum coke	0.1-0.2
Oxygen	0.4-0.5
Aluminum chloride	0.03

All the commercial TiCl₄ plants in the United States use fluid-bed chlorinators but static-bed chlorinators also can be used.

Titanium tetrachloride is a highly reactive liquid at room temperatures and reacts violently with moisture. Hence, all handling of the TiCl₄ is carried out under inert conditions to avoid contamination by oxygen or moisture in the air.

Unfortunately, the inherent impurities in the ore also form chlorides which have to be removed by fractional condensation before the next step, otherwise they are precipitated with the titanium dioxide and cause off-color pigments. Iron, vanadium, and silicon are the more deleterious impurities. Trace impurities are removed by distillation and/or chemical treatment.

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Processing to Pigment: The purified titanium tetrachloride is converted directly to titanium dioxide by oxidizing the $TiCl_4$ with air or oxygen at a high temperature. The resulting fine grained TiO_2 is calcined at about 500° to 600°C to remove any residual chlorine and hydrochloric acid that may have been formed in the reaction. The calcination also helps to improve some of the pigment characteristics. Aluminum chloride is added to the titanium tetrachloride to assure that virtually all of the titanium is oxidized in the rutile crystalline form. The chlorine formed during oxidation is recovered and recycled.

The process can produce pigments in either the anatase or rutile form. The cost per ton of pigment is believed to be less by the chloride process than by the sulfate process.

Titanium Metal

Titanium has two major advantages over other structural metals—its high strength/weight ratio, and its outstanding corrosion resistance. Disadvantages are its relatively high cost and difficulty in fabrication.

Applications and Consumption

The major applications of titanium metal have been in the aerospace industry, and consumption has been strongly dominated by military aircraft demands. The proportion of titanium consumption used for military planes has decreased somewhat but in 1981 was still estimated to be 35% compared to 40% for commercial planes, and 25% for nonaerospace applications. The heavy dependence on aerospace markets has led to severe fluctuations in demand. The most serious setback was in 1958–1959, when military aircraft production was cut back in favor of missile development, with a drop in titanium sponge production from about 17,000 tons in 1957 to 4600 tons in 1958 and 4000 tons in 1959. Gradual recovery and further fluctuations in demand led to successive new peaks in mill product shipments of 16,000 tons in 1969, 17,000 tons in 1974, and about 27,000 tons in 1980, with intervening lows coinciding approximately with cancellation of the supersonic transport program in 1971 and of the B-1 bomber program in 1977. The strong market in 1978 through 1981 resulted mainly from sharply increased rates of ordering for commercial aircraft such as the Boeing 747, Lockheed L1011, and McDonnell-Douglas DC10 in 1978–1979, and for the

Boeing 757 and 767 in 1979–1981, as well as moderately increased demand for tubing to be used in nuclear power plant condensers in 1979.

Of the titanium used for airplanes in 1980–1981, about 55% was for commercial, and 45% for military aircraft. The main use in engines is for compressor disks and blades, and other compressor components. In airframe structures titanium is used to reduce the weight of various parts such as frames, bulkheads, longerons, skin, fasteners, firewalls, ducts, tubes, fairings, landing gear assemblies, and for parts subjected to high temperature. Titanium is also used extensively in missile and space vehicle components.

Nonaerospace consumption was only 5 to 6% of mill product shipments for many years, but reached 20% of shipments or about 3,000 tons in 1973, and about 25% of shipments, or 6,700 tons in 1980. Besides the use in power plant condensers, the largest industrial application, nonaerospace applications for titanium metal include heat exchangers in the chemical and petroleum industries; anodes in electrochemical processing; evaporators for water desalination; and pumps, valves, tanks, piping, and other chemical processing equipment. Anticipated new growth areas include power plant gas turbine blades; salt water environment uses, including offshore drilling platforms, titanium-hulled submarines, and ocean temperature energy conversion; and possible automotive applications.

Processing to Metal

Kroll Process: Commercial production of titanium metal involves the reduction of $TiCl_4$ with magnesium or sodium metal, using various modifications of the Kroll process (Kroll, 1940).

The titanium tetrachloride used for manufacture of titanium metal is produced by chlorination of rutile, blends of rutile with altered ilmenite, or other high- TiO_2 concentrates, using fluid-bed chlorinators. Coke is used as a reductant, and the reaction is generally carried out at temperatures of 850° to 950°C. The liquid $TiCl_4$ from the chlorinator is purified by chemical treatment and distillation.

Titanium sponge producers in the United States and their 1982 production capacities are listed in Table 10.

At the Titanium Metals Corp. of America plant at Henderson, NV (Lloyd, 1956), reduction of $TiCl_4$ is carried out with magnesium in steel pots in gas-fired furnaces, under a helium

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TABLE 10—1982 United States Titanium Sponge Capacity

Sponge Producers	Annual Capacity, St
Titanium Metals Corp. of America (NL Industries, Inc. and Allegheny International, Inc.), Henderson, NV	15,000
RMI Co. (US Steel Corp. and National Distillers Corp.), Ashtabula, OH	9,500
Oregon Metallurgical Corp. (Publicly owned, with Armco Steel Co. as major stockholder), Albany, OR	4,500
International Titanium, Inc. (Wyman-Gordon Co.; Ishizuka Research Institute and Mitsui & Co., Ltd., Japan; and other US and Japanese interests)	2,500
Teledyne Wah Chang Albany, Albany, OR (Teledyne, Inc.)	1,500
Western Zirconium Co. (Westinghouse Electric Corp.)	500
Total	33,500

atmosphere, at a temperature above the melting point of magnesium chloride, but below the melting point of the titanium metal, which forms as a spongelike mass. The sponge is removed from the reactor in a dry room to avoid absorption of moisture and is crushed and leached with acid to remove residual magnesium and magnesium chloride. The magnesium chloride drained from the reactors is transported molten to the magnesium plant, where magnesium and chlorine are recovered by electrolysis.

Oregon Metallurgical Corp. (Oremet) and Teledyne Wah Chang Albany also use magnesium to reduce the $TiCl_4$ to metal, while RMI Co. uses sodium for reduction. Oremet uses an inert gas sweep to remove nearly all of the magnesium chloride from the sponge, ITI and Teledyne use vacuum distillation, and RMI uses dilute acid leaching.

Titanium sponge is converted to ingot by compacting and double or triple vacuum arc-melting, along with scrap and alloying constituents, as a consumable electrode, using a water-cooled copper crucible. Vacuum melting removes hydrogen, residual magnesium chloride, and other volatile impurities.

All of the sponge manufacturers except ITI are integrated producers. Producers of ingots from titanium sponge and scrap in 1982, besides the sponge producers, included Martin-Marietta Aluminum, Inc., Teledyne Allvac, Howmet Corp., and Lawrence Aviation Industries, Inc.

A National Materials Advisory Board report (Anon., 1983) on availability of titanium provides a broad, integrated overview of the titanium field.

Electrolytic Titanium: Electrolytic procedures for producing titanium metal have been extensively investigated with the object of developing a continuous process which would be more economical than the batch Kroll process

(Cobel et al., 1980; Leone et al., 1967; Prisco, 1966; Ramsdell and Mathews, 1960; Snyder, 1966). Early work was done by the US Bureau of Mines in Boulder City, NV. National Lead Co. was also involved in electrolytic titanium research as early as 1950. Titanium Metals Corp. of America built a semi-works plant and produced about 68,000 kg (150,000 lb) of electrolytic sponge titanium, but discontinued the operation in 1968 because of overcapacity for making sponge by the Kroll process. In 1980 D-H Titanium Co., a joint venture of Dow Chemical Co. and Howmet Turbine Components Corp., announced startup of an electrolytic titanium demonstration plant in Freeport, TX. The D-H process, which involves reduction of titanium tetrachloride in a fused salt bath, is based on early work done by the Bureau of Mines (Leone et al., 1967), research work by Dow, and pilot plant operation by Howmet at Whitehall, MI (Cobel et al., 1980). It is claimed that electrolytic processes will produce a higher purity product, require less capital investment, and consume less energy than plants using magnesium or sodium reduction (Minkler, 1980). The D-H venture was terminated in late 1982, mainly because of adverse market conditions.

Production and Prices

United States annual sponge and ingot production up to 1963, and ingot production from 1964–1980 are given in Table 11. Recovery to the 1957 peak of 17,249 st was not achieved until 1966, and two subsequent peaks were reached in 1969, 1974, and 1981.

From 1948 until 1954 the price of domestic titanium sponge metal was \$5.00 per lb. Since then the price dropped many times, reaching a low of \$1.32 in 1964 through 1972, before rising to reach \$2.70 in 1975, \$3.98 in 1979, \$7.02 in 1980, and \$7.65 per lb in mid-1981.

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retically pure ilmenite is $\text{FeO} \cdot \text{TiO}_2$. It was shown by Ramdohr (1950) that up to 6% Fe_2O_3 may be dissolved in solid solution, and at 1050°C a continuous solid solution series exists between ilmenite and hematite (Nicholls, 1955). Hematite may, and often does, occur with ilmenite as minute exsolution lamellae. Magnesium and manganese may substitute for the ferrous iron in ilmenite, which can produce the rare end-members MgTiO_3 (geikelite) and MnTiO_3 (pyrophanite), but usually these two elements are present as minor impurities. Magnetite is a common associate of ilmenite in igneous and metamorphic rocks, and in such coexisting pairs chromium, nickel, and vanadium tend to concentrate in magnetite while manganese concentrates in ilmenite.

In basic igneous rocks, notably anorthosites, gabbros, and basic lavas, ilmenite frequently occurs in intimate intergrowths with magnetite. The ilmenite forms lenses following octahedral parting planes in the magnetite host, and magnetite may, in turn, form crystallographically oriented inclusions within the ilmenite lenses.

Altered Ilmenite and Leucoxene: In sand deposits ilmenite frequently exhibits a degree of alteration caused by oxidation and removal of iron. The end product is essentially TiO_2 . The process was described by Temple (1966) as follows:

Alteration is initiated along grain boundaries and structural discontinuities within the grain. After going through an amorphous stage, oxidation and partial removal of iron from the ilmenite lattice results in an intermediate iron titanate of definite structure for which the name pseudorutile has been proposed. The alteration product at the stage of complete oxidation of the original iron in the ilmenite analyses 65-70% TiO_2 , as compared with the 52% TiO_2 of ilmenite. Complete removal of iron from the pseudorutile lattice results in a grain composed of crystallites of the mineral rutile. Only the three mineral phases: ilmenite, pseudorutile and rutile have been identified in the commercial titanium mineral concentrates studied. Natural occurrence, in sand deposits, indicates that in weathering final removal of iron from pseudorutile to give the rutile end product takes place only either above or in the zone of the fluctuating water table.

The alteration products of the mineral ilmenite are herein termed "altered ilmenite." Many commercial ilmenite concentrates actually consist of altered ilmenite. However, the term "leucoxene" is also applied to high- TiO_2 products of alteration. Commercial justification for distinguishing between the high- and low-iron products of alteration

lies in the fact that the former are used in the sulfate process by pigment manufacturers whereas the latter are not economically soluble in sulfuric acid but are used, as is rutile, for the production of titanium tetrachloride used for pigment and titanium metal manufacture.

Alteration is an extremely slow process which is aided by elevated temperature, so that older sand deposits in temperate and tropical regions of the world generally contain high- TiO_2 ilmenite. Younger deposits, for example, those found on modern beaches, and those in the higher latitudes usually contain unaltered ilmenite with a TiO_2 content around 50%, near the theoretical level for pure ilmenite.

Rutile: Rutile, the high pressure, high temperature polymorph of TiO_2 , is the commonest form in nature and is a widespread accessory mineral in high grade metamorphic gneisses and schists and in igneous rocks. It is also a common detrital mineral.

Commercial rutile concentrates run 95% TiO_2 or more, with SiO_2 , Cr_2O_3 , V_2O_5 , Al_2O_3 , and iron oxides comprising the remainder. Analyses of rutile from other occurrences may show major amounts of tantalum and columbium, which can enter titanium minerals because of the close similarity in ionic radius between Ti^{4+} and both Cb^{+5} and Ta^{+5} . There is also a high iron variety termed ferroan rutile.

Rutile may form by alteration from ilmenite or anatase, and while it is very stable over a broad range of geologic conditions, occasionally processes may be reversed so that rutile alters to sphene, possibly ilmenite, and more rarely anatase.

The characteristic color of rutile is reddish brown, but it may be black, violet, yellow, or green.

Classification of Deposits

Titanium minerals have been mined from both rock and sand deposits. Until about 1942, nearly all of the ilmenite and rutile produced commercially came from sand deposits, but about one third of the world's ilmenite in 1982 came from rock deposits. Rutile, however, is now produced exclusively from sand deposits.

Rock Deposits: Anorthositic Deposits—Nearly all of the known commercially important rock deposits of titanium minerals are associated with anorthositic or gabbroic rocks, and are of three main types: ilmenite-magnetite (titaniferous magnetite), ilmenite-hematite, and ilmenite-rutile. Ilmenite-magnetite deposits usually contain ilmenite and magnetite as

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Titanium Minerals

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granular intergrowths that can be separated rather readily to yield concentrates of ilmenite and magnetite which may be essentially homogeneous minerals, or may consist of intimate intergrowths of one mineral in the other. Ilmenite-hematite deposits usually contain these minerals as intimate intergrowths and yield an ilmenite-hematite, or hemo-ilmenite concentrate rather than a separate concentrate of each mineral. Ilmenite-rutile deposits contain rutile and ilmenite either as separate concentrations or occurring together.

Miscellaneous Deposits—Other types of rock deposits in the United States that have been mined, or seriously considered as sources of titanium, include a deposit of ilmenite disseminated in schist in Yadkin Valley, North Carolina (Broadhurst, 1955), and a complex deposit of rutile, anatase, and brookite in a pegmatitic phase of alkalic rocks surrounding sediments at Magnet Cove, Arkansas (Fryklund and Holbrook, 1950; Fryklund et al., 1954).

A perovskite deposit in southwestern Colorado owned by Buttes Gas & Oil Co. was estimated to contain about 50 million tons of TiO₂ (Thompson, 1977). Processes to convert perovskite to titanium dioxide were being investigated through 1982.

The US Bureau of Mines (Llewellyn et al., 1980) and the US Geological Survey (Force, 1980) investigated the porphyry copper ores and mill tailings as a possible source of rutile. It was concluded that this material, which contains about 0.3% of potentially recoverable fine-grained rutile, could constitute a sizeable domestic resource, but more work is needed to develop an economic recovery process.

Major occurrences of anatase and ilmenite in weathered carbonatite bodies at Tapirá, Salitre, and Catalão in Minas Gerais, Brazil, are under investigation as new raw material sources. Feasibility and pilot plant studies to determine grades and recoveries of possible future commercial titanium mineral concentrates have been carried out. Modifications in pigment manufacturing processes may be necessary to accommodate potential production as a feed, or beneficiation or slagging may be used to make concentrates acceptable to existing pigment plants, but successful exploitation by any avenue will cause these and possibly other carbonatite occurrences to be classed as an important rock ore type.

Occurrences of titanium minerals in other types of rocks are known, but are not considered to be of commercial significance (Force et al., 1976).

Sand Deposits: Beaches, bars, dunes, and stream sands in many parts of the world are enriched by gravity segregation of the heavy minerals that are chemically resistant to weathering and physically hard enough to withstand considerable abrasive action. The energy of currents, waves, and to a lesser extent, winds, mobilizes the sand grains and permits them to behave as individuals within a fluid medium. Where the energy decreases, the heavier particles fall out while the lighter ones are carried farther. The composition of the heavy mineral concentrate depends on the nature of the geologic terrane being subjected to weathering and erosion and supplying materials to transporting streams. If available at the source, titanium-bearing minerals, zircon, magnetite, chromite, rare earth minerals such as monazite, staurolite, kyanite, sillimanite, garnet, xenotime, precious metals, and diamonds may be concentrated in this way. The resultant gravity segregations are usually dark colored and are called "black sands." Not all black sands are ore mineral occurrences; those found on the beaches of volcanic islands, for example, may be mostly amphibole and pyroxene.

There is a wide variation in titaniferous black sands in terms of heavy mineral concentration, percentage of titanium minerals within the heavy mineral suite, and TiO₂ content of the titanium mineral concentrate. All of these factors interact in rating deposits according to quality and as to whether they are today's reserves or possible resources of the future. Furthermore, the presence or absence of valuable coproduct or byproduct minerals such as zircon is a complicating factor. A classification on the basis of mineralogy, as suggested in the following section, is only broadly applicable.

Sand deposits in which rutile is the only economically important titanium mineral occur along the eastern shore of Australia. Ilmenite, altered ilmenite, and rutile form inland elevated strand-line deposits in Western Australia and in older sands of the Atlantic Coastal Plain of the United States. Ilmenite and altered ilmenite are the principal titanium ore minerals in other Western Australian districts; in Kerala, India; in deposits north of the Black Sea in the USSR; and in Florida and Georgia. Relatively unaltered ilmenite is found in large beach and dune occurrences along the north-eastern coast of South Africa, in the Nile Delta of Egypt, and in still other Western Australian deposits, those closest to the pres-

ent coast. Sand deposits of titaniferous iron ores occur as dune and beach deposits in many volcanic areas, of which those in New Zealand are the outstanding examples.

Mode of Occurrence and Origin

Rock Deposits: The anorthositic deposits contain titanium minerals either as massive ore, or disseminated in rock ranging from anorthosite to gabbro in composition, and varying in grade from solid ore to almost barren rock. While there are metamorphic and hydrothermal features in some parts of these deposits, for the most part, they seem to have formed at magmatic temperatures by magmatic processes.

The only other type of ilmenite rock deposit to be exploited commercially was the Yadkin Valley deposit in Caldwell County, North Carolina (Broadhurst, 1955), which was operated by a Glidden Co. subsidiary from 1942 to 1952. The ore consists of small masses of ilmenite disseminated throughout a talcose body which lies conformably with the enclosing quartzite and mica schist.

The Hot Spring County, Arkansas, deposits have been studied extensively for possible commercial development, and some rutile was recovered from the Magnet Cove deposit from 1932 to 1944. The deposits occur in a complex mixture of alkalic igneous rocks intruding folded sedimentary and metamorphic rocks. Much of the titanium is in the form of rutile or brookite, but many other titanium minerals have been identified. The ore minerals are intimately associated with gangue (Fryklund and Holbrook, 1950; Fryklund et al., 1954; Toewe et al., 1971).

Sand Deposits: Titanium-bearing black sands are found mainly in ancient or modern ocean and sea beaches around and occasionally within continental land masses. They frequently form highly visible surficial layers between the high and low water marks which may extend intermittently along coasts for miles, but such concentrations, containing perhaps 80% heavy minerals, are not mined on a large scale because they are usually too shallow and narrow to represent major reserves. Movable bodies are multilayered occurrences of a similar nature left behind by retreating seas, or coastal dunes formed when heavy minerals from black sand beaches were being transported inland by wind action. Heavy minerals tend to be disseminated within such dunes rather than layered as in beach-type deposits.

The history of a black sand ore body may be simple or complex. The essential elements are: (1) a "hinterland" of crystalline rocks in which

the heavy minerals were accessory constituents, (2) a period of deep weathering, (3) uplift with rapid erosion and quick dumping into the sea of the products of stream erosion, and (4) emergence of the coastline with longshore drift and high-energy waves acting during the process of shoreline straightening. There may be intermediate stages such as partial concentration of the heavy minerals in a coastal plain sediment and subsequent elevation, erosion, and reconcentration. The sand brought to the sea by rivers is picked up and carried away from their mouths by longshore currents, forming offshore bars and filling in bays between headlands, particularly during storms. Where bars are formed, the sand-carrying waves drag bottom and lose their energy so that the heavy minerals fall on the seaward side while the light minerals are cast over the bar and into the quieter water beyond. Layer upon layer of varying concentrations of heavy minerals accumulates on the growing bar in this way. Where bays are being filled with sand, both heavy and light minerals are churned from the bottom by landward-rushing waves and are hurled up the beach slope. The smoother, slower retreat of each wave mobilizes the uppermost layer of sand deposited there, and draws away the light minerals, to be picked up again and again by waves as currents move them along the coast, while leaving the heavy minerals behind. Alternating periods of stormy and calm weather leave alternating layers of high and low concentrations of heavy minerals in the beach sand as it advances toward the sea.

Distribution of Deposits

Reserves

Ilmenite resources in rock and sand deposits in the United States, recoverable under the economic and technological conditions of 1981, were estimated to contain 18 million tons of titanium dioxide. Rock deposits in New York account for 29% of the total. The remainder is in beach and river sands in Florida (Garnar, 1980), Georgia, New Jersey (Markewicz, 1969), and Tennessee. An additional 94 million tons of titanium dioxide in ilmenite and 48 million tons in perovskite (Thompson, 1977), not recoverable under present conditions, occur in identified resources, widely dispersed throughout the United States. Major occurrences lie in Colorado, Minnesota, New Jersey, New York, and Wyoming.

Reserves of rutile in the United States are in sand deposits in Florida, Georgia, and Tennessee. The rutile in these deposits contains about 1.7 million tons of titanium dioxide.

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TABLE 12—World Reserves of Ilmenite and Rutile
Thousands of Short Tons of TiO₂ Content

Country	Ilmenite	Rutile
Arab Republic of Egypt	—	—
Australia	27,000	10,000
Brazil	2,000	67,000*
Canada	26,000	—
China	34,000	—
Finland	3,400	—
India	22,000	3,000
Norway	52,000	—
Sierra Leone	—	3,000
South Africa, Republic of	57,000	5,500
Sri Lanka	21,000	5,000
United States	18,000	1,700
USSR	7,000	3,000
Total	270,000	140,000

* Mainly anatase.

Identified but presently subeconomic deposits in Arizona, Arkansas, California, Florida, North Carolina, South Carolina, Tennessee, Utah, and Virginia contain an estimated 13 million tons of titanium dioxide in the form of rutile. The rutile in the Arizona and Utah resources occurs mainly as an accessory mineral in porphyry copper ores and mill tailings (Force, 1980; Llewellyn and Sullivan, 1980).

Estimates for world titanium reserves and resources are shown in Table 12. World reserves of ilmenite are estimated to contain 266 million tons of titanium dioxide, of which US reserves account for 7%. The titanium dioxide content of world rutile reserves is estimated at 97 million tons; US reserves represent 1.6% (Lynd, 1983).

Rock Deposits—Principal Producing Countries

United States: Sanford Lake District, New York—The Sanford Lake deposits (Gross, 1968), are located in the heart of the Adirondack Mountains. Discovery of these titaniferous magnetite deposits dates back to 1826. Several attempts to exploit the ores for iron prior to 1942 proved uneconomical because of difficulties with the associated titanium, and the isolated location (Bachman, 1914; Masten, 1923). Since 1942, National Lead Co. (now NL Industries, Inc.) has produced ilmenite concentrates for the titanium pigment industry, and a magnetite byproduct used in the steel and refractory industries and as heavy media in coal cleaning operations. The district is within the large anorthosite massif making up the central high peak area of the Adirondacks. All

of the various low silica rock types associated with the massif are found within the boundaries of the district. These consist of both the Marcy and Whiteface types of anorthosite and of gabbroic anorthosite, gabbro, and different grades of titaniferous magnetite ores. All of the rocks contain the same minerals and differ only in the percentages of these constituents.

There are four mineralized areas where an economic grade of ore has been found. Three of these have both gabbroic-type ore and anorthositic-type ore. The fourth has only gabbroic ore. The TiO₂ contents of the ores range from 9.5% to over 30.0% TiO₂. Ore bodies of both types are related to gabbro and conform to the configuration of the gabbro bodies within the anorthosite.

Except for a few thousand tons mined before 1900, all ore production has come from the Sanford Hill-South Extension ore body. Mining began on Sanford Hill in 1942, and as a result of further exploration and development work, was transferred in the early 1960s to the South Extension part of the ore body, which was overlain by glacial till and Sanford Lake.

GENERAL GEOLOGY—Rocks of the Sanford Lake district are regarded as members of a genetically related anorthositic series, the whole being part of the large Adirondack anorthosite massif. Locally, anorthosite grades into gabbro by an increase in the content of mafic minerals. Buddington (1939) divided this sequence into four rock types depending upon the amount of ferromagnesian minerals present: anorthosite with 0 to 10%, gabbroic anorthosite with 10 to 22.5%, anorthositic gabbro with 22.5 to 35%, and gabbro with over 35% mafic minerals.

For mine mapping purposes, rock types are designated as anorthosite, gabbroic-anorthosite, gabbro, and the various grades of ore. The relationship of rock and ore type to TiO₂ assay is shown in Table 13.

ECONOMIC GEOLOGY—The titaniferous magnetite ore bodies of the district are of two types. One type, referred to locally as "anorthositic ore," is associated with anorthosite waste rock as coarse-grained massive lenses of irregular shape, with little structure and having sharp contacts with the anorthosite. The second ore type, "gabbroic ore," occurs as fine to medium grained oxide-enriched bands within the gabbro, with well defined structures similar to those in the gabbro. Contacts with the gabbro range from distinct to gradational.

In the Sanford Hill-South Extension ore body, both types of ore occur. The anortho-

sory constituents, ering, (3) uplift dumping into the erosion, and (4) alongshore drift during the process. There may be partial concentration on a coastal plain, erosion, and right to the sea by away from their forming offshore between headlands, Where bars are waves drag bottom the heavy minerals the light minerals into the quieter layer of varying minerals accumulates away. Where bays a heavy and light the bottom by are hurled up the slower retreat of the outermost layer of waves away the light rain and again by along the coast, minerals behind. Around calm weather high and low content in the beach sand

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ited States are in Georgia, and Tennessee deposits contains titanium dioxide.

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Industrial Minerals and Rocks

TABLE 13—TiO₂ Assay of Various MacIntyre Mine Rock Types

Classification	%TiO ₂
Anorthosite	0-5.4
Gabbro	6.5-9.4
Low grade protore	9.5-13.4
Medium grade ore	13.5-17.4
High grade ore	17.5+

sitic type forms a footwall ore body and the gabbroic ore forms a hanging wall ore body. These are separated by various widths of anorthosite and/or gabbro rock. In some instances the two types of ore are in direct contact.

The ore body is designated by two names because it has been developed in two pits. Mining started where ore was exposed in outcrops on the west side of Sanford Hill. Diamond drilling indicated the ore lenses as becoming very narrow where they extended underneath the basin of Sanford Lake. Later magnetometer results, along with aerial work in 1955 and ground followup in 1959, revealed a change in strike and width of the magnetic anomalies. Diamond drilling proved the South Extension of the Sanford Hill ore body to be of commercial grade and tonnage. At Cheney Pond, about 2 km (1½ miles) west of the South Extension pit, a development drill program proved commercial tonnages of gabbroic ore, and revealed none of the massive anorthositic type. Oxide rock bands up to 30 m (100 ft) thick are found within a synclinal body of fine grained gabbro, which is in sharp contact with the underlying anorthosite. An extensive study of the petrology of the Cheney Pond deposit was carried out by Sun (1971).

Ore of both types occurs in two smaller ore bodies: the Mount Adams ore body, about two miles northeast of Sanford Hill, and the Upper Works or Calamity-Mill Pond ore body about three miles north of Sanford Hill.

MINERALOGY OF THE ORE BODIES—The ores of the Sanford Lake district contain both ilmenite and magnetite as granular aggregates and disseminated grains. The ratio of total Fe:TiO₂ is generally 2:1 or greater in the anorthositic ore, and is less than 2:1 in the gabbroic ore. Gabbroic ore is finer-grained than anorthositic ore.

The magnetite grains are seldom homogeneous, and normally contain some ilmenite in solid solution and up to 35% of ilmenite as exsolution intergrowths. The intergrown ilmenite occurs as tabular plates oriented parallel to the octahedral planes of the magnetite or along the boundary between magnetite grains.

A second highly magnetic phase, ulvospinel (Fe₂TiO₄), has been identified as a fine network within the magnetite of the Sanford Hill-South Extension ores. This ulvospinel was first identified by Ramdohr (1956), using high magnification metallography. Kays (1965) used X-ray techniques along with chemical assay data to estimate that the magnetite grains may have an ulvospinel content of 34%.

About 0.5% vanadium occurs in solid solution within the magnetite. No separate vanadium mineral has yet been identified.

Ilmenite occurs as a matrix around magnetite and is observed under the microscope to be corroded by magnetite. It is finer-grained than magnetite and can be distinguished megascopically in coarse-grained anorthositic ore by its high luster and conchoidal fracture, compared to the dull luster and parting planes in magnetite. In finer-grained ore, the ilmenite and magnetite are more equigranular and cannot be recognized individually in hand specimens.

The typical ore and gangue minerals and their weight percentages in both ore types are shown in Table 14.

Other minor minerals identified in the Sanford Hill-South Extension ore body include

TABLE 14—Typical Mineral Analysis of Ore Types in Sanford Hill Ore Body

	Gabbroic or Hanging Wall Ore, wt %	Anorthositic or Footwall Ore, wt %
Black opaques, total	61.5	77.3
Magnetics (magnetite)	25.7	40.8
Nonmagnetics (ilmenite)	35.8	36.5
Feldspar	19.2	10.3
Garnet	8.1	3.4
Pyroxenes (mostly clinopyroxenes)	6.6	4.7
Amphiboles (green and brown hornblende)	2.3	1.5
Sulfides (pyrrhotite and pyrite)	1.5	1.7
Apatite, spinel, chlorite, calcite	<1.0	<1.0

Titanium Minerals

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ORE BODIES—The ores in the district contain both ilmenite and magnetite granular aggregates. The ratio of total Fe:Ti is greater in the anorthositic than in the gabbroic and finer-grained than

are seldom homogeneous. They contain some ilmenite in about 35% of ilmenite as well as magnetite. The intergrown ilmenite and magnetite are oriented parallel to the magnetite or along magnetite grains.

In the anorthositic phase, ulvospinel is identified as a fine network of the Sanford Hill. Ilmenite was first identified (1956), using high magnification. Kays (1965) used X-ray fluorescence with chemical assay and magnetite grains may be as high as 34%.

Ilmenite occurs in solid solution with magnetite. No separate vanadium was identified. The matrix around magnetite is finer-grained than the magnetite. It is finer-grained than the magnetite and distinguished megacrysts in the anorthositic ore by the presence of a hoidal fracture, common and parting planes in the ore, the ilmenite is equigranular and can be distinguished in hand specimens.

Gangue minerals and in both ore types are

identified in the Sanford ore body include

body

Anorthositic or Footwall Ore, wt %
77.3
40.8
36.5
10.3
3.4
4.7
1.5
1.7
<1.0

chalcopyrite, sphalerite, molybdenite, prehnite, barite, leucocene, scapolite, epidote, orthoclase, and quartz.

In his extensive study of mineral paragenesis, Stephenson (1945) concluded that the large plagioclase phenocrysts were first to develop, followed by the finer-grained plagioclase, and later by the sequence: apatite, hypersthene, augite, hornblende, garnet, and ore minerals. The chlorites, carbonates, and scapolite formed as later alteration minerals as a result of deformation and minor hydrothermal activity. Kays (1965), in a study of Sanford Hill pit, agreed in general with the sequence given by Stephenson (1945), but pointed out that no one single paragenetic sequence holds rigorously for all rock types in the Sanford Lake district.

ORE GENESIS—Investigators have generally considered the Sanford Lake ores to have formed by magmatic segregation, as a result of such processes as simple segregation, filter-pressing of residual liquid with injection into the wall rock, and gravitational purification of the oxide melt by floating out of crystallized silicates with later injection, with replacement playing a minor role (Balsley, 1943; Bateman, et al., 1951; Buddington et al., 1955; Evrard, 1949; Osborne, 1928; Stephenson, 1945). Gillson (1956), however, related the variations in the anorthosites and the origin of the gabbro and ore to a series of pneumatolytic replacements involving andesination of Marcy anorthosite. Later solutions were assumed to be the source of the ferromagnesian and ore minerals.

Heyburn (1960) made reference to two stages of gabbro emplacement, one of them associated with the anorthosites, and the second a gabbroic intrusive rich in iron and titanium with sufficient volatiles to allow partial replacement of anorthosite by ore minerals.

Kays (1965) proposed that during granulation and shearing of the anorthosite, calcium and aluminum were released from the original laboradorite plagioclase, resulting in andesinization, but by a different means than proposed by Gillson (1956). Creation of pressure gradients by rock fracturing was then postulated to cause iron, magnesium, and titanium to migrate to the low pressure fractured areas, where they reacted with the calcium and aluminum released by andesinization to form ferromagnesian silicates, garnet, ilmenite, and magnetite. The resulting replacement could be partial, as in gabbro, or complete over large volumes, as in anorthosite.

Sun (1971) concluded that the Cheney Pond deposit is more likely to be of magmatic rather than replacement or metamorphic origin, stress-

ing evidence of magmatic crystallization temperatures and the layered nature of the ore bands, which resembles the structure of ultramafic stratiform sheets.

Gross (1968), after working for several years at the MacIntyre Development, concluded:

No one theory can explain satisfactorily all of the rock and mineral relationships now in evidence.

It is quite certain that all the rocks of the district are genetically related as shown by their mineral constituents. The primary mode of emplacement is partially or wholly obscured by subsequent metamorphic processes. It is likely that certain portions of the rocks have been remobilized one or more times by deformation pressures. Different degrees of plasticity are evident . . .

There is evidence that volatiles were present at some point in the history of the deposits, probably in both early and late stages. The faults and joints now exposed show movement along many surfaces. Along the major breaks there are breccia fragments of ore or gabbro in a matrix of carbonates. These are also the areas of recrystallized magnetite, large ilmenite crystal masses, and minor sulfide minerals . . .

The present faults and associated hydrothermal minerals represent the last minor sequence in a very long and complicated series of geologic events.

Virginia Titanium Deposits—The titanium ores of Virginia are also associated with anorthosite, and are of two types: (1) rutile and ilmenite disseminated in the border facies of the anorthosite and bordering gneiss, and (2) rutile and/or ilmenite with apatite in the form of dikelike masses which Watson and Taber (1913) named nelsonite after the county in which they are most common. Deposits of both types have been mined commercially, utilizing mainly the soft, saprolite portions of the ore bodies which form an upper layer about 9 to 37 m (30 to 120 ft) thick.

Rutile was first mined commercially at Roseland, VA, in 1900 by the American Rutile Co. The ore was obtained by open cut mining of both saprolite and hard rock. The mine was operated intermittently until 1949 when increased labor costs, low grade ore, and low market prices for rutile led to a shutdown of operations. The ore consists almost exclusively of disseminated rutile in the anorthosite (Fish, 1962; Hillhouse, 1960).

Commercial surface mining for ilmenite began in 1930 from a large saprolite ore body along the Piney River on the old Warwick

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Industrial Minerals and Rocks

Tract. This mine was first operated by the Vanadium Corp. of America, and later by the Southern Mineral Products Corp. (Hillhouse, 1960) until it was acquired by the American Cyanamid Co. in 1944. In 1958 the company transferred operations to the deposit on the S.V. Wood property near Lowesville about 5 km (3 miles) to the West (Fish, 1962), supplying ilmenite to its nearby sulfate process pigment plant until 1971, when both mine and pigment plant were closed down, mainly because the supply of readily mined soft ore at this location was running out.

Fish (1962) estimated the saprolite deposits in the area to contain reserves of titanium-bearing material in excess of 20 million tons, averaging 7.0% TiO_2 . Unweathered rock beneath the saprolite contains comparable titanium values, but mining and processing this ore would be more expensive. The ore is derived from two types of rocks; one, containing ilmenite as the dominant titanium mineral, is a diorite, and the other, containing ilmenite and rutile, is an anorthosite.

The nelsonite deposits are higher grade, but of limited size. Many of them are lenticular and pinch out at shallow depths (Fish and Swanson, 1964).

Davidson et al. (1946) studied the Piney River deposit and concluded that it was emplaced as a large dike fingering into its walls. Replacement was agreed to have occurred, but this was not regarded as proof that the main development of ore was by replacement.

Theories proposed regarding the origin of the Virginia titanium ores in general include magmatic segregation from the anorthosite, favored by Watson and Taber (1913), differentiation from a granodiorite magma, suggested by Moore (1940), and replacement by invading solutions, proposed by Ross (1941, 1947); and Hillhouse (1960).

Yadkin Valley Deposit, North Carolina—The Yadkin Valley deposit is about 21 km (13 miles) north of Lenoir, in Caldwell County. The ore occurs as a series of narrow, close-spaced lenses which form a nearly continuous vein about 305 m (1000 ft) long. The ore consists of small masses of ilmenite disseminated throughout a talcose body which lies conformably with the enclosing quartzite and mica schist (Broadhurst, 1955). Some rutile occurs as fine inclusions in the mica, but was not recovered.

The ore zone is parallel to the gneissic struc-

ture, is about 9 m (30 ft) thick, and was mined by quarrying, running about 30 to 35% TiO_2 . The mine was operated from 1942 to 1952 by the Yadkin Mica and Ilmenite Co., a subsidiary of Glidden Co. A flotation ilmenite concentrate was produced which contained 49 to 52% TiO_2 (McMurray, 1944), unusually high grade for a rock ilmenite.

Hot Spring County, Arkansas Deposits, (Magnet Cove, Christy, Hardy-Walsh)—These deposits occur in a complex mixture of alkalic igneous rocks intruding folded sedimentary and metamorphic rocks, many of which contain various quantities of titanium-bearing minerals (Fryklund and Holbrook, 1950). Much of the titanium is in the form of rutile or brookite, but many other titanium minerals have been identified. Rutile was recovered commercially from the Magnet Cove (Reed, 1949a) deposit from 1932 to 1944. A considerable amount of work has been done on ore dressing techniques for these ores (Fine and Frommer, 1952; Fine et al., 1949). The features contributing most to the difficulty of utilizing these deposits are their comparatively low grade, the larger deposits averaging 3 to 6% recoverable TiO_2 (Fryklund et al., 1954), the formation of large amounts of slimes during grinding, and the intimate association of ore minerals and gangue, resulting in low recoveries and comparatively low grade concentrates (Toewe et al., 1971). No commercial output of titanium minerals has been reported from the Christy (Reed, 1949) or Hardy-Walsh deposits.

Other US Deposits—Other deposits of potential commercial importance include the titaniferous magnetite deposits in the Laramie Range, Wyoming (Diemer, 1941; Frey, 1946; Pinnell and Marsh, 1954). Metamorphic rocks were intruded by anorthosite, which in turn was cut by gabbro and titaniferous magnetite dikes. The main dike at Iron Mountain consists of a granular aggregate of homogeneous ilmenite and magnetite containing very small intergrown ilmenite inclusions. In the Taylor deposit, as much as 60% apatite is locally present. Resources of high grade ore containing about 45% Fe and 20% TiO_2 , may amount to about 30 million tons. Further metallurgical research would be needed, and the geographical location is at present unattractive for commercial development.

Other large deposits occur in the San Gabriel Mountains in Los Angeles County, California, as disseminations in a gabbroic facies

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ck, and was mined 30 to 35% TiO_2 . From 1942 to 1952 the Iron Ore Co., a sub-fotation ilmenite which contained 49% TiO_2 (1944), unusually fine.

Kansas Deposits, by Walsh—These are a mixture of alkalic and sedimentary rocks of which contain titanium-bearing minerals (Wolbrook, 1950). In the form of rutile titanium minerals were recovered from Net Cove (Reed, 1944). A considerable amount has been done on these ores (Fine, 1949). The difficulty of their comparative analysis averaging 3 to 4% TiO_2 (Reed et al., 1954), and its association with sulfating in low grade concentration. No commercial use has been reported for these ores (Hardy-Walsh).

These deposits of ilmenite include the titaniferous in the Laramie (1941; Frey, 1946); metamorphic rocks which in turn was a magnetite dikes. The main consists of a fine-grained ilmenite in very small interstices in the Taylor deposit is locally present ore containing 1/2% may amount to their metallurgical value. The geographical distribution is reactive for com-

in the San Gabrielles County, California gabbroic facies

of an anorthosite (Moorhouse, 1938). Very large tonnages may be available, but the average grade is only about 4.5% TiO_2 .

Smaller deposits occur in nearly every one of the western states, for example in Montana (Wimmler, 1946); Minnesota (Broderick, 1917); Wichita Mountains of Oklahoma (Merritt, 1939); Boulder County, Colorado (Jennings, 1913); and the San Juan district, Colorado (Singewald, 1913).

Canada: Quebec—The geology and general characteristics of the Canadian titanium deposits were well described in an extensive and thorough report by Rose (1969). He concluded that the titaniferous magnetite and ilmenite deposits in eastern Canada were formed by magmatic differentiation and injection, mainly in Precambrian time, presumably from 850 million to 1,500 million years ago. There is an unmistakable genetic relationship between these deposits and anorthositic rocks. The anorthosite bodies, as exemplified by the Morin, St. Urbain, Lac St. Jean, Sept-Iles, and Lac Allard anorthosites, appear in general to be composite, multiple intrusions composed mainly of anorthositic and gabbroic (noritic) rock. According to Rose, (1969):

True anorthosite characteristically is host to the massive ilmenite-hematite lodes, whereas gabbroic anorthosite characteristically is host to the extensive deposits of low-grade, disseminated, titaniferous magnetite containing mixtures of titanomagnetite, ilmenite, ilmenite-hematite, and other intermediate members that possibly form a solid solution series of iron-titanium oxide minerals. Although generally separate, in places the two types of deposits, as well as the host rocks, appear to be transitional.

Although a few ilmenite and titaniferous magnetite occurrences have been found in rocks that were invaded by anorthositic magma, the major deposits are almost always within the intrusion itself. Low-titanium magnetite deposits are commonly found in Grenville-type rocks outside the anorthosite massifs.

The main deposits include: the sill-like Lac Tio ilmenite-hematite deposits being mined by QIT-Fer et Titane, Inc. (formerly Quebec Iron and Titanium Corp.), estimated to hold about 100 million tons of high grade open pit material; the dike-like Magpie Mountain medium grade titaniferous magnetite deposits, averaging 43% iron and 6% titanium, probably containing over 250 million tons of open pit material; the St. Urbain deposits with over 20

million tons of high grade ilmenite-hematite, and several million tons of slightly lower grade material near Ivry, and in the Lac du Pin-Rouge area, near St. Hippolyte-de-Kilkenny. Substantial amounts of low-grade titaniferous magnetite and ilmenite occur at many other localities in the Morin, Lac St. Jean, Sept-Iles, Lac Allard, and St. Urbain anorthosite areas (Rose, 1969).

Kish (1972) studied the chemical composition of the Quebec deposits, particularly with regard to the vanadium content, and reported that vanadium concentrations of economic importance have so far been found only in the titaniferous magnetite deposits. The composition and origin of selected titaniferous deposits were discussed by Lister (1966).

ALLARD LAKE (LAC TIO) DEPOSITS—The geology of the area in which the Allard Lake deposits occur was investigated by Retty (1944), who noted numerous concentrations of ilmenite within a mass of anorthosite, along the shores of several lakes. These ilmenite showings, while not large enough to warrant commercial development, led to detailed exploration of the anorthosite area in 1946 by Kennco Explorations, Ltd., which resulted in the discovery of the large Lac Tio deposit. The deposit lies between Allard Lake and Puyjalon Lake, about 40 km (25 miles) north of Havre St. Pierre on the north shore of the St. Lawrence River.

The geology of the area and the nature of the ilmenite deposits have been well described by Hammond (1949, 1952), and by Hargraves (1959). The most important lithological unit in the area is the Allard Lake anorthosite. It is one of several anorthosite masses occurring at intervals in the southeastern part of the Precambrian shield, in a line trending northeast from the Ontario-Quebec boundary to the Labrador coast. The Allard Lake anorthosite mass is about 145 km (90 miles) long, and 32 to 48 km (20 to 30 miles) wide, its length paralleling the Gulf of St. Lawrence. The several facies of the anorthosite range from almost pure feldspar rock through anorthositic gabbro, ilmenite-rich anorthosite, and norite. The norite occurs as steeply dipping sheets, as much as 6 km (4 miles) long and 914 m (3000 ft) thick, intruded into the anorthosite, and is rich in hem-ilmenite and magnetite.

The Lac Tio deposit is a flat-lying, tabular body about 1097 m (3600 ft) long, and 1036 m (3400 ft) wide. With an estimated tonnage of 125,000,000 st of ilmenite averaging 32% TiO_2 ,

and 36% Fe, it is the largest known ore body of its type in the world.

The ore consists of exsolution intergrowths of ilmenite and hematite, with coarse-grained ilmenite containing numerous blades and lenses of hematite up to 0.3 mm wide, which in turn may contain similarly shaped but smaller inclusions of ilmenite, in parallel orientation. The typical high grade ore contains about 75% ilmenite, 20% hematite, and 5% gangue minerals consisting of pyroxene, feldspar, and minor amounts of pyrite, pyrrhotite, and chalcopyrite.

The ore occurs in anorthosite and anorthositic gabbro and is identical in character with that in other deposits in the area. Inclusions of anorthosite are found in the ore, and do not show evidence of replacement by ilmenite. The ilmenite is very coarse-grained along its contacts with anorthosite, and the contacts are very sharp. Tiny dikelets of coarse granular ilmenite commonly cut the anorthosite at contacts with the ore bodies. On a basis of such direct field evidence, Hammond (1949, 1952) concluded that the Allard Lake ores are late magmatic, probably emplaced by a process of late gravitational liquid accumulation, with injection of the oxides into fractures within the anorthosite.

Hargraves (1959) recognized a genetically significant relationship between the ore deposits and the oxide-rich norite phases of the anorthosite rocks with which they are associated. The usual occurrence of the isolated ilmenite masses in anorthosite below norite sheets, with hemo-ilmenite concentrated at the base of the sheets, suggests that the norite sheets may have been the original source of the iron-titanium oxides. Hargraves (1959) presented evidence suggesting immiscibility between the oxide fraction and the silicate fraction from which pyroxenes crystallized, and emphasized that the crystallization of the oxide fraction was subsequent to all other primary crystallization. He suggested that:

Gravitational concentration by downward settling within the sheets could have been accentuated by contemporaneous deformation ("filter pressing") which in some places, caused it to be squeezed out of the sheets, and injected into surrounding anorthosite. In this way the isolated deposits in anorthosite are postulated to have been formed.

Based on his own extensive study of the St. Urbain deposits, and the similarity between these and the Allard Lake deposits, Gillson (1932, 1949) felt that the St. Urbain and Al-

lard Lake ore bodies are pneumatolytic replacement deposits.

The ilmenite-hematite ore produced from the Lac Tio operation contains about 34% TiO_2 and 40% Fe. Because of its high iron content it is not used directly for titanium dioxide pigment manufacture, but is subjected to further concentration and electric furnace smelting at Sorel, Que., to produce iron metal, and a high- TiO_2 slag which is widely used as a feed for sulfate process pigment plants.

China: The largest titanium deposit in China is reportedly the 1.1 billion ton Panzihua titaniferous magnetite deposit containing about 7% titanium in the form of ilmenite, near Dukou, Sechuan province (Brady, 1981).

Norway: The iron-titanium provinces of Norway have been described by Geis (1971), Vokes (1968), Carstens (1957), Michot (1956), Hubaux (1956), and others. There are three types of ilmenite deposits: (1) ilmenite, (2) vanadium-bearing magnetite-ilmenite, and (3) apatite-bearing magnetite-ilmenite. Production of ilmenite has come only from Type 1 deposits (Storgangen and Tellnes), except for a small amount produced from a Type 2 deposit (Rodsand), as a byproduct from magnetite production. These three commercial deposits all occur in the Egersund anorthosite in southwestern Norway.

Storgangen Deposit—The Storgangen ore body located near Hauge, was deposited in a fracture in anorthosite, forming a dike about 1585 m (5200 ft) long and 49 m (160 ft) wide, of unknown depth, dipping 45° to 50° N. The ore contains about 40% ilmenite and 9% magnetite with a gangue that consists mainly of hypersthene and plagioclase, with accessory biotite, pyrite, chalcopyrite, and spinel. The ilmenite contains about 13% hematite as exsolution lenses and lamellae in parallel orientation, ranging up to a few microns in width. The magnetite is essentially homogeneous, containing very little exsolved ilmenite. The ilmenite concentrate was produced by a combination of gravity, magnetic, and flotation methods. From this deposit, Titania A/S (NL Industries, Inc., subsidiary) mined 9 million st of ore from 1916 to 1966.

Tellnes Deposit—Around 1954, it became apparent that because of the increased demand for ilmenite, the amount of ore accessible at currently mined levels in the Storgangen deposit would be soon depleted. By 1956, two alternatives had been investigated: to extend operations to deeper levels at Storgangen, or to discover and develop a new ore source in nearby areas considered favorable to the oc-

currence of tit Storgangen sh depth was less production ra' other 10 to 1 which was dis vey in 1954, 220 million probably pre depth. After plant work to concentrate c ore, which i Storgangen the Tellnes operation (B

From 1916 to 1966, 9 million st of ore was produced from the Storgangen deposit. In 1954, about 330,000 st of ore were produced at Storgangen. The production capacity was 1,000,000 st in 1974. Production of concentrate reached 1,000,000 st. The Tellnes deposit (about 10 miles) east of Storgangen consists essentially of the same ore known outcrop and a surface

The ore is composed of ilmenite and magnetite by its textural characteristics into the anorthosite. The presence of exsolution lenses of ilmenite in the magnetite of the Tellnes deposit is characteristic of the Storgangen deposit.

The Tellnes deposit is a large ore—only about 10 miles from Storgangen following the Tellnes ore series, 3. The amount of ore—only about 10 million st per. As a result of the increase in demand for ilmenite, the amount of ore accessible at currently mined levels in the Storgangen deposit would be soon depleted. By 1956, two alternatives had been investigated: to extend operations to deeper levels at Storgangen, or to discover and develop a new ore source in nearby areas considered favorable to the oc-

Because of the increased demand for ilmenite, the amount of ore accessible at currently mined levels in the Storgangen deposit would be soon depleted. By 1956, two alternatives had been investigated: to extend operations to deeper levels at Storgangen, or to discover and develop a new ore source in nearby areas considered favorable to the oc-

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ore produced from contains about 34% iron. Because of its high iron content, it is used directly for titanium production, but is subjected to an electric furnace process to produce iron metal, which is widely used as a pigment plants.

The largest deposit in China is the Panzihua titanium deposit, containing about 7% ilmenite, near Dukou, (1981).

In the provinces of Norrbotten (Geis (1971)), Vokse (Michot (1956)), and others. There are three types: (1) ilmenite, (2) ilmenite, and (3) ilmenite. Production is from Type 1 deposits, except for a Type 2 deposit from magnetite. The commercial demand is for anorthosite in

The Storgangen ore was deposited in a dike about 9 m (160 ft) wide, dipping 45° to 50° N. The ore consists of ilmenite and 9% magnetite, with accessory hematite and spinel. The hematite is in parallel orientation, 10 to 20 microns in width, and is homogeneous, containing ilmenite. The ilmenite is produced by a contact metamorphic, and flotation process. Titania A/S (NL) mined 9 million

metric tons in 1954, it became the largest ore accessible at the Storgangen deposit. By 1956, two new mines were opened: to extend the Storgangen, or to develop a new ore source in the area accessible to the oc-

currence of titanium ore. Diamond drilling at Storgangen showed that the ore available at depth was less than expected, and at current production rates would have lasted only another 10 to 12 years. At the Tellnes deposit which was discovered by an aeromagnetic survey in 1954, drilling showed ore reserves of 220 million st, with another 110 million st probably present, based on projection to depth. After extensive laboratory and pilot plant work to demonstrate that a satisfactory concentrate could be made from the Tellnes ore, which is much finer grained than the Storgangen ore, it was decided to develop the Tellnes deposit as an open pit mining operation (Brun, 1957).

From 1960 to 1966 ilmenite was produced from both the Storgangen and Tellnes deposits. In 1966 production at Tellnes reached about 330,000 stpy, and production ceased at Storgangen. Since that time, production capacity was increased in three steps, and in 1974 production of ilmenite flotation concentrate reached a peak of 935,000 st.

The Tellnes ore body is about 40 km (25 miles) east of the Storgangen deposit, and consists essentially of an ilmenite-rich norite intruded into anorthosite. The ore body has a known outcrop length of 2682 m (8800 ft), and a surface area of about 56 hm² (140 acres).

The ore is magmatic in character, as proved by its texture, by apophyses of ilmenite into the surrounding rocks, by xenoliths of anorthosite in the ore itself, and by the presence of eruptive breccia (Dybdahl, 1960).

The Tellnes ore is much finer-grained than the Storgangen ore, the intergrowth of ilmenite and magnetite is more intimate, and the amount of magnetite is lower in the Tellnes ore—only 2% compared to about 7% in the Storgangen ore. Dybdahl (1960) gave the following average mineral composition for Tellnes ore: ilmenite, 39%; plagioclase, 36%; hypersthene, 15%; biotite, 3.5%; and accessories, 3.5%, including a little apatite, and some pyrrhotite containing nickel and copper. As at Storgangen, the ilmenite contains minute exsolution lenses and lamellae of hematite.

Because of the fineness of grind needed to liberate the ore minerals, and the relatively high phosphorus content present as apatite, extensive changes in the ore dressing procedure had to be made, resulting in an all-flotation ilmenite concentrate, and an acid washing step to remove apatite. The ilmenite concentrate contains 44.5 to 45.5% TiO₂, about 34.0% FeO, and 12.5% Fe₂O₃.

Tellnes ilmenite concentrate is the major feed material for a large number of European sulfate process pigment plants, and is in a particularly strong market position because of relatively stable North Sea freight rates, and its proximity to the European market (Anon., 1973c; Anon., 1978a).

Finland: Otanmäki Deposit—The ilmenite-magnetite deposit at Otanmäki is located almost at the geographical center of Finland. The Otanmäki deposit and a neighboring deposit at Vuorokas were discovered in 1938 as a result of magnetic surveys by Veikko Okko of the Geological Survey of Finland (Harki et al., 1956).

As described by Harki et al. (1956), the deposit at Otanmäki extends about 2 km (1.2 miles) within an east-west zone which curves northward in a semicircle at its east end. This circle is the eastern boundary of a mass of amphibolite occupying most of a roughly elliptical area within which the ore bodies are found. The ore occurs as lenses which are usually located along contacts between amphibolite and anorthosite, or between anorthosite and rocks that occur in a heterogeneous band along the southeast border of the ore zone. The anorthosite appears as continuous conforming lenses in the innermost border of the curve. A mass of gabbro borders the southwest part of the ore zone. According to Harki et al. (1956), it has been established that the ore is intrusive in nature, except possibly in the case of lower grade stratified ores.

The ore minerals, magnetite and ilmenite, occur as independent grains which after fine grinding are separated to produce magnetite and ilmenite concentrates. There are no microscopic intergrowths of magnetite and ilmenite, although the ilmenite contains minor amounts of intergrown hematite (Harki et al., 1956; Vaasjoki, 1947). The main gangue minerals are chlorite, hornblende, and basic plagioclase, with accessory spinel and sphene.

Reserves are about 28 million st containing 40% magnetite, 30% ilmenite, 1 to 2% pyrite, and 0.25 to 0.3% vanadium associated with the magnetite (Anon., 1978b).

Rock Deposits—Potential Sources

Brazil: Tapira and Salitre Titanium Deposits—These deposits are unique in that their major titanium mineral is the anatase (or octahedrite) polymorph of TiO₂, rather than rutile or ilmenite. The deposits occur in an alkaline pipe, 6 km (4 miles) in diameter, about 48 km (30 miles) southeast of Araxá in

Minas Gerais. According to the National Department of Mineral Production, proved and indicated reserves contain 108 million st of TiO_2 (Anon., 1980a). In places, anatase may make up as much as 70% of the ore. In preliminary tests concentrates containing up to 86% TiO_2 were produced with very low chromium and vanadium content, said to be suitable for producing TiO_2 pigments by the chloride process. These concentrates have some solubility in sulfuric acid (Anon., 1972).

Through 1979, about 12 million tons of anatase-bearing ore had been mined and stockpiled in conjunction with phosphate production.

Mexico: Pluma Hidalgo Deposit, Oaxaca—The Pluma Hidalgo Deposit occurs in an area known for some time to have scattered occurrences of rutile, and is located about 125 km (78 miles) south of the City of Oaxaca, the state capital. Starting in 1953, Republic Steel Corp. carried out an extensive program of exploration, but did not find high grade ore bodies large enough to justify a mining operation. In 1957, when the price of rutile dropped substantially, the project was discontinued.

Paulson (1964) described the dominant country rock as a quartz feldspar gneiss, or granulite, which may be classed as an anorthosite by analogy with the anorthosite associated with the similar Virginia titanium deposits. The common mineral association in ore zones is ilmenite, rutile, and apatite in a green rock that is mostly chlorite.

Regarding possible economic exploitation of the Pluma Hidalgo deposit, Paulson was of the opinion that instead of trying to find large zones of high grade ore, it might be better to block out a large tonnage of the irregularly distributed ore which, including the barren rock that would have to be removed with the ore, might have an overall grade that would permit mining by open pit methods.

Sand Deposits—Principal Producing Countries

United States: All commercially important titanium mineral sand deposits in the United States are within the Atlantic and Gulf Coastal Plain geologic provinces. States which have established or potential exploitable heavy-mineral-bearing sands are Florida, Georgia, New Jersey, and Tennessee.

Concentrations of heavy minerals in the coastal areas of the southeast are related to both recent and ancient marine shorelines, the latter of Pleistocene age. Up to seven old shorelines have been identified by different investigators (Cooke, 1941, 1945; Flint, 1940, 1942, 1947;

MacNeil, 1949; Parker and Cooke, 1944), but the most widely recognized are: (1) Okefenokee, 46 m (150 ft), (2) Wicomico, 31 m (100 ft), (3) Pamlico, 8 to 11 m (25–35 ft), and (4) Silver Bluff, 2 to 3 m (8–10 ft) above sea level. All are regarded as lines of farthest marine transgression during interglacial and postglacial periods, and all have produced commercial heavy mineral deposits. Mining began where black sands were exposed on modern beaches, and when these deposits were exhausted operations moved inland to the larger and harder-to-find deposits of the older elevated strands. Florida has three heavy mineral mines operating with possibilities for more in the future; Georgia's only deposit exploited to date recently has been worked out but, again, other occurrences of possibly economic size and grade are known.

In central New Jersey two operations have recovered titanium minerals and byproducts from Pliocene sands of the Cohansey formation, about 24 km (15 miles) inland from the present shore.

The host for heavy mineral deposits in western Tennessee which have been considered for mining is the Cretaceous McNairy sand, outcropping within the Mississippi embayment of the Gulf Coastal Plain. Past, present, and possible future ore bodies in each of the three areas of occurrence are considered in turn below.

Florida and Georgia—Storm-line concentrations of heavy minerals in modern beach sands have been mined for ilmenite at two locations on Florida's eastern beaches. Mining began at Pablo Beach near Ponta Vedra in 1916 (Martens, 1928), and Riz Mineral exploited a deposit on the ocean front near Vero Beach in later years. Similar modern beach, bar, and barrier island black sands are found on the northeast and west coasts of the peninsula and along the shore of the western panhandle. The ratios among species in heavy mineral suites in the western Florida occurrences are different from those in eastern deposits, probably because of dissimilar ultimate sources on opposite sides of the southern Appalachian Mountains. The potential ore reserves in the known near-shore concentrations are small, with the possible exception of Amelia Island in extreme northeastern Florida, Cumberland Island just to the north in Georgia, and several others of the Sea Island chain formed as barrier islands during the development of the Silver Bluff shoreline. Land values in the islands have increased because of their growing popularity as resort areas over approximately three decades

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Cooke, 1944), but are: (1) Okefenocomico, 31 m (100 m (25-35 ft), and 8-10 ft) above sea level. Lines of farthest glacial and all have produced heavy mineral deposits. Mining operations were exposed on these deposits were inland to the larger of the older elevated heavy mineral mines for more in the site exploited to date but, again, other economic size and

no operations have been conducted and byproducts of the Cohansey formation are inland from the

al deposits in western Georgia are considered for the McNairy sand, outcropping embayment of the Past, present, and in each of the three considered in turn

form-line concentrations of modern beach sands are found at two locations. Mining began at the Piedra in 1916 (Marine mineral exploited at a site near Vero Beach). Heavy mineral deposits are found on the northern peninsula and northern panhandle. The heavy mineral suites are different sources, probably because of sources on opposite sides of the Appalachian Mountains. Deposits in the known areas are small, with the Florida Island in extreme northern Florida and just north of several others of the Silver Bluff islands have increasing popularity as recently as three decades

since the heavy mineral deposits were first drilled, so that mining may not be economically competitive with tourism and recreation.

Elevated sand bars were mined by Riz Mineral south of Vero Beach and by Humphreys Gold Corp., on behalf of Titanium Alloy Manufacturing Co., in a Pamlico shoreline feature just west of Jacksonville Beach. These deposits are now mined out.

Just south of the St. Marys River, which forms Florida's northern boundary, and north-east of the community of Yulee, ITT-Rayonier owns land containing an unmined heavy mineral deposit which has been drilled by several organizations, most recently by Pennsylvania Glass Sand Corp., the ITT-Rayonier subsidiary. Ore grade lenses form low north-south ridges, interspersed with shallow swamps, and rest on clay and shell beds. The Yulee deposit is also a Pamlico shoreline development.

In Georgia other black sand concentrations, all related to the Pamlico shoreline, are located north and south of Brunswick and south of Savannah. Potential ore reserves are modest in all known cases, as they are at Yulee, but exploitation might be possible if the same mining equipment could be used at several deposits sequentially, and if a heavy mineral concentrate could be economically transported to a central separating plant.

TRAIL RIDGE, FL—The broad sand ridge that extends from the southern parts of Clay and Bradford counties in north-central peninsular Florida for 201 km (125 miles) northward into southeastern Georgia, called Trail Ridge, is thought to have formed by one or more of several processes in late Miocene or Pliocene time. It has been suggested that it developed as:

1) An accumulation of deltaic sediments from southward flowing rivers which was reworked by encroaching seas and partly washed away (Bishop, 1956).

2) A prograding bar built up on the seaward side of finer marine to estuarine deposits accumulating on its protected Gulf side (Brooks, 1966).

3) A residual sand ridge resulting from the weathering in situ of underlying sediments.

4) A barrier island originating as a ridge built up landward of a shoreline and cut by tidal inlets during coastal subsidence or sea level rise, forming lagoons behind the ridge (Hoyt, 1967).

5) A reworking, through the action of winds, waves, and currents, of the northern part of the remnant Lake Wales ridge, a possi-

ble deltaic deposit extending more than 241 km (150 miles) farther to the south (Pirkle and Yoho, 1970).

6) Sediments transported from the high terrace sands to the west of Trail Ridge (Pirkle, 1975).

Du Pont's Trail Ridge ore body occupies the southern 29 km (18 miles) of the western part of the feature, and is from 2 to 3 km (1 to 2 miles) wide. The base of the ore body is at an elevation of 44 m (145 ft) to more than 61 m (200 ft) above sea level, and the average thickness is 11 m (35 ft). It overlaps barren coarse sand on the east. An indurated layer of concentrated organic material comprised of decomposed remnants of roots, branches, and trunks of trees underlies the central portion, and the western margin lies on pre-Pleistocene clayey sand in many places (Grogan et al., 1964).

The heavy minerals are thinly layered and disseminated in brown, oxidized, cross-bedded sand. In random lenticular areas at various depths organic materials and clayey minerals cement the sand grains to form a poorly consolidated sandstone locally called "hardpan." The average grade in heavy minerals is low, only about 4%, but there are about 45% high-TiO₂ minerals in the heavy mineral suite (Pirkle and Yoho, 1970).

The titanium ore minerals are altered ilmenite, leucocoxene, and a very little rutile. Staurolite, zircon, tourmaline, spinel, kyanite, sillimanite, monazite, corundum, and topaz are also present. Authigenic pyrite occurs in small amounts associated with present-day swamps. The absence of monazite, garnet, and epidote, which are common in the underlying formations and in other southeastern heavy mineral deposits, implies different source rocks and a different age for the Trail Ridge minerals. The absence of these three minerals makes the separation and marketing of staurolite possible (see "Staurolite" chapter).

Alteration of the titanium minerals by oxidation and leaching of iron has been extensive. Grogan et al. (1964) wrote:

The TiO₂ content of the mineral grains is highest near the land surface, decreases rapidly from the surface to a depth of about 10 feet, and then remains essentially constant to the bottom. The iron content varies inversely with the TiO₂ content. The particle size of the titanium mineral grains ranges between 48 and 200 mesh, with the average size near 80 mesh. The grains are spherical, and some are porous as a result of leaching.

Their color ranges from black through brown, gray, and tan to light yellow or yellowish-white depending on the degree of alteration.

The term "ilmenite" is applied to the more magnetic of the titanium minerals. These particles are black with a metallic luster and range from 62 to 70% TiO₂.

The term "leucoxene" is applied to the less magnetic opaque titanium minerals which contain from 70 to 95% TiO₂. They have the same size and shape as the ilmenite grains but are lighter in color, and represent more advanced stages of alteration. Their magnetic susceptibility ranges from moderate for the darker grains to feeble for the very light colored grains.

Unaltered crystalline rutile is common in the nonmagnetic fraction. The grains are dark red in color and are mostly minus 150 mesh in size.

GREEN COVE SPRINGS, FL—About 32 km (20 miles) east-southeast of the south end of Trail Ridge an ilmenite-leucoxene-zircon-monzonite heavy mineral deposit was mined by Titanium Enterprises, a joint venture of American Cyanamid and Union Camp Corp., until 1978 when mining ceased for economic reasons. In 1980 the property was purchased and mining resumed by Associated Minerals (U.S.A.) Ltd., Inc., a subsidiary of the Australian firm, Associated Minerals Consolidated Ltd. The ore body is near the eastern margin of the Duval Upland, which is thought to be a regressional beach ridge plain, and is probably related to an ancient shoreline at an elevation of 27 to 31 m (90 to 100 ft) above present sea level or to the Wicomico shoreline of MacNeil (1949).

The ore zone at Green Cove Springs is 16 to 19 km (10 to 12 miles) long, 1 km (¾ mile) wide, and it averages about 6 m (20 ft) thick. The heavy minerals comprise 3 or 4% of loose to slightly consolidated quartz sands which are underlain by subgrade quartz sands, by brown and gray sands containing some clay, by shell beds, and finally, at a depth of 31 m (100 ft) or more below surface, by limestone and dolomite.

The grain size of both quartz and heavy minerals is smaller than at Trail Ridge. Also, the heavy mineral suite, containing a significant percentage of monazite together with minor amounts of epidote and garnet, is different. It has been suggested (Pirkle et al., 1974) that while the Trail Ridge concentration of heavy minerals was derived from the Northern Highlands of the northwestern part of peninsular Florida, the Green Cove Springs deposit was

formed from the sands of the Duval Upland to the east.

BOULOUGNE, FL—Humphreys Mining Co. in 1974 to 1979 mined a heavy mineral deposit about 3 km (2 miles) south of the town of Boulougne on the St. Marys River, which forms the boundary between extreme northern Florida and Georgia. It was located near the eastern edge of the Duval Upland at an elevation above sea level the same as that at Green Cove Springs, and had similarly fine sands containing monazite, garnet, and epidote. The two deposits probably had a common genesis.

The Boulougne ore body was 4 to 5 km (2½ to 3 miles) long north-south, 0.8 to 1.2 km (½ to ¾ mile) wide, and 2 to 8 m (5 to 25 ft) thick. The ore-bearing surface sands were underlain by sand with a diminished heavy mineral content, then by various colors of clayey sand, then by a thin shell bed, and finally by the sediments of the Hawthorne formation of middle to late Miocene age.

FOLKSTON, GA—Du Pont, in a program of systematic examination of elevated bars and old high level shorelines along the Atlantic Coast, discovered the Folkston heavy mineral deposit in 1952. It was situated in a flat, broad elevated area a few miles north of the Boulougne, FL, ore occurrence and the two may at one time have been one, later cut by the St. Marys River. The flat area is better described as a marine terrace rather than a sand bar or old shoreline, as it is up to 6 km (4 miles) wide and over 32 km (20 miles) long. The zone in which commercial deposits of heavy minerals were found, 8 km (5 miles) east of Trail Ridge, is not geomorphically different from the remainder of the terrace. It is a relatively thin layer of sand resting on clay. Three lenses were outlined in development drilling: the Main Area, the West Extension, and the North Extension. Each of the lenses was bounded by swamps, underlain by barren sand and clay, which were probably original depressions rather than erosion channels. Humphreys Mining Co. completed mining of the Main Area for Du Pont in 1974 and moved mining and primary concentrating equipment to Boulougne, FL.

Titanium minerals comprised 56% of the heavy mineral suite in the Main Area, and the average TiO₂ content of a combined titanium mineral concentrate was about 72%. The grain size averaged 90 to 94% —100 mesh. By-products were zircon and monazite.

New Jersey—The New Jersey Geological Survey, in an exploration program which grew

the Duval Upland

reys Mining Co. in y mineral deposit h of the town of River, which forms e northern Florida l near the eastern an elevation above t at Green Cove ine sands contain-epidote. The two mon genesis.

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vised 56% of the Main Area, and the combined titanium out 72%. The grain -100 mesh. By- monazite.

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Mineral	Grain Count
Ilmenite-leucroxene	85-90
Zircon	2-4
Kyanite-sillimanite	1-2
Staurolite	tr-1
Rutile, anatase	tr-1
Tourmaline	tr-2+
Garnet, monazite, epidote, andalusite, hypersthene	tr

out of observations of minor titanium mineral concentrations during investigation of monazite placers as sources of radioactive materials, identified the upper Tertiary sediments in the northern part of New Jersey's Coastal Plain as an ilmenite province in 1956 (Markewicz, 1969). The main heavy mineral formations were found to be the Miocene Kirkwood marine micaceous sand, silt, and clay, the Pliocene (?) Cohansey fluvial poorly sorted quartz sand, and the Pleistocene Cape May sands and gravels derived from the Kirkwood and Cohansey and from sediments farther inland. The Cohansey formation, which contains the greatest concentrations among these three, is ilmenite-rich in the northern third of its extent in New Jersey, in the vicinity of Lakehurst, about 48 km (30 miles) southeast of Trenton. Exploratory drilling by private companies resulted in the discovery of four ore bodies, and two heavy mineral mines were established.

LAKEHURST, NJ—The deposit of Glidden Pigments Group of SCM Corp. was located at Legler, about 3 km (2 miles) due north of Lakehurst, and was mined from 1962 to 1978. A mantle of Pensauken sand and gravel from 0.3 to 3.0 m (1 to 10 ft) thick overlay the Cohansey ore body, which was from 6 m (20 ft) to more than 12 m (40 ft) thick, with the average being 8 m (25 ft). A barren red sandstone 6 to 12 m (20 to 40 ft) thick underlay the ore, and beneath it was a zone in the Kirkwood formation, more than 12 m (40 ft) thick in places, averaging 4.5% heavy minerals. Only the Cohansey ore was mined.

The Cohansey sand is highly variable in color and in ilmenite, clay, and ironstone content. Occasional pebbles and limited gravel layers are present, and a coarse, iron stained, barren sand unit forms a bottom marker horizon. Cross-bedding, slump structures, roots and other pieces of organic material, and clay bodies up to 152 mm (6 in.) in diam are fairly common. Partially and wholly indurated iron oxide lenses and masses occur randomly above and below the water table (Anon., 1974a). A black, silty, lignite-charcoal band up to 5 m (15 ft) thick, found within the ore in the northwestern portion of the deposit, was interpreted by Markewicz as possibly the remains of a partially burned wooded swamp.

Heavy mineral content of the ore varied from 3% to more than 15% over distances of a few feet, with 5% being the average. The composition of the heavy mineral suite was reported by Markewicz as follows:

Glidden produced about 90,000 stpy of 61.5% TiO₂ ilmenite-leucroxene concentrate for its own consumption from 1962 to 1978.

MANCHESTER MINE—The Manchester mine of Asarco, Inc., also in the Cohansey formation, was about 97 km (60 miles) south of New York City, near Lakehurst, NJ. Geological features are similar to those at the Glidden operation at Lakehurst. Reserves were reported to be 180 million tons of sand averaging about 4% heavy minerals (Anon., 1974a) and 1.95% TiO₂ (Li, 1973). The operation was expected to have a 20- to 22-year life from 1973, when production began, based on a planned initial rate of 155,000 tons and a possible ultimate rate of 185,000 tpy of ilmenite, averaging 63% TiO₂. All ilmenite produced was under a sales contract to Du Pont. The mine was closed in March 1982 because of escalating costs and the prospect of a long-term oversupply situation. Figs. 1 to 4 are scenes of the operation.

Tennessee—A reconnaissance exploration program conducted by Du Pont to investigate reports of surface heavy minerals in 1957-1958 led to discoveries of ore grade occurrences of titanium minerals in the Cretaceous McNairy formation. McNairy is a poorly consolidated, clay-bearing fine-grained sandstone, about 91 m (300 ft) thick, which outcrops in a north-south belt just west of Kentucky Lake. The dip is very gentle to the west. Heavy minerals, including ilmenite, leucroxene, rutile, zircon, monazite, and minor amounts of kyanite, staurolite, tourmaline, and xenotime, are concentrated in the lower portion of the McNairy above the underlying Coon Creek formation. The ilmenite is somewhat altered, and concentrates have shown an average of about 62% TiO₂.

Ethyl Corp. and Kerr-McGee carried out exploratory drilling programs during the period 1970-1972, and both companies outlined several ore bodies. Production plans were deferred because of environmental problems and changing markets.

Australia: Australia is the world's most important heavy mineral sand mining country, producing 64% of the rutile mined in 1982, and 38% of the ilmenite.

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FIG. 1—General view of Asarco's dredge, pond, slurry pipeline, and pumping station at Manchester, NJ (courtesy of Asarco).

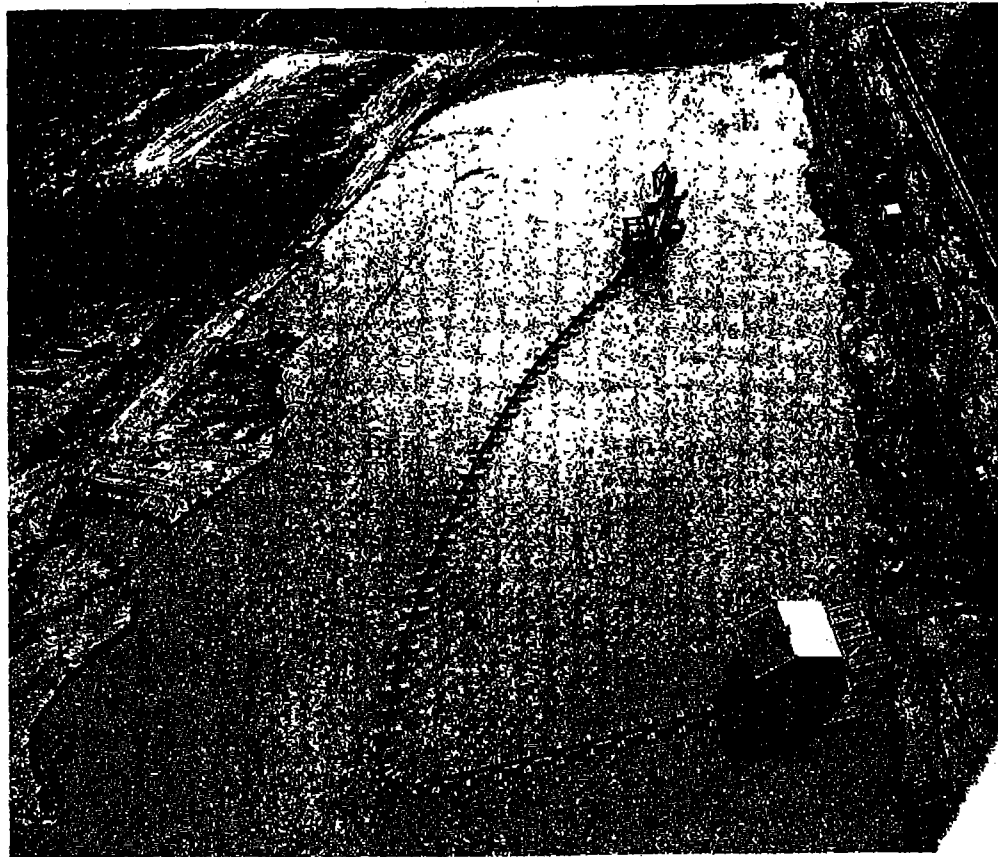


FIG. 2—Suction dredge recovered 20,000 gpm (20% solid) of titanium-bearing sands. The lake moved forward as the dredge advanced and closed in behind as clean sand from the concentration plant was returned (courtesy of Asarco).

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FIG. 3—Asarco's custom-built Dixie CS-20 suction dredge was designed to excavate sands from a depth of 20 m (65 ft). The slurry was pumped by pipeline to a terminal for processing (courtesy of Asarco).



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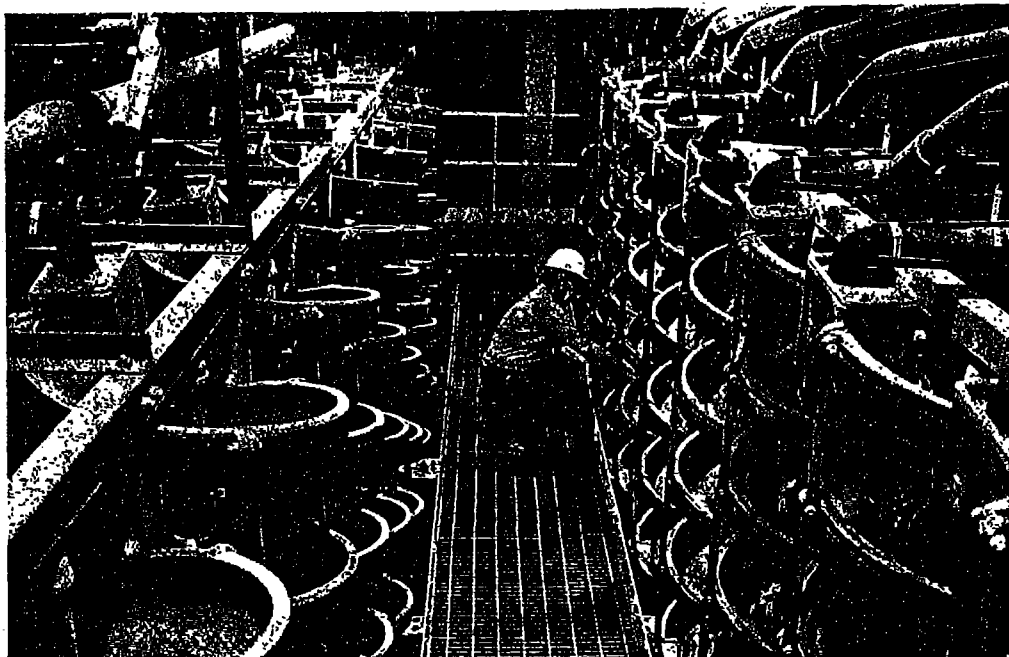


FIG. 4—View of a portion of the 1524 Humphrey spirals. They rejected over 95% of the slurry intake as waste in rougher, cleaner, and finisher cycles (courtesy of Asarco).

Heavy mineral concentrations occur widely around the Australian coast, and small black sand deposits have been reported in Tasmania, Victoria, South Australia, and the Northern Territory. Those at Nepean Bay on Kangaroo Island have been mined in the past. In addition to onshore beach-type deposits, offshore occurrences have been discovered and explored in shallow water along portions of the New South Wales-Queensland coasts. In 1982, however, mining was restricted to three areas: (1) the coast of New South Wales and Queensland from Newcastle to Gladstone, (2) near Bunbury, Capel, and Busselton on the west coast of Western Australia south of Perth, and (3) near Eneabba 29 km (18 miles) inland and about 225 km (140 miles) north of Perth (Fig. 5).

As elsewhere, the heavy mineral grains were derived from the erosion of granites, intrusives, quartz reefs, and sandstones, and transported to the coast and concentrated by water and wind action. They occur in present-day beaches, fossil beaches, buried strand lines, and coastal dunes, and may be up to nearly 32 km (20 miles) inland as in Western Australia.

Ratios among individuals in Australian heavy

mineral suites vary geographically. For example, between Sydney and Newcastle, rutile and zircon comprise about 90% of the concentrates, while farther north in New South Wales the rutile plus zircon content drops to 60 to 70%. Continuing northward, in southern Queensland the ilmenite level increases to about 60% of the heavy minerals. In the area between Busselton and Bunbury in Western Australia ilmenite makes up about 90% of the heavy mineral fraction, and near Eneabba concentrations contain 40 to 60% ilmenite, and about 10% rutile.

There is also a geographical variation in the chemical composition of ilmenite. Along the east coast ilmenite is generally too high in chromium to be suitable as a raw material for pigments manufacture by the sulfate process, and has found only a limited market in the Japanese steelmaking industry. The chromium content does, however, decrease from south to north, and the ilmenite is apparently suitable for upgrading to rutile grade material by some beneficiation processes. In Western Australia ilmenites from the Bunbury-Busselton area average 54 to 57% TiO_2 , while Eneabba ilmenite grades around 61% TiO_2 .

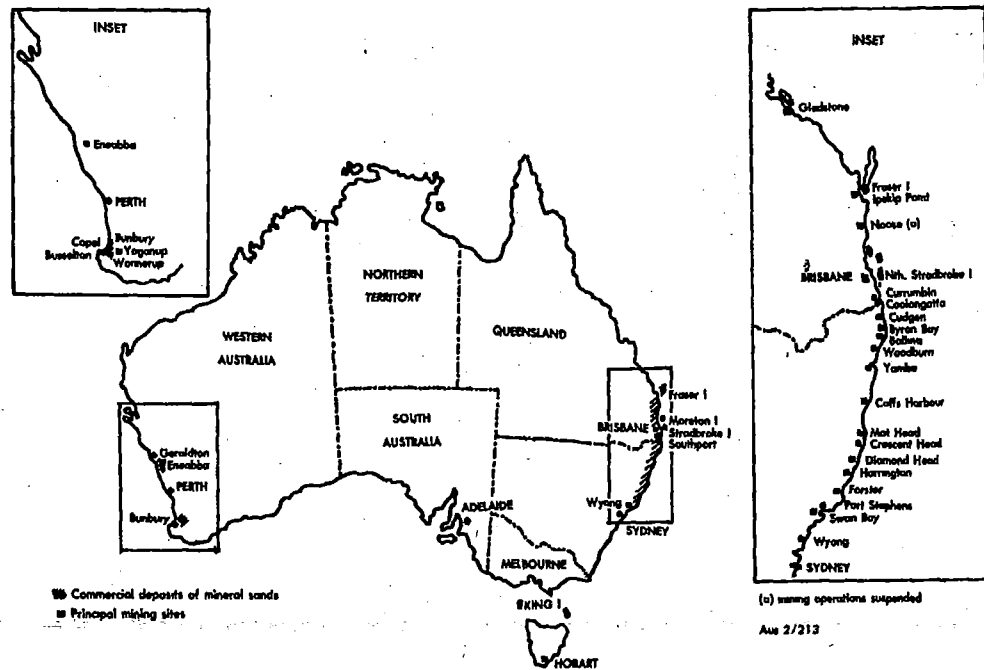


FIG. 5—Location of principal ilmenite and rutile mineral sand reserves and mining operations in Australia, 1980 (Anon., 1980c, and Ward, 1972).

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hically. For example, rutile and ilmenite in New South Wales drop to 60% in southern Queensland. In the area of Bunbury in Western Australia, about 90% of the heavy minerals near Eneabba consist of 60% ilmenite, and

the variation in the grade of ilmenite. Along the coast, the grade is generally too high in a raw material for the sulfate process, a limited market in the area. The chromium content increases from south to north, apparently suitable for the material by some Western Australian operations. The Busselton area and the Eneabba ilmenite

Titanium mineral mining began in eastern Australia in 1934. Ore bodies were modern beach placers containing up to 50% heavy minerals, mostly rutile and zircon. All these high grade deposits have been exhausted over the past 40 years, and the average grade in the east by 1980 was about 3% heavy minerals. The increased cost of working lower grade deposits farther inland has been offset by improved techniques for mining and processing, and some ore bodies containing less than 0.25% TiO_2 as rutile (plus at least as much zircon) are now mined successfully on the east coast. In Western Australian ore bodies titanium minerals must be more highly concentrated because of the relative scarcity of rutile, and although there are wide variations within individual deposits, the average is between 5 and 10% heavy minerals. Mining of heavy mineral sands began in Western Australia in 1956.

The development of the large and important Eneabba ore field began in 1970. Rutile occurs in the heavy mineral suite there with ilmenite and leucosene, so that with full-scale production commencing in 1974 and 1975, Western Australia became an important source of rutile for the first time.

Australia's titanium reserves are shown in Table 15. Table 16 lists company names, locations, estimated reserves, and 1980 production of rutile and ilmenite.

Eastern Australia—Ore bodies are in ancient beaches and bars in New South Wales and parts of Queensland. On North Stradbroke and Fraser Islands they are in high coastal dunes. A variety of mining equipment including dredges, bulldozers, front-end loaders, and bucket wheel excavators is employed by the seven producers.

Associated Minerals Consolidated Ltd. (AMC) is the world's leading producer of rutile and zircon, operating the world's largest mobile sand mineral concentrator on North Stradbroke Island off Brisbane. The suction-cutter dredge is 25 m (81 ft) long and 12 m (40 ft) wide. It is followed by a 34 x 34-m (110 x 110-ft) pontoon-mounted concentrator with a capacity of 1500 stph.

The Forster, N.S.W., mining plant of Mineral Deposits, Ltd., the second largest mineral sand producer in Australia, has a capacity of 900 to 1500 stph. It consists of a suction-cutter dredge, a 400-ton pontoon-mounted surge bin, and a concentrator mounted on a 24 x 31-m (80 x 103-ft) pontoon.

Consolidated Rutile Ltd. mines 91-m (300-

TABLE 15—Titanium Reserves of Australia, Thousands of Short Tons

	Rutile	Ilmenite
East coast	6,500	14,400
West coast	3,500	36,000
Total	10,000	50,400

Source: Anon., 1980b.

ft) dunes on North Stradbroke Island by bulldozer, frequently moving a sand-receiving trommel and slurring unit to keep it close to the mining site. The sand is pumped to a nearby wet concentrator built in several basic units for rapid dismantling and moving a few times a year. Heavy mineral concentrates are barged to the dry mill on the mainland at Meeandah near Brisbane.

The opposition of conservationists to sand mining on Fraser Island led to the withdrawal of export licenses for Fraser Island concentrates at the end of 1976, and to restrictions on sand mining in other areas in Queensland and New South Wales.

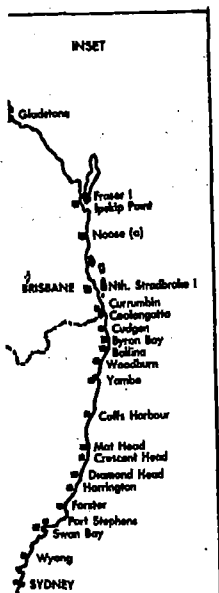
Western Australia—Heavy mineral concentrations occur in three separate strand lines in the Bunbury-Busselton area: the present beach, the Capel line, and the Yoganup line, with the Yoganup line being oldest and 16 km (10 miles) inland. The TiO_2 content of the titanium mineral fraction of the heavy minerals increases with distance from the present coast.

Longshore drift in the area is southward and westward toward Cape Naturaliste, and it appears that longshore currents acting in the past sorted sands brought to the coast by north-westward-flowing rivers, creating heavy mineral deposits along beaches near their mouths. The existence of the old Yoganup and Capel lines indicates two past episodes of shoreline standstill.

There are no mining operations now on the beach. Cable Sands Pty. Ltd. and AMC are mining the Capel line, and Westralian Sands is working the Yoganup line. Both dredging and dry mining with scrapers, bulldozers, draglines, front-end loaders, and backhoes are practiced. In some deposits iron oxide-cemented, hard lenses near the bottom of the ore, which contain up to about 70% heavy minerals, are drilled, blasted, removed from the pits in blocks, and stored for possible future milling.

The Yoganup line sand has a high clay content, requiring dewatering of tailings in a series of large settling ponds. Water is scarce, and is conserved by recycling.

Commercial concentrates of ilmenite, leu-



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mining operations in

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Industrial Minerals and Rocks

TABLE 16—Australian Producers of Titanium Minerals, 1980

Company	Location Mines (m) and Separation plants (a)		Reserves		Production		Associated Companies and Controlling Interests
			Thousand st Rutile	Thousand st Ilmenite	Thousand st Rutile	Thousand st Ilmenite	
East coast							
Associated Minerals Consolidated Ltd.	N. Stradbroke Island, Qld.	m,s	800	2,000	71	NA	Consolidated Goldfields Australia Ltd., 81.7%
	Southport, Qld	s					
	Jerusalem Creek, N.S.W.	m					
	Kempsey, N.S.W.	m					
Consolidated Rutile Ltd.	Hexham, N.S.W.	s	1,100	2,400	60	NA	Cudgeon RZ, 60%, and Union Corp., Republic of South Africa
	N. Stradbroke Island	m					
Currumbin Minerals Pty. Ltd.	Meeandah, Qld	s	200	200	4	NA	Neumann Associate Companies Pty. Ltd.
	Currumbin, Qld	m,s					
Mineral Deposits Ltd.	Kingscliff, N.S.W.	m	900	2,000	50	NA	Utah Mining Australia Ltd., 84%
	Crescent Head, N.S.W.	m,s					
Rutile and Zircon Mines (Newcastle) Ltd.	Myall Lakes/Hawks Nest, N.S.W.	m,s	300	700	39	NA	Peko Wallsend Ltd., 50%, Kathleen Investments Australia Ltd. 50%
	Harrington, N.S.W.	m,s					
Reserves unavailable for mining because of environmental considerations			3,100	7,100	—	—	
Total east coast			6,400	14,400	224	60	
West coast							
Allied Eneabba Ltd.	Eneabba, W.A.	m,s	2,000	10,000	60	325	E. I. du Pont de Nemours, 69%
Associated Minerals Consolidated Ltd.	Capel, W.A.	m,s	1,600	13,000	40	433	Consolidated Goldfields Australia Ltd., 61.7%
	Eneabba, W.A.	ms					
Cable Sands Pty. Ltd.	Capel, W.A.	m	—	2,000	—	191	Kathleen Investments, principal shareholder.
	Bunbury, W.A.	s					
Westralian Sands Ltd.	Yoganup, W.A.	m	—	11,000	—	434	Tioxide Australia Ltd., 40%
	Capel, W.A.	s					
Total west coast			3,600	36,000	100	1,383	
Total Australia			10,000	50,400	324	1,443	

Sources: Anon., 1980b; and industry contacts.

NA = Not available

coxene, zircon, and monazite are produced from this region of Western Australia.

Exploration northward toward Perth and beyond resulted in the discovery of heavy mineral occurrences in old strand lines at Boyanup, Waroona, Bull's Brook, and Gin Gin. Rutile appears significantly in the heavy mineral suites at Bull's Brook and Gin Gin. The ilmenite is reported to be high in chromium content and it could be more suitable as a raw material for beneficiation than for direct sale.

ENEABBA—It was suggested by Lissiman and Oxenford (1973) that the heavy mineral deposits at Eneabba were formed by agencies acting similarly to those which formed the ore bodies in the Bunbury-Busselton area. Rapid erosion of a Mesozoic sedimentary rock highland contributed sand to a westward-flowing stream which emptied into a bay partially protected on the southwest from south-to-north longshore currents by a headland. Longshore drift produced countercurrents within the bay which concentrated black sands on the beaches south of the mouth of the stream. There are several distinct strand lines marked by north-trending bands of high heavy mineral concentration at the bottom of the ore zone, and they

are thought to have been formed during relatively brief periods of sea level standstill. The strand lines are at successively lower levels from east to west. The geologic history of the ore field is made complex by evidence of reworking of the higher strand lines by waves which must have been associated with a sea which rose again, perhaps repeatedly, and by wind which created disseminated heavy mineral sands between and over the strand line deposits. Ore bodies in the northern portion of the district, which is about 16 km (10 miles) long and over 2 km (1½ miles) wide, are thought to have been formed by wind concentration of heavy minerals from black sand dunes then exposed in areas to the south.

Total reserves of the Eneabba district are in excess of 20 million tons of heavy minerals. Rutile, ilmenite, leucocoxene, zircon, and monazite are present in variable proportions from one area to another, but the average ratios may be 1:5:0.2:2:0.2, respectively. Shipments of concentrates are from the port of Geraldton.

The development of Eneabba for mining presented considerable challenge because of its remoteness and relative lack of labor, power, water, transportation, and nearby port facili-

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ties. Furthermore, a portion of the ore, which occurs both in free-flowing sand and in harder, clay-rich sands, is bound up in nodules and in cellular and solid masses of iron oxide-cemented material locally called *laterite*. Extensive pilot testing of concentrating and separating methods and pilot mining were carried out to prove the physical and economic feasibility of heavy mineral operations. Production from Eneabba will make an important contribution to world titanium mineral and zircon markets for the next 15 years and more, and could compensate for diminishing production of rutile and zircon from the east coast.

KING ISLAND—Beach placers containing heavy minerals are located along the central part of the east coast from Naracoopa some 11 km (7 miles) along Sea Elephant Bay north to Cowper Point. The heavy mineral content is high, up to about 60%. Rutile and zircon occur in about equal proportions. Accessory minerals are leucoxene, ilmenite, magnetite, garnet, and cassiterite.

Naracoopa Rutile Ltd., a subsidiary of New Mount Costigan Mines Ltd., mined the sands by dragline and used trucks to haul to a wet plant stockpile. A dry plant had a production capacity of 10,000 stpy of rutile and 10,000 stpy of zircon. In early 1972 Buka Minerals N.L. acquired Naracoopa's mining properties and plant through its subsidiary, Kibuka Mines Pty. Ltd., and recommenced production after a reconstruction program.

China: Coastal sand deposits in Guangdong and Guangxi provinces contain ilmenite, zircon, and other heavy minerals (Brady, 1981).

India: At one time India was a leading producer of ilmenite from the state of Kerala (formerly Travancore-Cochin). The beach sands were mined in the Manavalakurichi (M.K.) area and later the Quilon deposit of ilmenite near Chavra was put into production. These deposits supplied the bulk of the titanium ore used by the US prior to World War II.

The two deposits have more differences than similarities. The ilmenite in the M.K. deposit analysed only 54% TiO₂ and the sand was rich in garnet and monazite. The ilmenite in the Quilon deposit analyzes about 60% TiO₂. The sand carried almost no garnet and is high in monazite in only two places. Analyses of ilmenite from these areas are shown in Table 17.

The M.K. deposit consisted of buried seams of rich black sands at or just above the present ocean level. The beach sands were rich only when the monsoon storms sorted out the light minerals from the heavy ores.

TABLE 17—Ilmenite Analyses, India

	1, %	2, %
TiO ₂	54.1	60.4
FeO	25.6	9.55
Fe ₂ O ₃	15.3	24.6
Cr ₂ O ₃	0.09	0.17
V ₂ O ₅	0.23	0.36

Source: Gillson, 1959.

1. Travancore, "M.K."
2. Travancore; average "Quilon."

The Quilon deposit is not only much larger but the ilmenite is of a better grade. The deposit is a barrier beach extending parallel to the old shore in front of the mouths of two large rivers, the Panalur at Neendakara and Pallikal Todu. The ocean beach is black with layers carrying 80% heavy minerals and dunes on the beach are gray with 40 to 50% heavy minerals. Below them are old beaches now buried under dunes formed before the shore retreated, which are as rich as those now being washed by the waves. The extent of the old buried beaches has never been completely determined.

Malaysia: Substantial tonnages of ilmenite are produced in Malaysia as a byproduct of tin mining either as rough concentrates in mills using magnetic separation techniques or in the form of *Amang*, a crude mixture of heavy minerals which has to be further treated to recover the ilmenite content. The main centers of production are at Perak and Ipoh. The deposits are alluvial in nature.

Sierra Leone: A deposit along the Sherbro River was originally developed as a joint venture of Pittsburgh Plate Glass Co. and British Titan Products. Although relatively high grade ($\pm 1.5\%$ TiO₂) the sands were extremely fine and disseminated in lumpy lateritic clay. Reserves are estimated to be between 3 and 30 million tons of contained rutile. The ore problems plus mechanical and political difficulties caused Sherbro Minerals to shut down in 1971 after only two years of operation.

Bethlehem Steel acquired 85% ownership of the property in 1976 (15% Nord Resources) and conducted an extensive prospecting and geological investigation that extended into 1977, finding higher grade deposits ($\pm 2.5\%$ TiO₂) than that mined by Sherbro. Improvements were made in both the wet and dry flow-sheets and as of 1981 the operation now called Sierra Rutile Limited was approaching specifications and design capacity of 110,000 stpy.

Rutile grades are highest in the topsoil, averaging 2.5% TiO₂, and in the basal sands and gravels, with up to 3.0% TiO₂. The average

olated Companies and
Controlling Interests

olidated Goldfields
alla Ltd., 61.7%

eon RZ, 50%, and Union
p., Republic of South Africa
ann Associate Companies
r. Ltd.
Mining Australia Ltd., 84%

Wallend Ltd., 50%,
teen Investments Australia
1. 50%

du Pont de Nemours, 59%
olidated Goldfields
ustralia Ltd., 61.7%
teen Investments, principal
shareholder.
de Australia Ltd., 40%

formed during rela-
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sively lower levels
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neabba district are in
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zircon, and mona-
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average ratios may
ively. Shipments of
port of Geraldton.
Eneabba for mining
allenge because of its
ack of labor, power,
1 nearby port facili-

grade of the Mogbwemo deposit where Sierra Rutile began mining in 1979 is over 2.0% TiO₂ (Anon., 1981).

South Africa, Republic of: Shipments of rutile and zircon were started in 1977 from the Richards Bay mineral sands operation in Natal. Richards Bay Minerals manages the combined affairs of Tisand Pty. Ltd. and Richards Bay Iron and Titanium Pty. Ltd., the companies responsible for the operation of the mine and the smelter, respectively. A high-TiO₂, low-magnesium-plus-calcium slag (RB slag) containing 85% TiO₂ has been produced from ilmenite since 1978, and is reportedly suitable for use in either the sulfate or chloride titanium dioxide pigment processes. Since 1980, production rates have approached planned annual capacities of 440,000 tons of RB slag, 220,000 tons of low-manganese iron, 53,000 tons of rutile, and 110,000 tons of zircon. Proven reserves were estimated at 770 million tons grading 5% ilmenite, 0.3% rutile, and 0.65% zircon. Principal shareholders at the end of 1980 were QIT-Fer et Titane, Inc. (32%), General Mining Union Corp. (30%), and the Industrial Development Corp. of South Africa Ltd. (16%).

Operations in 1980 were in an area 17 km (11 miles) long and 1 km (0.6 miles) wide adjacent and parallel to the shoreline. The ilmenite, rutile, and zircon, along with magnetite, are evenly distributed throughout the sands which occur as dunes up to about 38 m (125 ft) in height on a clay base (Anon., 1980d).

Sri Lanka: Sri Lanka contains extensive beach deposits of titanium-bearing sands at Pulmoddai, Tirukkovil, Kelani River, Kalu River, Modoragam River, Kudremalai Point, Negombo, and Induruwa.

The Pulmoddai area contains 5.6 million st of titaniferous material with 2.451 million st of contained TiO₂. The deposit extends for a distance of 7 km (4½ miles), has a maximum width of about 91 m (300 ft), and a thickness of about 2.4 m (8 ft). There is no overburden. The deposit contains about 80% ilmenite and rutile. The average mineralogical composition of the black sand is as follows (Anon., 1974):

Ilmenite	70-75%
Rutile	10-12%
Zircon	8-10%
Sillimanite	±1%
Monazite	±0.4%

Other minerals present include spinels, garnet, tourmaline, etc., with quartz and shells as the main waste materials.

The separation of rutile has been adversely

affected by the presence of excessive amounts of residual ilmenite and quartz in the tailings. The separation of zircon has been hampered by inadequate water and insufficient wet tabling equipment to handle the extremely fine-grained Pulmoddai ore.

Sand Deposits—Potential Sources

Brazil: Brazilian deposits of heavy minerals on ocean beaches occur in a zone about 161 km (100 miles) long, extending north from the northeast corner of the state of Rio de Janeiro up into the state of Espirito Santo as far north as the Rio Doce. There is also a zone in southern Bahia. Deposits are known to exist near Natal in the state of Rio Grande do Norte. Fig. 6 shows the location of the ilmenite deposits of Brazil (Gillson, 1950). Rutile deposits also are found in the state of Goias.

The minerals of the Brazilian beaches are:

Mineral	% Heavy Mineral
Magnetite	tr to 3
Ilmenite	35-75
Monazite	1-20
Zircon	5-35
Rutile	1/2-5
Sillimanite	1-1/2-5
Kyanite	1/2-2
Corundum	tr-1/2
Spinel	1/4-5
Staurolite	tr-3
Others	tr-3

The ilmenite assays from 39.7 to 61.6% TiO₂. Table 18 lists Brazilian ilmenite and rutile analyses.

Egypt: Rich deposits of black sands occur along the northern beaches of the Nile Delta for about 241 km (150 miles). There are two types: one is dark in color and contains about 70 to 90% heavy minerals and a second which is grayish-yellow to dark gray and contains about 40% heavy minerals. The deposits cover areas 10 km (6 miles) long and a few meters (yards) wide and up to 0.5 m (1½ ft) in thickness.

The black sand concentrate is composed of ilmenite, magnetite, zircon, rutile, monazite, and garnet. Analysis of typical concentrates follows:

Ilmenite	—55%
Magnetite	—15-20%
Zircon	—7-8%
Garnet	—4-6%
Rutile	—1.5%
Monazite	—0.5-1%

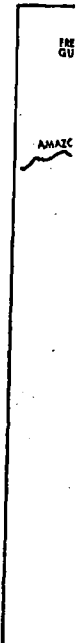


FIG. 6

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TiO₂
FeO
Fe₂O
SiO₂
CaO
MnO
MgO
H₂O
H₂O⁺

Source

1. Ilr
2. Ilr
3. Ilr
4. Ilr
5. Ilr
6. Ilr
7. Ma
8. Ilr

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of excessive amounts of quartz in the tailings. This has been hampered by insufficient wet tabling and extremely fine-grained

Sources

Sources of heavy minerals in Brazil are in a zone about 161 km long extending north from the mouth of Rio de Janeiro to Santo as far north as also a zone in southern Brazil known to exist near Rio Grande do Norte. In the northern part of the ilmenite deposits (de-1950). Rutile deposits are found in the state of Goiás.

Brazilian beaches are:

- % Heavy Mineral
- tr to 3
- 35-75
- 1-20
- 5-35
- 1/2-5
- 1-1/2-5
- 1/2-2
- tr-1/2
- 1/4-5
- tr-3
- tr-3

from 39.7 to 61.6% Brazilian ilmenite and

of black sands occur in the delta (about 100 miles). There are two colors of sand and contains about 10% of black sand and a second which is dark gray and contains 10% of black sand. The deposits cover a long and a few meters to 0.5 m (1 1/2 ft) in

concentrate is composed of ilmenite, rutile, monazite, and garnet of typical concentrates

- 55%
- 15-20%
- 8%
- 6%
- 5%
- 0.5-1%



FIG. 6—The heavy mineral deposits of Brazil (Gillson, 1950).

New Zealand: Ilmenite and associated heavy minerals are found in New Zealand on the west coast of South Island from Jackson Bay to Karamea and on the west coast of North Island at the mouth of Waikato River, Muriwai, and at Manukan Heads. Total reserves near Westport are estimated to be between 17 to 31 million tons. Tests of the sand from Westport indicate the titanium content of the ilmenite averages about 47%.

Approximately one billion tons of sand are available between Karamea and Jackson Bay from which ilmenite could be recovered. These deposits on the west coast of South Island are believed to be one of the world's major reserves of low chromium ilmenite.

South Africa: Ilmenite-bearing sands occur in scattered deposits along the east coast of the Republic of South Africa from the area of East London to the Mozambique border and northward. Ilmenite sands also occur along the west coast particularly in the Vannhydororp district.

Titanium minerals are found on the east coast in three types of deposits:

- 1) Older red and brown coastal sands.
- 2) Recent dunes and beach sands.
- 3) Alluvium in coastal lagoons.

Older red and brown coastal sands occur in a belt of undulating fixed dunes which is roughly parallel to the coast. The belt ranges from a few meters (yards) to 6 km (4 miles) or more in width. Some dunes are as high as 152 m (500 ft) high but the average height is much less.

The heavy mineral content varies from 2 to 25%. The heavy mineral content is about:

- Ilmenite—70-80%
- Leucocoxene—2-5%
- Rutile—2-5%
- Zircon—8-10%
- Magnetite—2-8%
- Monazite—tr-0.3%
- Garnet, pyroxene, etc. 1-5%

Recent dunes and beach sands are partially derived from the older sands and contain the same mineral suites.

TABLE 18—Rutile and Ilmenite Analysis, %, Brazil

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
TiO ₂	58.5	61.6	55.6	38.9	66.5	70.5	79.3	69.0	75.2	96.7	92.9	93.5	97.8	97.1	95.6
FeO	35.4	32.0	36.6	—	26.2	24.6	19.8	30.9	21.7						
Fe ₂ O ₃				44.2	1.8					2.0	6.8	6.6	2.3	3.0	3.4
SiO ₂	0.2	2.5		4.0	5.2					0.5	0.4	0.1	0.2		0.7
CaO	0.9														
MnO	0.1														
MgO	2.5														
H ₂ O-110°	0.1														
H ₂ O+110°	2.7														

Source: Abreu, 1962.

1. Ilmenite from coastal sand, S.G.
2. Ilmenite and rutile, Bom Jardim, M.G.
3. Ilmenite from Pissaguera, P.R.
4. Ilmenite from São Sebastião, S.P.
5. Ilmenite and rutile, Bom Jardim, M.G.
6. Ilmenite and rutile, Anápolis, G.O.
7. Material from riverbed, Rio Grande, M.G.
8. Ilmenite and rutile, Santa Quitéria, C.E.
9. Ilmenite and rutile, Neópolis, S.E.
10. Rutile, Mossamedes, G.O.
11. Rutile, Mossamedes, G.O.
12. Rutile, Corumba, G.O.
13. Rutile, Pirenópolis, G.O.
14. Rutile, Santa Luzia, G.O.
15. Rutile, Average of shipment from G.O.

Ilmenite concentrates occur in the alluvium in coastal lagoons, i.e., lagoon sands and in the bars at river mouths.

On the west coast, ilmenite-bearing sands exist in the Vannhydrodorp District between Strandfontein and the mouth of the Zout River. One deposit, a recent dune, skirts the coast for 6 km (4 miles) and another on the Geelwae Karoo is found in a narrow modern beach about 8 km (5 miles) long. The sands are unconsolidated and fine to medium grained.

Analyses of ilmenites from South Africa are shown in Table 19.

Titaniferous sandstone containing up to about 50% ilmenite with lesser amounts of rutile and zircon occur in the Ecca series of the Karoo system. They outcrop in several areas, principally near Bothaville about 483 km (300 miles) from the east coast in the Orange Free State. Total reserves are estimated at 85 million tons of material, some of which might be recovered with future technological improvements.

The Cape Morgan Titanium Mining Co. has produced a small amount of ilmenite in the Komga District from coastal sands.

Uruguay: Black sands are found northeast of Montevideo at Agua Dulces, in the state of Rocha. The sands extend along the coast for a distance of 11 km (7 miles) with an average depth of 5.5 m (18 ft). Reserves are estimated at 3.3 million tons of heavy minerals, with an average 2.5% heavy mineral concentrate. The composition of the heavy mineral fraction is approximately:

Ilmenite	60%
Zircon	5%
Rutile	1%
Monazite	0.6%

In addition, titanium sand deposits are known to exist in the following areas:

China: At Luanping and Chente, and the coast of Jiangsu province.

Korea: Resources of 2,535,000 tons with 507,000 tons of contained TiO_2 .

Mozambique: Rutile and ilmenite are known to exist on the coastal beaches of Mozambique north of 16° 30' latitude and near Vila Luisa, about 40 km north of Lourenco Marques.

TABLE 19—Analyses of South African Ilmenites

	1, %	2, %	3, %
TiO_2	50.5	46.6	41.6
FeO	38.2	39.51	34.1
Fe_2O_3	9.2	9.11	19.7
Cr_2O_3	0.2	0.10	0.0
V_2O_5	0.12	2.76	0.92

Source: Anon., 1959.

1. Ilmenite concentrate, Umgababa, Natal; Analysis Government Laboratory, Malaya.
2. Ilmenite concentrate, Isipingo, Natal; analysis, Div. of Chemical Services, Pretoria.
3. Ilmenite fraction, Vannrhynsdorp District, Cape Province; analysis, Div. of Chemical Services, Pretoria.

USSR: Black Sea deposits; Aldan River; Boludka River; Pit River in Siberia; Sylvista River; Chusovaya River; and Vizhai River in the Urals.

Exploration and Evaluation

Hardrock Ilmenite Deposits

Hardrock ilmenite deposits, because of their inherent magnetic properties, are readily amenable to the application of aero and ground magnetic geophysical surveys. With few exceptions, these deposits respond to such an application by reflecting abnormally positive magnetic intensities (gammas).

Examples can be cited, however, where negative magnetic anomalies are associated with such deposits. In such cases, the ore occurs either as a titaniferous-hematite concentration or a titaniferous-magnetite occurrence when the titanium content is greater than the iron content. Theoretically, it would seem possible that a commercial deposit may exist where no magnetic response would be obtained. Such a deposit has not yet been found.

Once such anomalies are mapped, further exploration may take place in the form of detailed surface geological observations and ultimate drilling to first test the anomalies and hopefully to delineate a viable ilmenite deposit.

MacIntyre Development: The original discovery of magnetite-ilmenite deposits at MacIntyre Development, Tahawus, NY, was made from surface outcrops. Extension of these outcrop locations has been made through use of geophysical methods and diamond drilling.

Geophysical—Since the ore is magnetic, the geophysical methods used have been for the purpose of outlining magnetic anomalies. Early work was by dip needle readings over a grid

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South African Ilmenites

2, %	3, %
46.6	41.6
39.51	34.1
9.11	19.7
0.10	0.0
2.76	0.92

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lalaya.
ngo, Natal; analysis, Div.
ria.
isdorp District, Cape
mical Services, Pretoria.

deposits; Aldan River;
in Siberia; Sylvista
; and Vizhai River in

d Evaluation

deposits

deposits, because of their
ties, are readily amen-
of aero and ground
veys. With few excep-
spond to such an ap-
ormally positive mag-
s).
l, however, where nega-
s are associated with
cases, the ore occurs
hematite concentration
etite occurrence when
greater than the iron
it would seem possible
posit may exist where
ould be obtained. Such
en found.
s are mapped, further
lace in the form of de-
al observations and ul-
test the anomalies and
viable ilmenite deposit.
ment: The original dis-
nenite deposits at Mac-
ahawus, NY, was made
s. Extension of these
been made through use
ls and diamond drilling.
the ore is magnetic, the
sed have been for the
agnetic anomalies. Early
ile readings over a grid

pattern extending outward from surface out-
crops. With the advent of the aerial magnetom-
eter the entire property was flown. This pro-
duced anomalies well beyond any previous
work extending to areas of deep overburden
and under-lake area.

Aerial work was followed with detailed
ground magnetometer readings taken on 15-m
(50-ft) spacings along section lines 30 m (100
ft) apart. This served to guide the location of
diamond drill holes for exploratory drilling on
one or two sections with drill holes spaced
122 m (400 ft) apart on section.

The initial ground magnetometer work on
any anomaly is a section across the center of
the anomaly at right angles to the long axis in-
dicated from aerial work. The magnitude and
gradient of the ground anomaly compared to
the magnitude and gradient of the aerial anom-
aly, along the same section, gives an indication
of depth and configuration of the source of the
anomaly.

Drilling—If initial diamond drilling indi-
cates an economic deposit, development drilling
proceeds on a set grid pattern of 61 or 91 m
(200 or 300 ft). Intermediate holes are drilled
where necessary to fill in major gaps in geo-
logic interpretation of structure, or ore con-
tinuations.

Core Sampling—Drill cores are visually
logged and split for chemical assay. In ore
areas, samples are taken of the entire core and
composited in 1.5-m (5-ft) intervals for assay.
In waste areas samples may be taken every
1.5 m (5 ft) and composited for a maximum
of 8 m (25 ft) of core. Routine assaying is
done to determine TiO_2 and total iron content.
Based upon past experience, the nominal cut-
off for ore is 13.5% TiO_2 .

Mill Testing—Metallurgical laboratory work
is done using core assay rejects to determine
milling characteristics. Concentrates from the
laboratory work are used for testing end use
performance. Complete analyses are run on
concentrates to determine presence and quan-
tity of detrimental elements.

Tellnes Deposit, Norway: The Tellnes il-
menite deposit near Hauge-I-Dalane in Norway
was discovered in 1954 as a result of an air-
borne magnetometer survey carried out for
Titania A/S, with the object of locating new
sources of ilmenite to provide an alternative
to developing additional underground ore at
Storgangen. Anomalies were also found at
four other locations, so that ground geological
study and diamond drilling had to be done at
all of these sites to be certain that the best

deposit was selected for development. A total
of 10,058 m (33,000 ft) of drill holes was
completed in 1956, and showed the total
amount of ore in the Tellnes deposit to be
about 300 million tons, averaging 18% TiO_2
(Brun, 1957; Anon., 1978a).

Allard Lake (Lac Tio) Deposit, Quebec:
Ground Surveys—Preliminary investigation of
the original ilmenite discoveries at Allard Lake
(Hammond, 1949), indicated that all of these
were too small to be of commercial importance.
A detailed exploration program was carried
out in 1946 to more thoroughly explore the
area of 647 km² (250 square miles) where
ilmenite had been found along certain of the
lakeshores.

Geologic prospecting parties carried out
traverses originating from the shores of the
larger lakes, at 0.4-km (¼-mile) intervals in
an east-west direction, normal to the strike of
the previously known ilmenite occurrences.
Mapping along and on both sides of the line
of traverse was supplemented by dip needle
readings at 61-m (200-ft) intervals or less. This
work resulted in the discovery of eight ilme-
nite deposits, among them the very large Lac
Tio deposit.

Drilling—A diamond drilling program fol-
lowed to explore the Lac Tio deposit in depth.
A series of vertical holes was drilled at 61-m
(200-ft) intervals along five east-west sections
to an average depth of 91 m (300 ft). Cores
were sampled in 8 m (25-ft) lengths where ore
intersections were sufficiently long. The spe-
cific gravity was determined on all samples be-
fore shipment for analysis. Later drilling on
the portions of the ore body to be mined was
carried out on a 15-m (50-ft) grid pattern.

Core Testing and Grade Control—Because
of the marked difference in specific gravity be-
tween ore and gangue, it was found that densi-
ty measurements gave a reliable measure of
ore content. The accuracy of the method is
about 2%, sufficient for the method to be used
for controlling grade during mining.

Aeromagnetic Survey—An airborne magne-
tometer survey was carried out to explore the
remainder of the anorthosite mass for other
ilmenite deposits closer to the coast which
might be developed more economically. Flight
traverses were flown in a northwest-southeast
direction at 152-m (500-ft) elevation, complet-
ing some 7200 km (4500 miles) of air traverse
in a two-month period. The survey was first
carried out over the known ore occurrences to
obtain an indication of what results to expect
from a new ore body.

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Industrial Minerals and Rocks

No new deposits were discovered as a result of the aeromagnetic survey, but strong negative anomalies were obtained over all the known major ore bodies. Areas of disseminated ilmenite in anorthosite generally showed positive magnetic anomalies.

Otanmäki Deposit: The Otanmäki ilmenite-magnetite deposit and a neighboring deposit at Vuorokas were discovered in 1938 as a result of magnetic surveys by the Geological Survey of Finland (Harki et al., 1956).

Sand Deposits

Exploration: There are only a few large areas of the world where the granite-clan rocks and high-grade metamorphic gneisses which are likely to contain ilmenite (not titaniferous-magnetite) and rutile are close enough to continental margins to have contributed their erosion products to the sediments of coastal plains. Well-sorted sands are much more likely hosts than unsorted sands. These are the areas on which exploration efforts should be focused. Since the alteration of ilmenite to remove iron is aided by humic acid developed by the decomposition of organic material near the water table in hot and humid climates, it follows that the highest TiO₂ ilmenites are more likely to be found in the tropical and temperate regions of the world.

Titanium minerals are dark-colored and their concentration, as in black beach sands, tends to be fairly readily noticeable against the light brown or white quartz. Many sand ore bodies, therefore, have been discovered through surface observation of high-grade placer zones formed on beaches and along the courses of streams, and by following their traces into the larger, lower grade concentrations which constitute economic ore bodies.

There are areas in which potential heavy mineral concentrations in ancient beach sands may be masked by younger sand, gravel, or soil. Exploration under these circumstances then involves interpretation of geomorphic and subsurface geologic data to define areas which could have been beaches or dunes in the past, and then drilling to obtain samples.

Field Techniques—In areas where heavy mineral concentrations are suspected but where the concentration level is difficult to estimate because of dissemination, as in dunes, hand panning of samples is an excellent method of rapidly producing a clean concentrate. A hand magnet gives a quick identification between ilmenite and magnetite or titaniferous-magnetite. The presence of potentially valuable by-

product zircon, monazite, kyanite-sillimanite, etc., can be determined with a hand lens. A Geiger counter or Scintillometer also helps in identifying radioactive minerals such as monazite and zircon. Wind and current action can develop very high-grade layers of heavy minerals on the surface which have no economic significance; thus samples for panning and examination should be taken from the maximum convenient depth. Often an idea of the vertical distribution of heavy minerals can be gained from observation of wave-cut cliffs in sands behind the beaches, cutbanks in stream margins, road cuts, construction excavations, and material encountered in sinking or drilling wells. Dark, heavy minerals may even be observed in the sand brought to surface by burrowing insects and small animals.

Hand augering with a two-man crew is possible to a depth of 6 m (20 ft) or more with a jointed auger stem and is reasonably rapid and inexpensive. Some heavy-mineral bearing sands contain so much clay that they are difficult to hand auger and a mechanical auger mounted on a light off-the-road vehicle (like a post-hole digger) is preferable. The samples so obtained are not precise because of the contamination of the hole by sand falling into it. The hole cannot be advanced nor reliable samples obtained below the water table when the material is free-flowing and easily disturbed by the auger.

Drilling—For the first phase of development, drilling equipment should have a depth capability of at least 15 m (50 ft) and preferably 30.5 m (100 ft). The selection of the type of drill will depend upon the "stiffness" of the ground as influenced by clay, hardpan, caliche, indurated and iron-oxide cemented layers; the presence of roots, stumps, and other organic material; as well as upon the elevation of the water table.

The truck-mounted jet drill is a popular exploration and development tool of the southeast US. One-inch flush-jointed steel pipe, with a chisel lower end or bit and perforations near the bit to permit water to jet forward and downward, is attached to a hammer of about 136 kg (300 lb) which is activated in 0.3-m (1-ft) strokes by a hand-held rope about a capstan winch. Water is supplied to the bit by a swivel connection above the hammer and by a duct through it. As the hammer rises, falls, and turns, it causes the bit to chop and churn into the ground and drives a 59-mm (2-in.) casing downward. The water pipe is within the 59-mm (2-in.) casing. The bit of the water pipe is

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Drill is a popular ext tool of the south-nted steel pipe, with nd perforations near to jet forward and a hammer of about 3 activated in 0.3-m old rope about a cap-plied to the bit by a e hammer and by a mmer rises, falls, and chop and churn into 9-mm (2-in.) casing is within the 59-mm of the water pipe is

about 25.4-mm (1-in.) or less ahead of the casing when casing and hammer are in contact. The sand sample is flushed out of the hole continuously by water rising in the annulus between water pipe and casing, and is collected at the surface in vessels or tubs. A jet drill under favorable conditions with short moves between holes can drill about 61 m/d (200 fpd) of hole. Its disadvantages lie in its inability to penetrate very hard layers, and the casing can stick in tenacious clay.

The auger-within-an-auger type of drill has good depth and penetration capabilities, particularly in the less free-flowing sands. The internal auger is advanced about 1.5 m (5 ft) to collect a sample on its flights, then the external auger is put down to the same depth to form a casing, and the internal auger is withdrawn for sample collection. There is some possibility of particularly fluid sands below the water table invading the casing when the internal auger is raised.

In Australia extremely light, gasoline-powered augers, portable and operable by two-man crews, have been developed and used for rapid, low-cost depth investigations. They are particularly successful in high, clean dunes.

A truck-mounted rotary drill driven by rapid strokes of a hydraulic hammer is also very useful. The drill string is a double pipe, and compressed air forced down the inner pipe returns the sample in the annulus between the drill-pipe and casing. A drag bit with hardened cutting edges may be used.

It is important in all types of machine drilling to avoid contamination of samples by material originating higher in the walls of the hole. The hole and casing should be flushed free of loose sand after collecting each sample, and before the bit is advanced farther.

The nature of the sand and other materials penetrated by the drill is usually logged by a geologist, who makes a rough estimate of heavy mineral content and variation by panning a small portion of each sample.

Depending on hole diameter, a 0.9 or 1.5-m (3 or 5-ft) sample may be too large for laboratory requirements. If so, a simple heavy duty rifle may be used to reduce the weight to about 2 kg (5 lb). The bulk of the samples may then be bagged or drummed and left at the hole site for future reference.

Geophysical Techniques—Some titanium mineral ore bodies contain sufficient iron to be detectable by magnetometers in ground or airborne surveys, but many are too dilute and shallow to respond.

If monazite or radioactive zircon is present, low-level radiometric surveys may help in exploration. Scintillometers and Geiger counters are sometimes useful on the ground to define horizontal limits of ore and to detect internal variations in heavy mineral concentrations close to the surface.

The problem of downward contamination during drilling can lead to a misrepresentation of the total depth of ore because the heavy minerals, being higher in specific gravity, are hardest to remove by flushing with air or water and may be reported even when the hole has been advanced into barren underlying sand. A scintillometer probe with a surface recording instrument can show a sudden decrease in radioactivity from the walls of the hole at the true bottom of the ore. Radiometric surveying of all or at least some of the holes drilled during development of an ore body is a highly desirable check on the fidelity of drilling and sampling.

Evaluation of Deposits: An economic titanium mineral deposit must have reserves large enough to support depreciation over a period of at least 10 to 20 or more years. The capital investment in 1980 was in the range of \$75 to \$80 million in the US for a mine and mill plant with an output of 100 to 200 thousand stpy of ilmenite (or equivalent rutile) with given "normal" geologic parameters. Significant contributions can be made by zircon and other byproducts. Another general rule is that a new and separate ore body, if its production is to be all ilmenite which cannot be treated in an existing mill, should have a minimum reserve of about 1 million tons of recoverable TiO₂ in the titanium minerals. Small, high-grade concentrations are uneconomic under the present conditions.

The definition of economic reserves depends, of course, upon many factors, among them:

- 1) Cost of mining and milling, as influenced by depth of overburden (if any); cost of surface and mineral rights; and availability of water, power, labor, and transportation facilities for bulk shipments.
- 2) Recoverability in mining and milling.
- 3) Cost of treatment and disposal of waste slimes.
- 4) Cost of waste water treatment and land reclamation.
- 5) Distance to markets and cost of transport.
- 6) Ability of markets to absorb the type of titanium minerals to be produced, and prevailing prices for titanium minerals and byproducts.

Specifications—In the titanium mineral industry, as in some others, grade and reserve do not completely define the quality of a deposit. Titanium minerals for pigments manufacture must meet specifications regarding those chemical elements which would reduce the whiteness of the titanium pigment. These include chromium, manganese, vanadium, and columbium. To be considered economic for the chloride process, the ilmenite product should contain at least 60% TiO_2 .

There are no industry-wide specifications for ilmenite in the pigments industry. Usually consumers and producers establish typical, maximum, and minimum levels, for TiO_2 and other oxides in the concentrates, in separate purchase contracts. In general terms, ilmenites containing not more than a few tenths of 1% of the elements—chromium, manganese, vanadium, and columbium—may be marketable. A few tenths of 1% of the oxides of aluminum and phosphorus may also be acceptable.

In ilmenite the ratio of ferric to ferrous oxide is important. Ferric oxide is objectionable in the sulfate process because it must be reduced to the ferrous condition in the processing, and this requires more handling and increases cost.

TiO_2 concentrates used in the chloride process (including ilmenite) must be low in Ca, P, and Mg. During chlorination, calcium and magnesium form gummy substances which cause plugging difficulties and which cannot be removed easily.

Thus, it is extremely difficult to generalize, since conditions and costs vary widely in different parts of the world, but some *minimum* guidelines for the industry in typical locations are about as follows:

Southeastern United States

Recoverable reserves, contained TiO_2 : 1 million tons.

Average heavy mineral content: 3–4%, cutoff of 2%.

Average TiO_2 content of raw ore: 1% or a little less.

Average depth of ore: about 5 m (15 ft) for dredging, with a cutoff at 1.5 m (5 ft).

Eastern Australia (Rutile and Zircon)

Recoverable reserves, rutile: about 300 thousand tons.

Average heavy mineral content: 1%, cutoff around 0.5%.

Average TiO_2 content of raw ore: about 0.5%, cutoff around 0.2%.

Western Australia (Ilmenite, Altered Ilmenite, Rutile, and Zircon)

Recoverable reserves, heavy minerals: about 3 million tons.

Average heavy mineral content: about 5%, cutoff around 2.5%.

Clay minerals or slimes in heavy mineral sands are important because they must be removed. In addition, the disposition often calls for impoundment, sometimes with flocculation, and dewatering. Clay and other slimes require extra equipment and cost for removal and disposal, obscure the vision of operators who keep the equipment adjusted, and reduce the specific gravity contrast. Particle coatings make high tension separation more difficult, and in the case of zircon, may affect the sales value of the mineral. It is not unusual to find clay contents of 15% by weight, and some ore sands, notably at Eneabba in Western Australia, contain up to about 30% slimes in some places.

Particle size, shapes, and grain size distribution of the ore minerals can affect both mill recovery and marketability. Relatively coarse, well-rounded, uniformly sized grains are generally most desirable. A titanium mineral concentrate with the majority of the grains passing a 200-mesh screen may have limited market appeal, particularly to pigments manufacturers using the chloride process. The finer the particle size the more difficult it is to achieve good recovery in the three kinds of concentrating equipment normally used: gravity, high-tension, and magnetic.

Coating of particles by iron oxide or by secondary silica can change their natural magnetic and electrostatic properties, and such coatings may require removal prior to separation. Iron oxide cementation may produce nodules, cellular or even uniform masses of material so hard that the deposit requires drilling and blasting in mining. Liberation of grains can be poor in milling.

Angular minerals are more troublesome to separate in both wet and dry equipment and increase maintenance costs due to abrasion wear in pumps, screens, and piping.

Deposits in which a high proportion of the titanium content is in the form of secondary anatase present recovery problems. The anatase is the result of natural weathering of ilmenite and is both fine-grained and friable.

Testing and Evaluation—The number of drill holes required to give confidence in ore reserve calculations will vary directly with the irregularity of the deposit in depth, heavy mineral content, clay content, degree of concentration or development of hardpan or caliche, and abundance ratios among the members of the

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Titanium Minerals

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heavy minerals: about 3

Iron content: about 5%,

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heavy mineral suite. Ore bodies tend to be several times greater in length than in width, reflecting their origins in narrow beach zones. The frequency of holes across the strike in the direction of most rapid change in physical characteristics should be much greater than along the strike. Where physical conditions such as the absence of swamps or particularly steep dune slopes permit, a regular grid system of drilling leads to simpler and probably more reliable ore reserves estimates. Holes at 30.5 m (100-ft) intervals along lines spaced 91 m (300 ft) apart have been found to make a good pattern in some deposits. Reserves in other deposits have been defined with holes at 15-m (50-ft) intervals on lines 152 m (500 ft) apart.

There are two common tests for ore or non-ore indications: weight percent of heavy minerals as determined by separation in bromoform or acetylene tetrabromide (which has a slightly higher specific gravity and separates shell fragments from minerals more effectively) and weight percent TiO_2 in the raw sand by wet chemical analysis. Both imply a knowledge of the mineralogical composition of the heavy mineral suite. Thus the total heavy minerals or total TiO_2 can be more or less directly related to weight percent of titanium minerals in the sand. In new areas either or both of these tests should be preceded by petrographic examination of heavy mineral concentrates from panned samples.

Once the presence of ore has been indicated and drilling changes from exploration to development, material handling and rapid analysis become critical, as up to about 50 samples a day, each representing 1.5 m (5 ft) of hole, can be generated by a single drill. Each sample should be dried, weighed, and screened to remove coarse particles. It is then slurried, agitated, decanted to remove slimes, dried, and weighed again. The original weight minus the weight of the coarse fraction and the weight of the dry sample after desliming gives the weight of slimes. The sample may then be split to a convenient size, say 50 g, for heavy mineral determination. The "sink" fraction is washed, dried, and weighed, and its weight related to that of the original dried sample.

Heavy mineral concentrates from samples from one out of every few holes should be petrographically examined and their mineralogical compositions determined by grain counting. Magnetite, which can be mistaken for ilmenite under the microscope, and ilmenite, which can be difficult to differentiate from rutile, may be removed as discrete fractions

with different settings of a magnetic separator prior to petrographic study. Grain counting should be by skilled technicians, and all laboratory personnel should be alert to the possibility of the introduction of error due to coatings of iron oxide, silica, and clay. An acid or caustic attrition scrub of the heavy mineral concentrate can improve the accuracy of identification. Data gathered in such detailed studies of both titanium minerals and byproducts can be valuable in guiding mining operations. The information is highly susceptible to computer analysis for projections of production rates and economics.

The precise methods of laboratory tests outlined can produce determinations of heavy mineral contents higher than those obtained in later production. The difference is due in part to recoverability in the concentrator phase of milling. The addition of a mechanical heavy mineral concentrator such as a jigging table or a spiral to the sample analysis flow pattern after desliming and before separation in a heavy liquid can lead to a better early knowledge of recoverable reserves.

The weight of sand per unit volume varies among ore bodies, and the volume to weight conversion factor for reliable ore reserve calculations should be established by careful measurement of excavated volumes of representative sand types, and by averaging their dried weights. In the southeastern United States the factor varies from 41 to 45 kg (90 to 100 lb) per 0.03 m^3 (cu ft). Exceptionally high grade sands have higher densities.

There is enough difference in physical characteristics of heavy mineral deposits that the best mining and milling methods for a new discovery may not be obvious. Pilot tests, either by commercial consulting organizations specializing in heavy mineral treatment and mill flowsheet design, or in a pilot plant erected at the site, are extremely valuable.

Garnar (1978) outlined a laboratory procedure for determination of separation characteristics, using a sample large enough to furnish at least 2 kg (5 lb) of heavy mineral concentrate. The heavy minerals are concentrated on a laboratory size shaking table, then split magnetically at 7,000 gauss to separate the ilmenite. The magnetic portion is passed over a laboratory high tension unit and the conductor fraction cleaned. The final conductor fraction is examined under the microscope, and if it contains 98% or more opaques, it is probably free from surface coatings that could interfere with dry milling. If coatings are pres-

ent they may be removed by high energy attritioning. However, some ores may require treatment with acid or sodium hydroxide to remove coatings.

Material for pilot tests may be gathered by excavation with standard earth moving equipment or, preferably, by sinking numerous regular, vertical pits through the ore body by backhoe and/or by hand. Cribbing or concrete culvert sections may be necessary to keep the pits from caving. Pit walls can be channel sampled and the collected sand assayed to check results from nearby drill holes. This provides confidence in exploration and development drilling and sampling.

The degree of alteration of ilmenite in the deposit, together with the presence or absence of rutile, will determine the TiO_2 level of the concentrates that can be produced. Pilot plant work should be directed to production of various concentrates and testing the marketability by close communications and providing bulk samples, up to a few thousand tons, to consumers. Technical liaison between would-be producer and consumers is vital at this stage.

Complete chemical analysis should be performed on all potential products. The most sensitive elements in titanium mineral concentrates which can affect the whiteness of the pigment or interfere with the pigment manufacturing process include chromium, calcium, and magnesium. Some pigments manufacturers permit only a few tenths of 1% of these elements in their raw materials. The sum of the oxides of iron and titanium is employed as a measure of the purity of titanium mineral concentrates in some cases.

Because titanium minerals have various physical and chemical properties, each mineral product is not always suitable for utilization by each consumer. There is considerable latitude and flexibility in some instances because of highly developed technology, but most pigments manufacturing plants operate within narrow limits as far as the quality of the raw material is concerned. Usually both the raw material and the plant have to be tailored to fit one another, and in all cases the chemical and physical properties of a titanium mineral product have to be well-known to enable a manufacturer to judge its suitability. In a relationship such as this, naturally the best way to effect accurate evaluation of a titanium mineral deposit is through very close cooperation between would-be producer and would-be consumer, through all stages of exploration, bulk sample testing, development, and plant design and operation.

Evaluation of Results: The titanium mineral industry is restricted, with relatively few producers worldwide supplying relatively few consumers. Evaluation of a newly discovered and developed deposit is therefore undertaken within a narrow framework of economic and materials supply considerations. Present and future prices for products and byproducts under long-term purchase contracts have to be established with pigment manufacturers, and production rates forecast from pilot plant information. All aspects of production costs including those involved with pollution control and reclamation are taken into account in the economic model. Again, close liaison with consumers is essential as these companies, dependent on steady supply, are reluctant to enter long-term arrangements unless they can have reasonable assurance that the project is economically viable.

Preparation for Markets

Hardrock ilmenite Deposits

MacIntyre Development, NY: Mining—Geologic sections and plans, produced from drill results, are used to determine open pit mining plans including waste and ore tonnages, mining ratios, and mining sequence. These, in turn, determine equipment and manpower requirements, and overall mining costs.

Mining is carried out on 14-m (45-ft) benches in an open pit using large blasthole drills, electric shovels, and diesel-electric trucks.

Milling—Ore from the mine is reduced in three stages of crushing to -14-mm ($-\frac{9}{16}\text{-in.}$) size. At the -64-mm ($-2\frac{1}{2}\text{-in.}$) size there is a magnetic separation step which discards about 20% by weight as a waste. Ore is reduced in size to $-208\ \mu\text{m}$ (-65 mesh) in rod mills and ball mills. Magnetic separators remove the magnetite fraction of the ore, and the non-magnetics are treated by flotation to produce an ilmenite concentrate and tailing. A flowsheet of this milling process is shown in Fig. 7.

Prior to 1972, the ore was ground to $-590\ \mu\text{m}$ (-28 mesh) and was then fed to wet magnetic separators to remove magnetite. The non-magnetic fraction was sized and fed to tables. Finer products went to a flotation plant to produce a flotation ilmenite concentrate. The wet table concentrate was dried and subjected to high intensity magnetic separation, producing a coarser ilmenite concentrate. A flowsheet of this earlier milling process is shown in Fig. 8.

Magnetite concentrate is dewatered on a filter and stockpiled. Ilmenite is filtered and then dried prior to shipment.

The titanium mineral is a relatively few progressively discovered and therefore undertaken in the rank of economic operations. Present and future contracts and byproducts contracts have to be made by manufacturers, and from pilot plant into account in the production costs with pollution control into account in the close liaison with these companies, deare reluctant to enter unless they can have the project is eco-

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Titanium Minerals

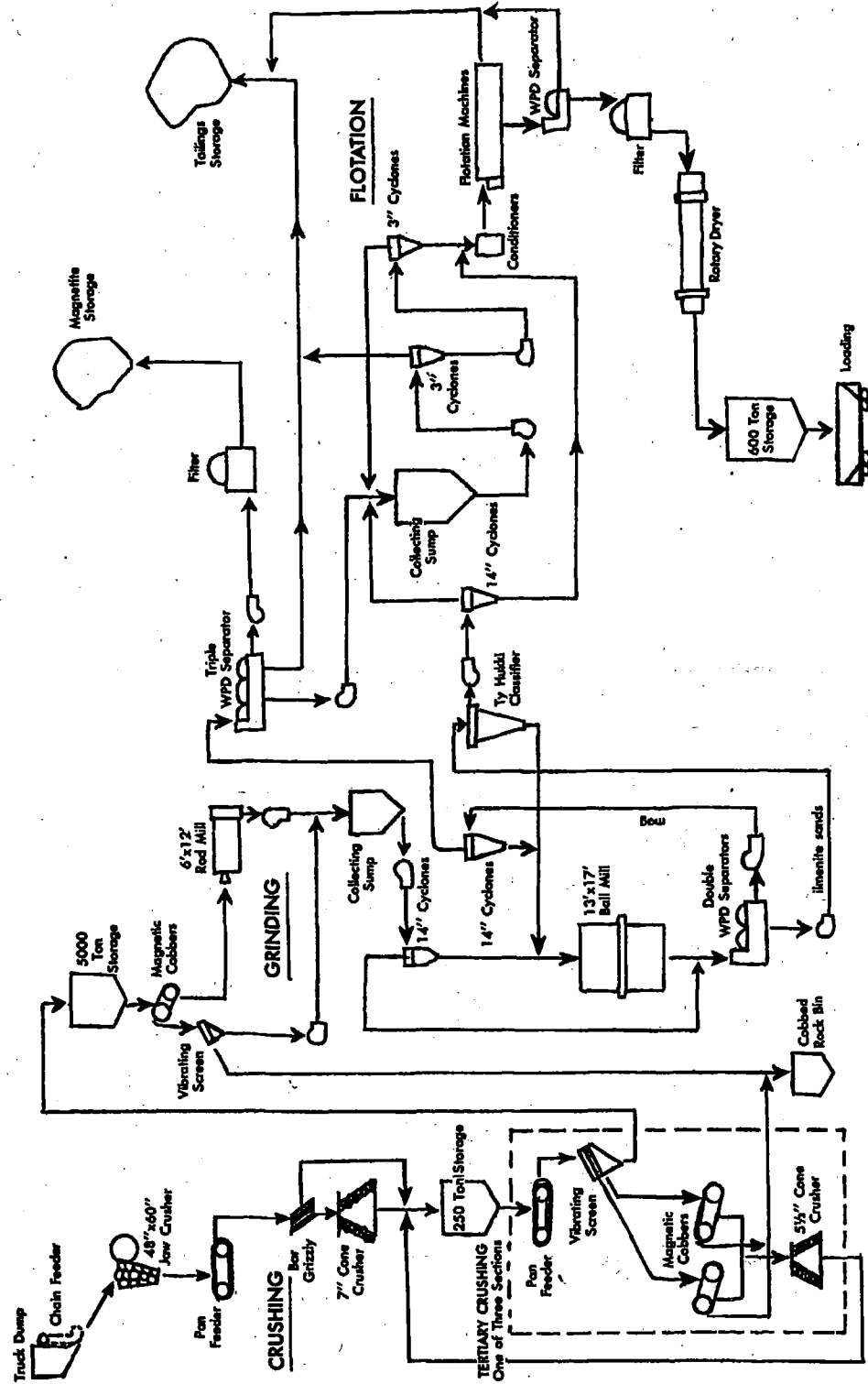


FIG. 7—Flowsheet for all-flotation ilmenite, MacIntyre Development, NL Industries, Tahawus, NY (courtesy of NL Industries, Inc.).

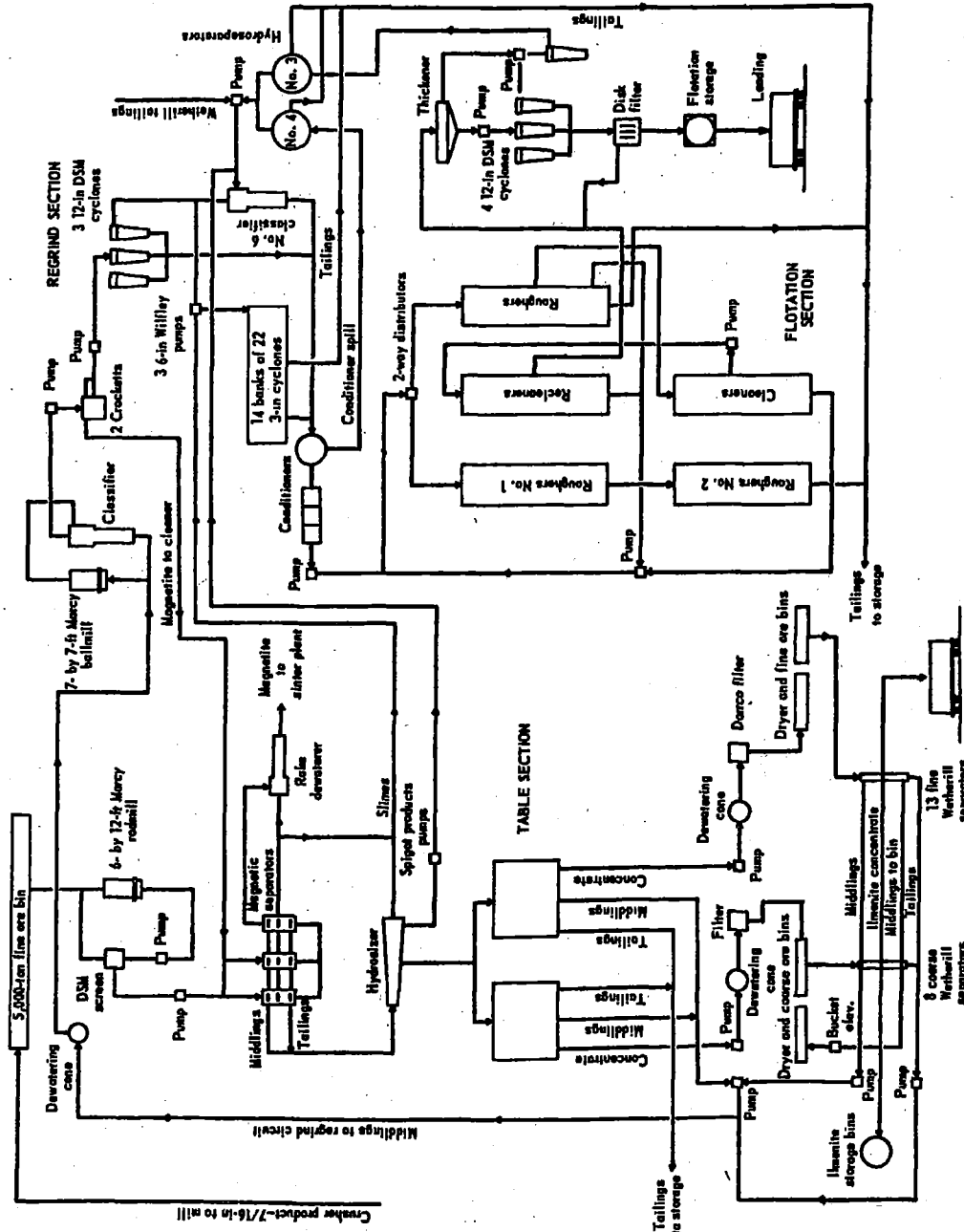


FIG. 8—Flowsheet for magnetic and flotation ilmenite concentrates, MacIntyre Development, Tahawus, NY (Peterson, 1966).

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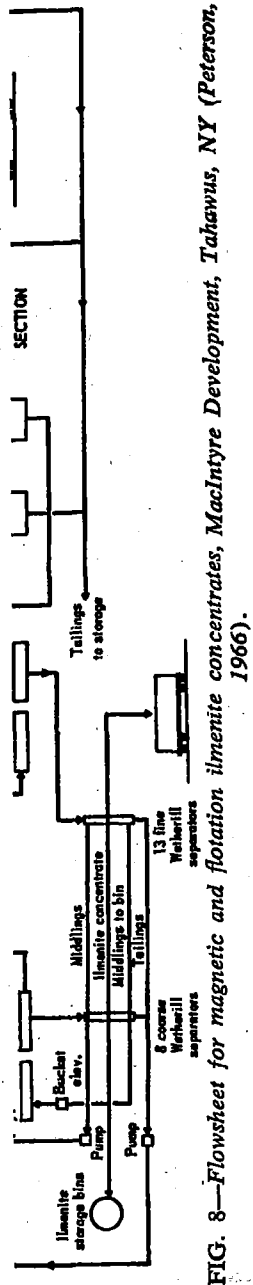


FIG. 8—Flowchart for magnetic and flotation ilmenite concentrates, MacIntyre Development, Tahawus, NY (Peterson, 1966).

Transportation, Markets, and Consumption.—Ilmenite and magnetite concentrates are shipped by rail in open cars. Ilmenite went mainly to the NL Industries TiO_2 pigment plant at Sayreville, NJ. A relatively new use for ilmenite is as a substitute for barite in well-drilling muds. The magnetite has been used as blast furnace feed, in refractories, and for heavy media separation in the coal industry.

Tellnes Deposit, Norway: Mining and Milling.—The ore at the Tellnes deposit (Anon., 1978a; 1973c; Brun, 1957) is mined in an open pit using 12 to 14-m (40 to 46-ft) benches. The primary processing plant, including crushing, grinding, magnetic separation, and flotation is located close to the mine. The ilmenite flotation concentrate passes by gravity in slurry form through a pipeline in an underground tunnel to the final processing plant near Jossingfjord, where leaching and drying are carried out. The leaching is done with dilute sulfuric acid to remove apatite. The magnetic concentrate is transported by means of a smaller pipeline through the same tunnel. The ilmenite is dewatered on disk filters, to about 7% moisture, and dried in a rotary kiln.

The magnetite slurry is partially dewatered and subjected to flotation treatment to remove sulfides. The sulfide-free magnetite is dewatered, filtered on drum filters, and stored. The sulfide fraction is combined with a sulfide product from the ilmenite flotation circuit, thickened, and filtered. Production of these byproducts has been about 40,000 stpy of magnetite concentrate (65 to 65.5% Fe) and 10,000 stpy of sulfide concentrate (4 to 4.5% Ni and 2 to 2.5% Cu).

Transportation, Markets, and Consumption.—Fully processed concentrates are stored in underground silos beneath the leaching and drying plant. A belt conveyor in a tunnel takes material from the silos directly onto ships in Jossingfjord.

Titania A/S is by far the largest producer of titanium concentrates in Europe and is the only important exporter in Europe. Even Spain and Finland, which produce ilmenite themselves, import some from Norway. Besides its proximity to the European market, Titania A/S has the advantage of relatively stable North Sea freight rates.

Tellnes ilmenite is the major feed material for the Kronos (NL Industries) group of sulfate plants in Europe, including plants in West Germany and Belgium as well as the Frederikstad plant in Norway. In addition, Titania has supplied companies in the United Kingdom,

Italy, Spain, and other European countries, including Czechoslovakia (Anon., 1973c).

Allard Lake Deposit, Quebec: Mining.—The ore at the Allard Lake deposit is mined by open pit methods. The mined ore has a grade of 32 to 36% TiO_2 and 39 to 43% iron. It is shipped by rail and boat via Havre St. Pierre to the company's beneficiation and smelting plant at Sorel, Que., for further processing (Elliot, 1959; Hatch and Cuke, 1956; Guimond, 1964; Hammond, 1949; Peirce, 1949).

Beneficiation.—The ilmenite-hematite ore is crushed, and beneficiated at Sorel by heavy media (magnetite) separation of the $-6.4\text{-mm} + 1400\ \mu\text{m}$ ($-\frac{1}{4}\text{-in.} + 14\text{-mesh}$) fraction, and Humphreys spiral concentration of the $-1400\ \mu\text{m}$ (-14-mesh) portion. Sulfur is eliminated from the combined gravity concentrates by heating in rotary kilns, using as fuel excess carbon monoxide from the electric smelting furnaces.

Because of its intimate intergrowths of ilmenite and hematite, the physically beneficiated concentrate, averaging 36.8% TiO_2 and 41.8% Fe, is still not high enough in TiO_2 content for direct use as a pigment plant feed. It is, therefore, smelted by a process developed by QIT-Fer et Titane, Inc. for the purpose of utilizing this type of high iron titanium ore.

Smelting.—The smelting process used by QIT uses little or no flux, the furnace charge consisting of ilmenite-hematite concentrate with 0 to 10% lime and 8 to 14% low ash coal. Due to the extremely corrosive nature of titanium slag, it is necessary to keep the melt within solid banks of ore to prevent the slag from attacking the refractory lining. The average furnace measures $15 \times 6 \times 6\ \text{m}$ ($50 \times 20 \times 20\ \text{ft}$), and has 610-mm (24-in.) diam graphite electrodes on 2-m (6-ft) centers, heating the charge to 1500° to 1700°C , to produce a titanium-rich slag containing 70 to 74% TiO_2 , and a form of pig iron known as Sorelmetal. QIT planned to increase the TiO_2 content of the slag to 80% in 1984. A flowsheet of the Sorel beneficiation and smelting process is shown in Fig. 9.

Transportation, Markets, and Consumption.—QIT slag is widely used as sulfate pigment plant feed and is shipped by rail and by boat to various plants in Canada, the United States, and Europe. Production capacity has been periodically increased from 240,000 stpy of slag in the mid-1950s to a capacity of about 960,000 stpy slag (2.0 million tons ore) in 1980.

Otanmäki Deposit, Finland: The ilmenite is produced as a flotation concentrate, amounting

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Industrial Minerals and Rocks

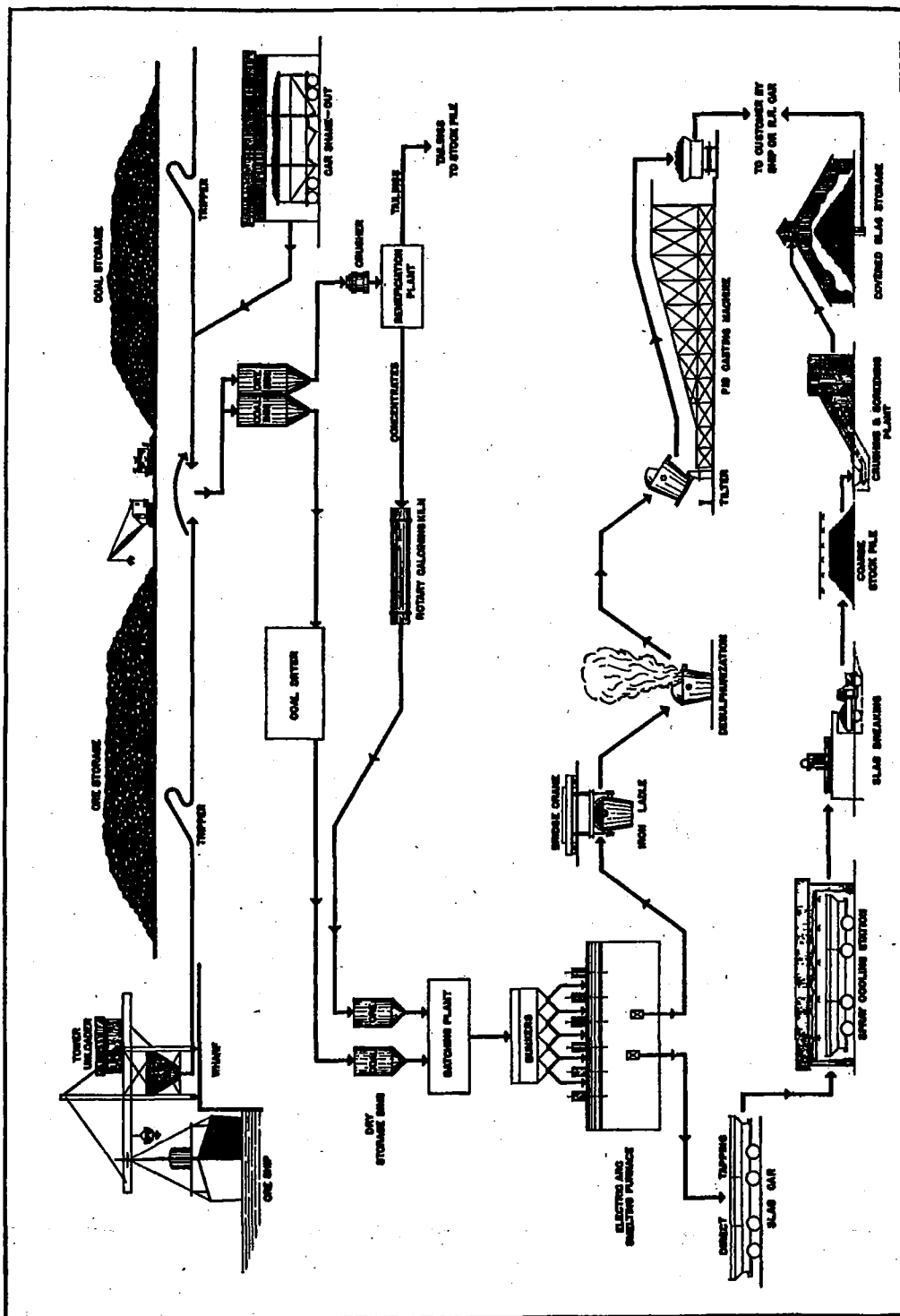


FIG. 9—Flowsheet for Quebec Iron and Titanium Corp. smelter, Sorel, Que., Canada (Lynd, 1960).

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to about 160,000 stpy. Most of this is consumed domestically, but some is exported to other European countries. A vanadium-bearing magnetite is produced as a byproduct (Anon., 1971c; Anon., 1978b; Harki et al., 1956; Runolinn, 1957).

Beach and Alluvial Sand Deposits

Mining Methods: Sand titanium mineral deposits are most commonly mined by suction dredge where the ground is not excessively "stiff" because of clay, hardpan, or induration of heavy mineral layers due to cementation by iron oxide. Dredges of widely different power and production capacity are used, depending on local conditions and desired production rates (see Figs. 1-4). The minimum dredging depth is about 1.5 m (5 ft), the maximum about 21 m (70 ft). The elevation of the dredge pond is adjusted to compensate as much as possible for variations in topography. The lowest practicable cutbank above the water level in the pond is maintained to avoid wave-producing shocks caused by sudden collapse of large volumes of sand into the pond, but high coastal dunes on North Stradbroke Island in Queensland, Australia, are successfully dredged with sloping banks over 15 m (50 ft) high.

Some deposits are mined by dragline, some by bulldozer, some by front-end loader, and some by bucket wheel excavator. Occasionally a combination of equipment types is employed. Particularly rich but highly cemented layers near the bottoms of some Western Australian deposits are mined in their softer portions by backhoe.

Clearing and stumping of the land surfaces precedes mining, and it is now becoming standard in the industry to remove any topsoil which may be present and to pile it aside for spreading over the refilled excavation after mining has passed through.

In all cases the object of mining is to excavate the heavy mineral sand and transport it to a "wet plant," which makes the first step of milling through gravity concentration. Large trommels, mounted either on dredges or on mobile supports in dry mining operations, remove roots, lumps of clay, and oversize gravel, boulders, and cemented nodules or fragments before the slurried sand is pumped to the wet mill. In dredging operations the wet mill floats on pontoons moored to the bank and moved periodically to keep up with dredge advances. In dry mining the gravity concentrator is located close to the mine. In both cases the tailings of quartz and other light materials are

returned to the mined excavation, so that at any given time part of the ore body is being prepared for mining, part is being mined, part is being filled, and part is being reclaimed.

There is some expansion of the ore sand in mining due to disturbance of grain packing, so that the volume returned to the excavation may be 4% or so greater than that removed. The creation of unfilled excavations is not unavoidable in normal heavy mineral sand mining, although it is possible to resculpture the surface by planned distribution of tailings to leave low hills and small lakes or ponds if desired. Replanting can be accomplished by seeding fast-growing, hardy grasses and fertilizing, or simply by resspreading the stockpiled topsoil with its retained fertile seeds of native plants. In the pine forests of the southeastern United States, where trees are valuable for papermaking, it has been demonstrated that pine seedlings planted in areas where sand dredging has been done grow at a natural rate.

Processing Beach and Alluvial Sand Deposits: Throughout the world, there are mining companies producing titanium, zirconium, and rare earth minerals from marine beach deposits. To concentrate and separate these sandlike minerals, a combination of gravimetric, high tension (electrostatic), and magnetic separations is the standard method. The metallurgy is straightforward and well-understood, and the valuable minerals are produced from the sands with relative ease.

When the minerals occur in stream placer deposits the production of high-grade products along with a high recovery presents a more difficult task of ore dressing.

Physical Characteristics of the Deposits and Minerals—BEACH DEPOSITS—In the marine beach deposits, the sands are very well-sorted and the entire mineral suite is usually well-classified. The deposits are, to a large degree, unconsolidated free grains of sand. In some cases, there is cementation of grains due to organic matter, iron, or carbonates. The mining engineer must be fully aware of these conditions as the presence of these coatings not only creates mining but recovery and grade problems as well when the marine deposit is mined and concentrated. This type of deposit being formed on a beach tends to be long and shallow and may not be uniform in mineral composition due to the concentration characteristics of the waves and of the wind. The evalua-

§ This portion of the chapter was written by W. P. Dynenforth, formerly Vice President, Mountain States Engineers, Tucson, AZ, now Marketing Executive, Colorado School of Mines Research Institute, Golden, CO.

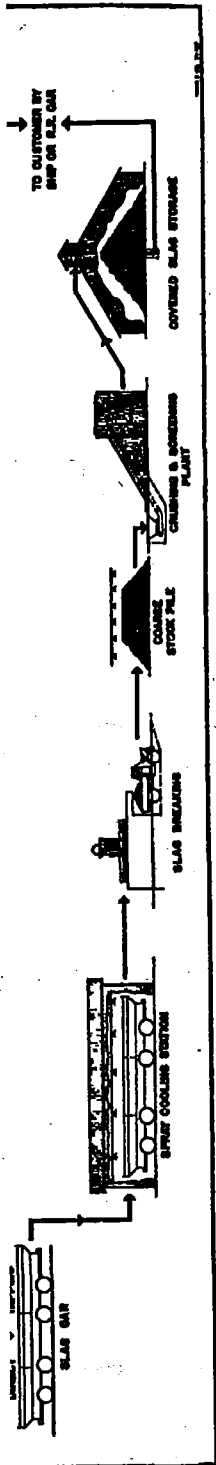


FIG. 9—Flowsheet for Quebec Iron and Titanium Corp. smelter, Sorel, Que., Canada (Lynd, 1960).

tion of this type of deposit cannot be done on the basis of heavy minerals alone (those heavier than quartz), since the distribution of rutile and ilmenite and other commercial minerals in relation to noncommercial heavy minerals may vary to a large degree throughout the deposits.

Besides being well-sized and classified, usually unconsolidated, and easy to mine, these deposits have presented the ideal situation of a maximum degree of weathering. This means that there will be very few grains that aren't clearly a single mineral and that usually the high iron materials such as magnetite have almost completely disappeared. Also the ilmenite will usually be weathered to the point that the iron has been sufficiently leached away to leave an ilmenite high in TiO_2 . It is interesting to note that many of the beach deposits from which monazite and zircon are produced are worked primarily because of the quality of the ilmenite which they can produce.

ALLUVIAL DEPOSITS—Alluvial deposits formed in stream beds present an entirely different problem to the mining engineer. Instead of uniform grain size and the classified characteristics of a beach deposit, the commercial mineral values may vary from $-75 \mu m$ to 2 mm (-200 mesh to 10 mesh) in size. Any one mineral such as monazite in an alluvial deposit may vary from $-75 \mu m$ to $+600 \mu m$ (-200 mesh to $+30$ mesh) in size. The deposits are usually a heterogeneous mixture from clay on up to boulders depending on the age and source material of the stream.

These deposits, of course, present an entirely different mining and concentration problem. Extensive weathering and smoothing of the grains has not taken place so that one may have to contend with cemented grains of two or more minerals, and/or the grains are more likely to be coated with iron or clay.

Mining and Concentration Methods—The beach-type deposits, providing they are deep and extensive enough, are usually exploited by suction dredging. This has been considered the least expensive way of mining, provided the material is unconsolidated and that the cross section of the deposit lends itself to maintaining a dredge pond. Due to irregular cross section of some deposits in Africa, dredging was found to be impractical, so they are being mined by draglines. Dragline-type mining is useful where comparatively rich deposits may be worked, in that this method allows selective winning of rich streaks and material in pockets. Draglines also are able to remove consolidated

as well as unconsolidated overburden simultaneously.

A bucket-line dredge was planned for use on a marine beach deposit in the southeastern United States. It was believed that the higher capital cost of the equipment would be offset by more efficient mining of the ore, and that the ability of the large bucket-line dredge to carry its own concentration equipment should keep costly pumping of sand and water to a minimum. The plant was never built due to a titanium recession in the late 1950s.

Bucket-line dredges are almost a necessity for most stream-type deposits. They are required to break up the clay and other forms of consolidation as well as to handle the large stones, boulders, and even stumps and logs. Where only small gravel and stones occur, suction dredges have been used but they present a problem of lower mining recovery because the largest stones are left in the bottom of the pond. This is a mining recovery problem created by the loss of heavy minerals which are concentrated by water action into the interstices of the porous rocks.

Concentration of the minerals from sands is to date best done in small plants by use of wet shaking tables. For larger production, the spiral concentrator has been standard over a period of years. Flotation has been used to some degree. At the present time, there is a great deal of interest and work being done on various types of gravity concentrators to provide large tonnage rates of feed in comparatively light weight and low cost concentrating devices.

Jigs have been studied and adapted for this kind of concentration in many places. They were actively used in the British Titan Products' operation in Africa and are still being studied in a number of places. There are a number of separators being developed and used that incorporate the sluicing principle. In the United States, examples of this type of separation action are found in the Cannon ring-conformation pinched-slucice concentrators, the Lamflo sluice concentrator developed by Carpc, and the pan concentrator developed by Du Pont. In Australia the Reichert cone concentrator, which is also operated on the sluice principle, has been very successful for large tonnage operations (Paterson, 1977). All of the separators based on the sluice principle require a feed density of 55 to 60% solids which results in quite a saving in water when compared to other gravity methods.

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Titanium Minerals

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stream-type deposits, the jig is usually chosen. The jig has long been used on alluvial deposits containing gravel and tests have indicated that they are the concentrating device least sensitive to extreme grain size variation. The jigs also allow large throughput capacity in a small space and can be mounted on the dredge. Mounting the concentration equipment on the dredge allows maximum maneuverability for the stream deposits that may be comparatively narrow and crooked.

SEPARATION OF THE VALUABLE HEAVY MINERALS FROM EACH OTHER—Two quite different flowsheets are required to separate the minerals and to produce commercial products from the two types of deposits. High-purity minerals are particularly difficult to produce at high recovery from stream deposits due primarily to the grain size distribution and also due to the unweathered characteristic of the deposits which means there are many middling products to be dealt with. These middlings create heavy circulating loads, are contaminants to finished products, and their disposal can cause losses in recovery.

Minerals concentrated from stream deposits will often require attrition scrubbing to remove surface coatings of organics, clay, and iron. The sands from beach deposits will often be uncoated. A beach mineral concentrate, however, that has been produced with the use of saltwater, may require a freshwater wash to remove salt prior to the dry separation steps.

Once the minerals are concentrated and the surfaces of the grains are clean, the next problem that confronts the ore dresser is the size range of the minerals. Table 20 shows the size range distribution of the heavy mineral concentrate from a typical Florida beach-type deposit as compared to the screen analysis of a concentrate from an alluvial deposit.

TABLE 20—Comparison Chart of Screen Analyses

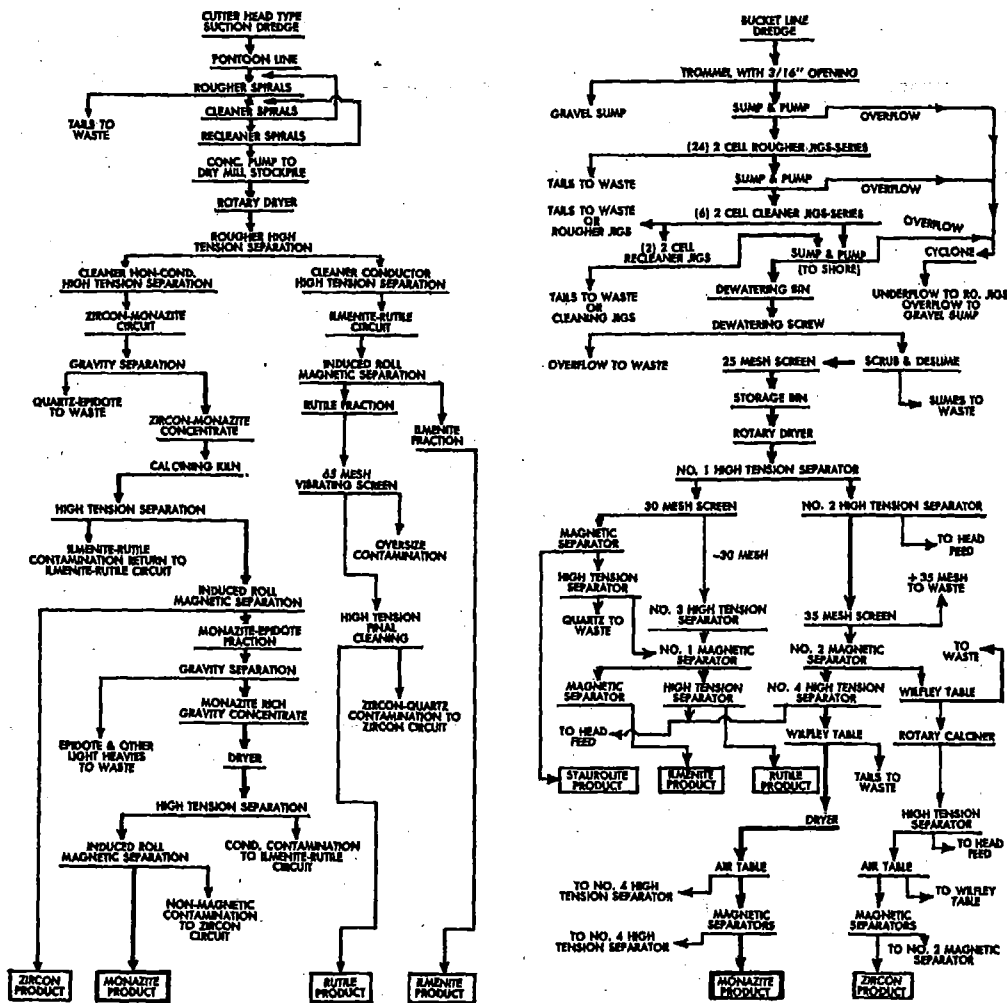
Alluvial Concentrate		Beach Concentrate	
Screen Size, Mesh	%	Screen Size, Mesh	%
+20	9.6	+20	—
—20	9.8	—20	—
—28	14.2	—28	—
—35	9.5	—35	—
—40	14.5	—40	—
—48	18.6	—48	0.5
—65	13.9	—65	7.8
—100	6.1	—100	37.0
—150	1.9	—150	45.0
—200	1.0	—200	9.7
	100.0		100.0

Since the minerals from beach deposits are very well-sized and classified usually no further sizing is considered necessary. Normally grade of product and recoveries have been acceptable as produced without sizing. Further study seems to point out that even in beach-type deposits, sizing or classification may eventually be incorporated for optimum recoveries.

Sizing of the minerals concentrated from stream deposits is a must and can be accomplished in two ways. The entire feed to the dry separation plant can be sized into fractions which are handled separately in the mill or they may be introduced into the mill as unsized feed wherein the natural sizing effects of the various separation equipment are employed to do simultaneous separation and sizing.

A good example of taking advantage of the sizing effect of separating devices appears in nearly all of the plants producing rutile and its associated minerals. Grains of coarse quartz, and/or staurolite or garnet are thrown off the rotors of both the high tension (electrostatic) and magnetic separators, since their mass and kinetic energy cannot be overcome by high voltage or magnetic fields present which are adjusted to the highest recovery of the bulk of the finer minerals present. These coarse grains report finally with the nonmagnetic conductor fraction which is typically rutile or cassiterite. It is considered a very simple system to purposely allow these coarse grains to follow through to the end of the flowsheet where they can be scalped off by a small screen rather than to attempt to screen the entire feed to the mill. At some plants, however, the occurrence of coarse-grained rutile requires a modification of this method. Screening is employed at two points in the circuit in conjunction with high tension sizing: (1) between the rougher and thrown cleaner rolls and (2) between the final pinned product of the pinned cleaner rolls and the primary magnetic separators used for zircon-quartz, monazite-staurolite separation. In the first case, coarse staurolite is rejected as oversize with some coarse rutile. This oversize product is then treated separately by magnetic and high tension separators at special settings to recover the rutile. In case two, the valuable minerals, zircon and monazite, are $-500 \mu\text{m}$ (-35 mesh). Thus, screening at this point eliminates coarse quartz and staurolite, reduces the load on the magnets, and improves the overall efficiency. Figs. 10a and b are typical flowsheets for processing beach deposits and alluvial deposits.

If the entire feed to a plant is sized, it



FIGS. 10a, b—Typical flowsheets for processing beach sands (left) and alluvial deposits (right).

creates the problem of multiple lines of separation equipment or an alternate of bulk storage and batch processing which requires a large amount of operational attention and resetting of the circuit. Accordingly, an alluvial flowsheet is usually designed to accept an unsized feed on a continuous basis and to make use of the sizing effect occurring during separation. At first glance this gives the appearance of a complicated flowsheet but after the operation and technical personnel have had time to balance the flow of the various minerals in accordance with their size, the production of finished mineral products is accomplished with

a minimum of operational changes. Highest recoveries can be gained by continual study and development of this type of return products system.

The rather simple flowsheet as commonly used for the production of titanium minerals and byproducts from beach sands is shown along with a flowsheet used for the production of same from an alluvial deposit. Notes on the various types of separation equipment are given, particularly on the alluvial flowsheet. The relative difference in the flowsheets required to produce valuable minerals from the two types of deposits is very apparent.