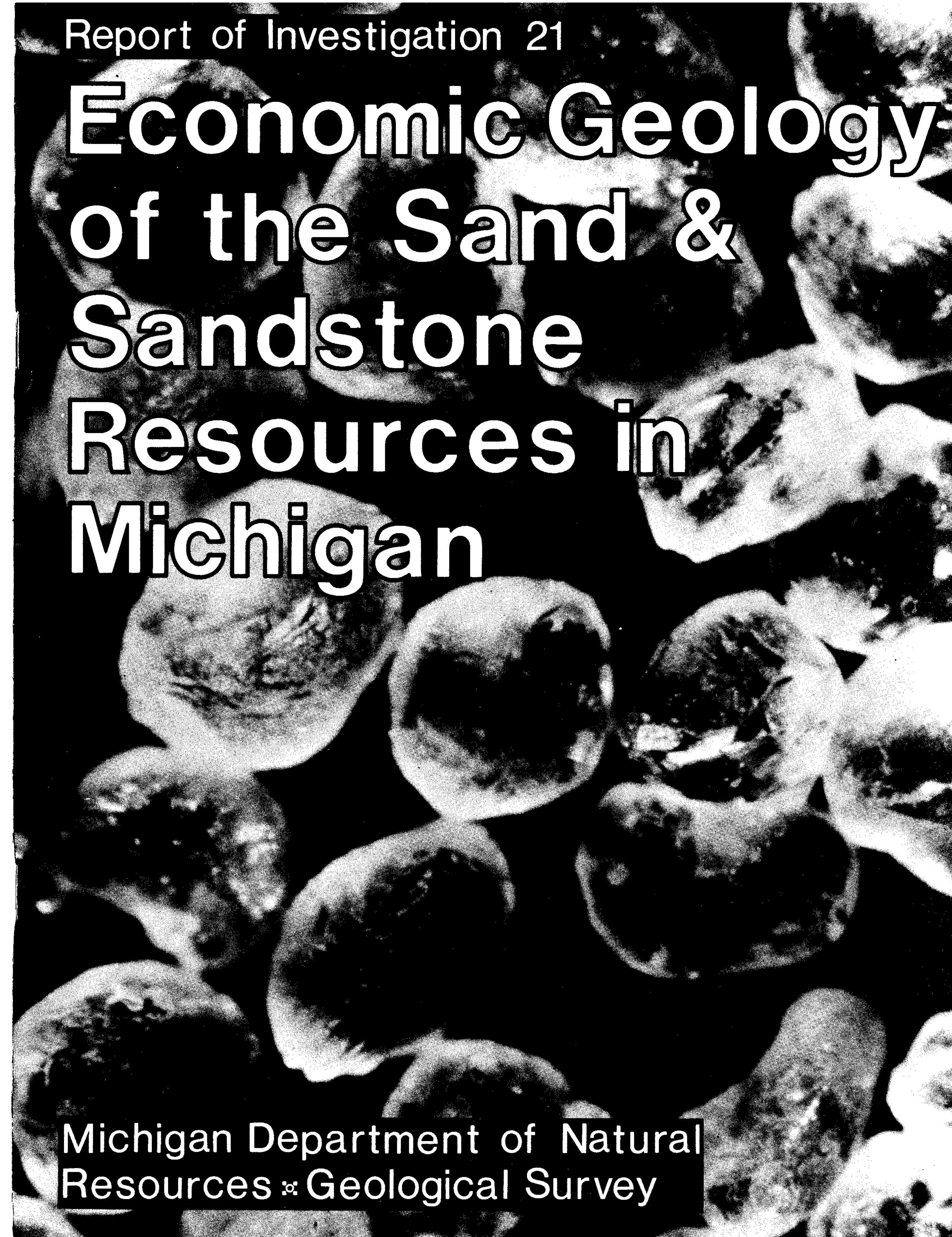
Report of Investigation 21

Economic Geology of the Sand & Sandstone Resources in Michigan



Michigan Department of Natural Resources ¤ Geological Survey

About the Cover: An enlargement of a photomicrograph of the Sylvania Sandstone from the Ottawa Silica Company in Rockwood, Michigan. This is the same material as shown in Figure 14 (page 14), but magnified approximately 275X.

Geological Survey Division

Report of Investigation 21

ECONOMIC GEOLOGY OF THE SAND AND SANDSTONE RESOURCES OF MICHIGAN

by

E. Wm. Heinrich

Lansing, Michigan

1979

STATE OF MICHIGAN
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DEPARTMENT OF NATURAL RESOURCES
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PREFACE

The writer has been concerned with the non-metallic mineral resources of Michigan for thirty years, and in detail with mineral products obtained from sands and sandstones for a decade. This report presents a summary of field and laboratory studies most of which were conducted between 1967 and 1977. These data are coupled with summaries from both older and recent literature in an attempt to present a complete and modern description of the economic geology of the sand and sandstone resources of Michigan. I am indebted to several of my students and colleagues for assistance. Former students are Chris A. Drexler who studied the Lake Michigan dune sands and Vincent Del Greco who studied the Sylvania Sandstone at Rockwood. I have drawn heavily on both of their Master's studies in presenting this summary. In addition, my colleagues, Professors L. I. Briggs, J. A. Dorr, Jr., D. F. Eschman, W. R. Farrand, and K. K. Landes have permitted me to pick their brains for many pieces of information. To all of these I extend my special thanks. Laboratory studies were conducted in the Department of Geology and Mineralogy of The University of Michigan.

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Abstract

The extensive sand and sandstone deposits of Michigan constitute one of the most important mineral resources of the State. Ranging in age from Precambrian to Recent, they supply (or have supplied) a great diversity of products: various types of dimension stone and building stone; aggregate sand for use in concrete and allied construction materials; fill sand; foundry sands for molds and cores; glass sands; and abrasive and other specialty silica products. Setting standards in their respective industries are two preeminent deposits: 1) the Sylvania Sandstone (Devonian) which is one of the premier glass sands of the United States and 2) the Lake Michigan dune sand which is the preferred sand (Lake sand) for molds and cores in gray iron foundries, particularly for the automotive industry. Similarly in the past grindstones and other abrasive tools, produced in Huron County, were considered the highest quality materials available in the United States (Lake Huron bluestone).

Although in general the reserve situation for both the Sylvania glass sand and the Lake Michigan dune sands is good, future production complications will result from zoning restrictions, reservations for park land, housing development competition and ecological regulations.

INTRODUCTION

In the field of economic geology and mining, Michigan has long been world famous for its native copper and iron deposits. Equally or even more important, but geologically less spectacular, are the Michigan productions of limestone, gypsum, rock salt, glass sand, foundry sand, construction sand and gravel and other non-metallic mineral commodities. In terms of dollar value Michigan, in 1975, ranked high among the states in the production of a variety of non-metallic minerals. The state ranked first in production of gypsum, peat and marl; second in rock salt; third in construction sand and gravel; fourth in cement; and fifth in lime, clay and shale.

Among the non-metallic raw materials of peculiar geological interest are sands and sandstones, inasmuch as they are used in a wide variety of ways, based on a wide variety of combinations of physical and chemical properties. These properties include bulk chemical composition ("purity"), grain-mineral composition, color, degree of consolidation, grain size and grain-size distribution, shape and roundness of grains, and nature and amount of cement.

Sandstones and sands yield products that have manifold applications: 1) dimension stone: building stone, rip-rap, flagging; 2) aggregate: in concrete, cements, plasters, bituminous paving mix, terrazo; 3) fill sands; 4) molding and core sands in the foundry industry; 5) abrasive: blasting sands, engine sands, whetstones; 6) metallurgical silica: silicon metal, ferrosilicon alloys; 7) glass sand; 8) fillers in paints and bitumens; 9) sand filters; and 10) silica flour. Most of these products have been obtained from Michigan sandstones and sands.

Utilization of Michigan sandstones and sands has passed through two overlapping historic periods with contrasting main products:

1. Nineteenth century and until about the end of World War I:
   Building stone
   Abrasive wheels and scythestones;

2. Pre-World War I to date:
   Glass sand
   Molding sand
   Construction sand.

Two of Michigan's present sand products are particularly outstanding and preeminent in their fields of utilization. These are the Sylvania Sandstone, one of the world's finest glass sands, and the Lake Michigan dune sands ("Lake sand") which set the standard for molding sands in the automotive foundry industry. Similarly in the past, the Marshall Sandstone was the source of the finest grindstones obtainable in the United States until they were superseded by those from Ohio and subsequently by wheels of synthetic abrasives. Still further removed in time was the Jacobsville Sandstone, renowned as a handsome building stone throughout eastern and central United States. It is doubtful that any other state can claim a similar record of producing four completely different sandstone-sand products, each foremost in its particular application.

MIDDLE PRECAMBRIAN QUARTZITES

General

In the Marquette district, a number of quartzite units of Middle Precambrian age occur in formations belonging to the Marquette Range Supergroup. The formations are, upward from the base, the Enchantment Lake Formation, Mesnard Quartzite, Kona Dolomite, Wewe Slate, Ajibik Quartzite, Siamo Slate, and Negaunee Iron Formation. Some units in both the Mesnard and the Ajibik are thick-layered, light-colored and vitreous and resemble, at least in outcrop, the Precambrian Lorrain quartzites that crop out on the north shore and in the Georgian Bay areas of Lake Huron in Canada. Most of the quartzite production in this area of Canada goes into ferroalloys, but some is used as a metallurgical flux stone. For such uses, low iron contents are required and, in addition, alumina must be kept within acceptable (and low) limits. In such rocks, the iron is normally present as secondary hematite and the alumina in sericitic muscovite.

Several dozen specimens of both the Mesnard and Ajibik quartzites were collected for petrographic evaluation for possible use as high-quality silica sources.

Mesnard Quartzite

Results on two specimens of Mesnard Quartzite are:

No. 2620. Sericitic quartzite, north of Mud Lake, near Marquette.
Hand-specimen: Gray-white, slightly schistose, with films of sericite, a slightly waxy texture.
Microscopic: Largely a relict sedimentary texture with little recrystallization. Angular to subrounded quartz grains in a matrix of silty quartz, sericite and very fine-grained chlorite. The metamorphic character of the rock is evident from the orientation of the sericite which is in thin, elongate streaks and "veinlets" which are largely parallel. In cross-cutting sericite "veinlets" the individual sericite flakes also are parallel with this orientation. This sericite orientation is at an angle of about 30° to relict sedimentary layering exemplified by finer-grained bands of quartz particles. The sericite corrodes quartz-grain margins slightly. Zircon, ilmenite, tourmaline, rutile.
Evaluation: Much too impure as a silica source.

No. 2621. Mt. Mesnard.
Hand-specimen: Gray-white, peppered by minute red spots. Some thin snow-white quartz veinlets.
Microscopic: A recrystallized granoblastic fabric. Most grains show some wavy extinction. Considerable grain-size variation. Local patches of finer-grained quartz have appreciable hematite cement as thin interstitial films. In coarser parts, thin grain-boundary films of sericite lie between the quartz grains. A few grains of zircon.
Evaluation: Probably a borderline rock, with a little too much iron.

Ajibik Quartzite

Seven specimens, representing a wide variety of Ajibik quartzites, have been evaluated petrographically.

No. 2630. North of Maas Mine, Negaunee.
Hand-specimen: Light red, with thin relict (?) sedimentary (?) bands of darker red color.
Microscopic: A partly recrystallized fabric, partly granoblastic and with grain outlines partly relict detrital. Most grains moderately undulatory in extinction. Narrow streaks of cataclastic grinding. Local marginal sericite as incomplete films on quartz grains. Hematite widespread as very fine-grained flakes, concentrated in small patches and as partial grain rims. Estimated to contain $\sim$1% Fe_2O_3. No heavy accessories noted.
Evaluation: Too much hematite.

No. 2632. North of Maas Mine, Negaunee.
Hand-specimen: Medium-gray, slabby, with a sugary texture.
Microscopic: Granoblastic, undulatory, well-sorted. Very minor scattered flakes of interstitial sericite. A slight trace of hematite; no heavies noted.
Evaluation: A very good-looking rock.

No. 5000. Harvey Quarry, Marquette; near fault.
Hand-specimen: Dark gray, crisscrossed by numerous, randomly oriented fractures coated by hematite.
Microscopic: Medium- to coarse-grained granoblastic fabric with superimposed cataclastic shears. Much mortar structure at grain margins in cataclastic zones which also are rich in minute hematite flakes. Sericitic grain-boundary films are variable from a few flakes to partial to complete.
Evaluation: Not of value, owing to hematite introduction during shattering.

No. 5001. East side of Negaunee (Figure 1).
Hand-specimen: Very uniform, gray-white, subconchoidal fracture.
Microscopic: Generally uniformly grained save for a finer-grained, folded band. Granoblastic fabric, grains moderately undulatory. Very subordinate and very thin grain-boundary films of sericite. A trace of zircon.
Evaluation: A very good-looking rock, worth a chemical analysis.

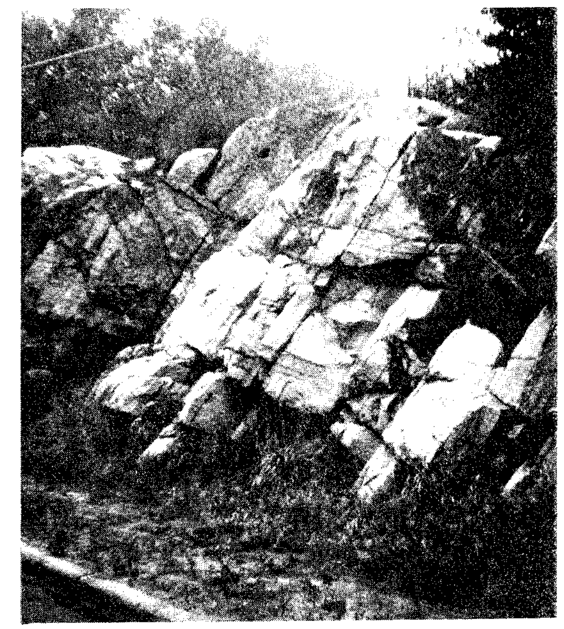

Figure 1. Thick-bedded, uniform Ajibik Quartzite, east side of Negaunee.

No. 5002. East side of Negaunee.
Hand-specimen: Dark gray, coarse-grained, uniform.
Microscopic: An arkosic quartzite. Coarse, subangular pieces of quartz, K-feldspar-perthite and rocks (quartzose schist) in a silty matrix of quartz and sericite. Strongly bimodal. Matrix also contains much hematite in flakes and patches, and chlorite. Feldspar fragments strongly sericitized.
Evaluation: Much too impure.

No. 5003. East side of Negaunee.
Hand-specimen: Spotted by green ovoids 2 to 10 mm long in a green-gray matrix (Figure 2). Hematite veinlets along fractures.
Microscopic: Granoblastic, undulatory. The spots consist of clusters of minute pale green chlorite flakes, pleochroic from pale tan to light green and dusted by tiny opaque specks. The chlorite alters to hematite. Hematite also along fractures.
Evaluation: Too high in Mg and Fe.

Figure 2. Ajibik Quartzite with green "spots" of chlorite, east side of Negaunee.

No. 5004. East of Negaunee.
Hand-specimen. Greenish white with green ovoid spots, 2 to 5 mm. Cut by numerous ramifying and crisscrossing hematite veinlets.
Microscopic: The spots consist of $\sim$10% chlorite as interstitial flakes and grain-boundary films. Rest of rock contains $\sim$1% chlorite as scattered flakes. Traces of sericite. Fabric is granoblastic, interlocking.
Evaluation: Too high in Fe, Mg and Al.

Summary

The Mesnard appears unlikely to provide high-silica quartzite. Some specimens of Ajibik appear very promising, especially Nos. 2632 and 5001. A systematic sampling program with chemical analyses appears to be warranted.

JACOBSVILLE SANDSTONE

Building Stone

By 1893 building-stone quarries were operating in the Jacobsville Sandstone of Lower-Middle Cambrian age (Hamblin, 1958) at four localities in the Northern Peninsula. At that time the Jacobsville was referred to as the "Upper Peninsula Sandstone" or "Lake Superior Sandstone" and was regarded as equivalent to the Potsdam. Later reports included both the Jacobsville and the Munising in the "Lake Superior Sandstone". Parker (1895) lists the following operating quarries and their 1892 productions:

1. Portage Entry, 16 miles southeast of Houghton at Portage Entry (i.e., at Jacobsville), 226,000 cu. ft.

2. Portage Redstone Company, same location, 275,000 cu. ft.

3. Lake Superior Redstone Company, same location, 10,000 cu. ft.

4. Kerber-Jacobs, same location, - ?

5. Michigan Redstone Company, Marquette, 50,000 cu. ft.

6. Rock River, 25 miles east of Marquette, 1,000 cu. ft.

In addition to being intensively employed locally in the Northern Peninsula (especially in Marquette and Houghton-Hancock) for churches, public buildings, breweries, and residences, the stone enjoyed a wide geographic market. It was shipped as far west as Kansas City, south to St. Louis and east to Cleveland, New York and Philadelphia. Duluth, Chicago and Buffalo were the lake ports utilized for inland distribution. The main recognized color varieties were the redstone (uniformly red) and the variegated (red streaked and mottled with white). The former sold for 90¢ per cubic foot delivered at any lake port, the latter for only 75¢ per cubic foot. The Marquette stone (brown and purplish) was regarded as the handsomest stone quarried, but amounts were limited. The Jacobsville Redstone, more widely used, was available as dimension stone in sizes up to 30 inches thick. In addition to its use as ordinary building stone, surfaces of the blocks could be carved readily into intricate relief designs.

By 1899 the value of sandstone produced for building stone in Michigan reached $102,447.00 (rough), $57,682.00 (dressed). A maximum value of $136,280.00 (rough) was reached in 1902, after which a decline set in. In 1911 the rough value was only $5,682.00 (Smith, 1914). The Portage Entry Redstone Company is recorded as operating at least through 1923, but ceased operations sometime before 1926. In 1926 the only stone quarried was produced by the City of Marquette for concrete aggregate, and the saga of the famous Jacobsville building stones, the Jacobsville Redstone, the Marquette Brownstone and the Portage Redstone had ended.

In addition to its handsome color, the stone had the advantages of being readily workable, surface-hardening rapidly upon exposure to air, and being fire-resistant. A single sample of Jacobsville from a small quarry in Section 34, T52N, R33W, Baraga County tested by Makens et al. (1972) had the following properties:

Compressive strength*	12060	psi
Tensile strength*	440	psi
Modulus of rupture	919	psi
Porosity (total)	13.8	%
Permeability*	8.11	md.
Percent absorption*	6.18%	
Abrasion (% wear)	12.32 (100 rev.) 51.28 (500 rev.)	
Specific gravity	2.63-2.69	
Hardness* (scleroscopic)	33	

*average value

Disintegrated Jacobsville Sand

Babcock (1973) discovered and reported on a potential industrial sand deposit on East Dollar Bay Mesa, east of Dollar Bay in Houghton County. The bulk test sample was obtained from Section 34, T55N, R33W, center of north line of NW¼ of the SW¼, Torch Lake Township, Houghton County. According to Babcock the mesa is capped by well-sorted, bleached, flat-lying Jacobsville Sandstone and loose sands derived mainly from the Jacobsville. The test sample consisted of an off-white, friable, well-sorted sandstone.

The size analysis is given in Table 1, the chemical analysis in Table 2.

U.S. Standard Mesh	Weight Percent
+20	0.30
+30	1.70
+40	28.39
+50	53.13
+70	12.63
+100	2.45
+140	1.26
+200	0.07
-200	0.07
	100.00

Table 1. Size analysis of East Dollar Bay Sand (Babcock, 1973)

The mineralogy of the sand is: > 95 percent quartz grains, 40 percent of which have secondary, crystallographically-oriented quartz overgrowths; feldspar--several percent, tan-yellow detrital grains, some partly altered; 1 percent micaceous species, including a kaolinitic mineral; traces of dolomite and hematite; heavy minerals include leucoxene, tourmaline, magnetite-ilmenite, apatite and zircon with a total of > 2.96 sp. gr. fraction = 0.008 wt. percent.

Proximate Chemical Analysis of East Dollar Bay Sand[a]	Head	Leachable	Theoretical Remainder
SiO_2[b]	98.76	--	--
TiO_2	0.045	0.034	0.011
Al_2O_3	0.72	0.106	0.614
Fe_2O_3[c]	0.071	0.031	0.040
CaO	0.021	0.012[d]	0.009
MgO	0.036	0.016	0.020
K_2O	0.330	0.012[e]	0.318
Na_2O	0.021	0.007[e]	0.020
CO_2	0.016	--	--
(Total impurities)	1.260	0.210	1.032
Molar Ratios			
Ca/Mg	0.96	1.23	0.74
K/Na	9.24	10.08	9.35

[a]dry, unprocessed, -10 mesh sand ground to -100 mesh. (Analysis not totaled because of potential rounding errors and approximate nature of values obtained.)

[b]SiO_2 by difference. This value also includes a negligible percentage of water tied up in hydrous authigenic minerals.

[c]Fe(total) as Fe_2O_3.

[d]in dolomite; inferred.

[e]in hydromuscovite (approximately 0.14 percent).

Table 2. Proximate chemical analysis of East Dollar Bay Sand (Babcock, 1973)

From the chemical and mineralogical data, the sand is not sufficiently pure to serve as a glass sand without beneficiation. Total iron is too high for flint-grade glass but is in the range specifications for amber glass. Aluminum and alkalies also are too high for a glass sand. The size distribution is suitable for either glass sand or for foundry sands. Possibly because of this and the presence of feldspar the material should be tested for foundry-sand purposes. Although the deposit appears to have considerable areal extent (~5 square miles), it seems to have a limited thickness.

The deposit appears to represent an example of the weathering-beneficiation of a protore material (the ferruginous Jacobsville) mainly by the leaching of most of the cementing limonite-hematite.

MUNISING FORMATION

The Munising Formation, which unconformably overlies the Jacobsville, is Upper Cambrian in age (Hamblin, 1958). In contrast to the Jacobsville, most of which is red, the Munising, in general, is white to light colored or gray. Three lithologic units are recognized by Hamblin (1958); in ascending order they are: 1) basal conglomerate, 2) Chapel Rock member, and 3) Miner's Castle member.

The Chapel Rock member is 40 to 60 feet thick, whereas the Miner's Castle member constitutes the upper 140 feet of the Munising Formation. Other contrasts are given in Table 3.

	Chapel Rock	Miner's Castle
Major Minerals	98% + quartz	95-98% quartz
Minor Minerals	---	feldspar
Cement	silica, uncemented to ortho-quartzitic; calcite only local, near fractures	silica, less abundant; calcite abundant in some beds but not widespread
Coherence	variable; generally more coherent than the Miner's Castle	generally friable and porous
Accessories	zircon!; minor tourmaline, apatite, rutile, garnet	garnet! opaques; minor zircon, tourmaline, rutile; pyrite common in middle
Sorting	well-sorted	poorly sorted

Table 3. Comparison of the Chapel Rock and Miner's Castle members of the Munising Formation (adapted from Hamblin, 1958).

Because of its light color, high quartz content, excellent sorting and favorable location with respect to water transportation, the Chapel Rock member has been considered as a potential glass sand (Figure 3). Sampling and testing, particularly of material from Grand Island, have been conducted by at least one major glass company. However, the poor sorting, more variable mineralogy and local pyrite content are features that make the Miner's Castle member undesirable as a glass-making raw material.

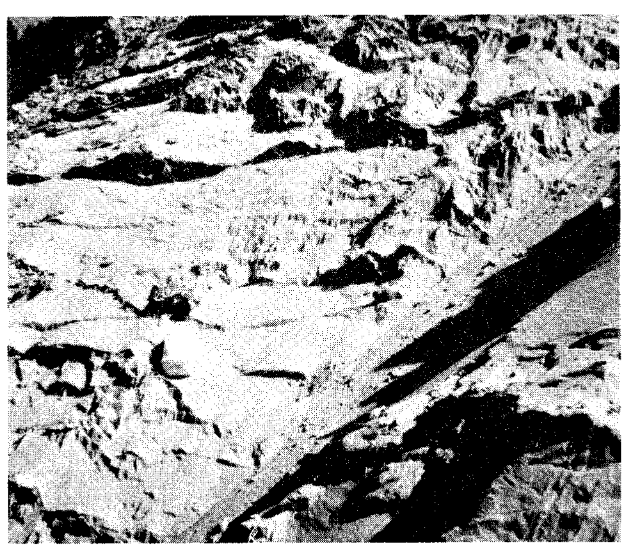

Figure 3. Somewhat disintegrated Chapel Rock Sandstone, Munising Formation, Pictured Rock Park.

SYLVANIA SANDSTONE

(by E. Wm. Heinrich and V. Del Greco)

Introduction

The Sylvania Sandstone represents a major geological-economic anomaly, inasmuch as it is one of the finest glass sands in the western hemisphere. Because of its structure and general character, and its overburden of glacial debris, it also is one of the most poorly exposed units of this type in the United States. Hence, most of the information on it stems from a very restricted number of surface exposures, the remainder coming from drill holes.

The sandstone is presently being quarried by the Ottawa Silica Company at its Rockwood Quarry about one mile east-southeast of Rockwood in Wayne County, Michigan, chiefly for flint-grade glass sand (Figure 4).

Previous Studies

The Sylvania has been well established as a stratigraphic unit since 1871 (Newberry, 1871), and its general geology has been documented for nearly three-quarters of a century (Sherzer, 1900; Grabau and Sherzer, 1909). It was originally identified in northwestern Ohio (Newberry, 1871) where all four known exposures are in Lucas County and on the south bank of the Maumee River in Wood County. The formation is named after the town of Sylvania in Lucas County just across the Michigan-Ohio boundary. The geology of the formation in Ohio has been described in detail by Carman (1936) who also reviews the earlier history of its study in the region around the west end of Lake Erie. An early study of the formation in Michigan was by Natress (1910).

Modern studies of the formation in Michigan were not completed until the 1950's. These include studies on the petrology by

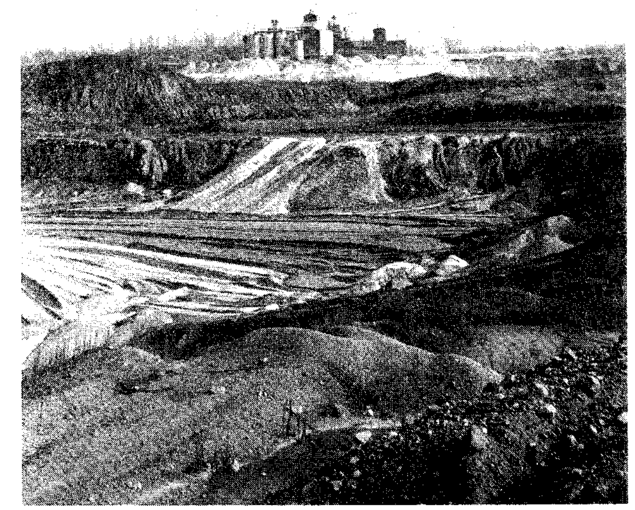

Figure 4. Plant of the Ottawa Silica Co., Rockwood.

Enyert (1949), on the general geology by Landes (1951), on the stratigraphy by Ehlers et al. (1957) and on origin by Briggs (1959).

Relatively recent studies by Hatfield et al. (1969) and by Del Greco and Heinrich (1973) have provided considerable new detailed information on the petrology and genesis.

The formation also has been identified in the subsurface of southern Ontario, close to the Detroit River (Dyer, 1929; Reavely and Winder, 1961).

Glass Sand

Nearly all of the silica for glass arrives in some form of quartz, except for the minor amounts that accompany the aluminum and the alkalies in feldspar and/or nepheline. Three categories of specifications apply to the silica, called "quartz sand" by the glass industry, irrespective of its geological mode of origin. These categories are grain-size, chemical, and mineralogical specifications and are described as follows:

1. Grain-size specifications. These vary somewhat from company to company. One common distribution is:

   +30 mesh - none
   +40 mesh - not over 3%
   -80 mesh - not over 35%
   -140 mesh - not over 5%

Coarse quartz grains (+30 mesh and larger) do not melt completely, forming a type of structural defect in glass. Very fine-grained material (-150 mesh) tends to blow out of the furnace batch, thus changing its composition, and to cake and clog the checkers of the furnace.

2. Chemical specifications (in weight percentage):

		Flint	Amber
Fe_2O_3	not over	0.025	0.12
TiO_2	not over	0.03	0.10
CaO	not over	0.10	0.10
MgO	not over	0.10	0.10
organic		tr	0.10
SiO_2		rest	rest

There is some slight latitude in the above, depending upon the exact composition of each of the other glassmaking raw materials contributed to the batch.

It can readily be appreciated that for flint-grade glass sand, the requisite extremely low iron content is commonly the critical factor in the evaluation of the deposit. Very few sands and sandstones contain so little iron naturally; hence they may require beneficiation. The Sylvania is one of those very rare sandstones that are exceedingly low in iron, and consequently it requires no beneficiation.

3. Mineralogical specifications

Especially undesirable are certain heavy detrital accessory minerals ("refractory heavy minerals", or R.H.M.) that occur in sandstones, e. g., kyanite, sillimanite, corundum, etc. which do not melt at glassmaking temperatures and remain as "stones". Again, because of its protracted geological history, the Sylvania is not only essentially devoid of most R.H.M., but is very poor in *all* heavy detrital accessory species.

	Flat Glass	Container Glass
SiO_2	72.0%	73.0%
Na_2O	16.5	18.0
CaO	9.0	7.0
MgO	1.5	0.5
Al_2O_3	1.0	1.5
	100.0	100.0

Table 4. Compositions of soda-lime glasses.

Geology

Distribution and Thickness

The Sylvania has a very restricted outcrop, or sub-drift distribution, appearing as a narrow northeast-southwest strip across the southeastern corner of Michigan and extending southward into northern Ohio as an even narrower belt. South of Detroit it underlies the

Detroit River and in the subsurface it extends barely into the southwesternmost corner of Ontario. The shape of the near-surface area looks like the letter "C", open to the southeast. The length of the strip from its southern end in Ohio to the Detroit River is about 55 miles, and the near-surface extent eastward into Ontario is about another 20 miles. In Lucas County, Ohio, the formation averages about 50 feet in thickness increasing northward to about 90 feet in Wayne County, Michigan.

Dipping northwestward into the Michigan Basin, to the northwest the formation disappears beneath younger strata and thickens in this direction to a maximum thickness of nearly 400 feet in the subsurface of the southeastern corner of Washtenaw County, Michigan. In Ontario the maximum recorded thickness is 125 feet.

Stratigraphic Relations

The Sylvania is a blanket, mainly orthoquartzitic sand body of Lower Middle Devonian age. It forms the base of the Detroit River Group in southeastern Michigan and adjacent Ohio and Ontario. In Table 5, the stratigraphic position of the unit and its relationship to other stratigraphic units of the area as well as equivalency with units of other areas are shown. The Sylvania Sandstone is considered to immediately overlie the Bois Blanc Formation in southeastern Michigan. Above the Sylvania is the rest of the Detroit River Group consisting of the Amherstburg Dolomite, the Lucas Dolomite and the Anderdon Limestone. An unconformity separates the top of the group from the next formation, the famous Dundee Limestone. Thus the Sylvania Sandstone is a clastic "break" in a major carbonate sequence, a position that can be interpreted as a hint toward a marine site of deposition.

In northern Ohio the Sylvania rests disconformably on the Raisin River Dolomite of the Silurian Bass Islands Group. However, to the north in the Michigan subsurface, the Devonian Bois Blanc Limestone is interposed beneath the Sylvania and Raisin River. Thus from north to south the Sylvania lies on progressively older rocks. Southeastward, erosion has truncated the Sylvania.

Structure

In southeastern Michigan the Sylvania dips at a very low angle northwestward toward the center of the basin. In Ohio, it lies on the flank of the Lucas County monocline, dipping about 6^{o} west. The strike of the beds in southwestern Ontario is east-west, dipping at a low angle northward. This change in attitude of the Sylvania beds involves a flexure around the nose of a broad, north-plunging anticline, probably the northern extension of the Findlay Arch.

The eastern end of the Sylvania in Ontario is deflected southward along the side of the Chatham Sag, the axis of which strikes northwest-southeast.

Exposures

In Michigan the recorded surface exposures of the Sylvania are known at the following localities:

1. Ottawa Silica Company, Rockwood Quarry (formerly Michigan Silica Company), NE¼, Section 15, T5S, R10E. About one mile east-southeast of Rockwood, Wayne County (Figures 5, 6).

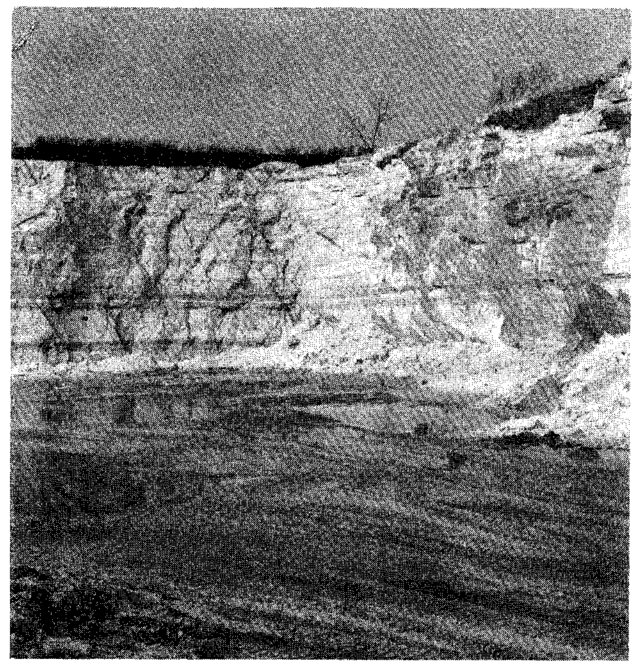

Figure 5. Face of the Ottawa Silica Co. Quarry, Rockwood.

2. Maumee Stone Company Quarry, SE¼, Section 29, T5S, R10E. Wayne County (Hatfield et al., 1968, locality B).

3. Twin Lakes Park (Toll's Pits), SE¼, Section 3, T6S, R8E. See also Sherzer (1900, p. 54). About 7 miles northwest of Monroe, Monroe County.

4. Cummins Quarry, SE¼, Section 2, T8S, R6E. About 6½ miles south-southeast of Petersburg, Monroe County, exposed in 1948-1949 in a 2-ft deep trench in the quarry floor.

5. Monroe County Quarry, SW¼, Section 13, T6S, R7E, Monroe County (Hatfield et al., 1968, locality D).

Epochs	Stages	New York (Generalized)	Northern Michigan	SE. Michigan and NW. Ohio
Upper Devonian	Conewango	Oswayo Fm.	? ?	? ?
		Cattaraugus	Antrim Shale	Antrim Shale (SE. Michigan)
	Cassadaga	Conneaut Group		
	Chemung	Chemung Ss.		Ohio Shale (NW. Ohio)
	Finger Lakes	Enfield Shale		
		Ithaca Shale		
		Genundewa Ls.	Traverse Group: Squaw Bay Ls.	
Middle Devonian	Taghanic	Geneseo Shale		
		Tully Formation	Thunder Bay Limestone	
			Potter Farm Formation	
	Tioughnioga	Hamilton Group: Moscow Fm.		
		Ludlowville Formation	Norway Point Formation	
			Four Mile Dam Fm.	Ten Mile Creek Dolomite
	Cazenovia	Skaneateles Formation	Alpena Ls.	
			Newton Creek Limestone	
			Genshaw Fm.	
			Ferron Point Formation	Silica Formation
			Rockport Quarry Ls.	
			Bell Shale	
		Marcellus Formation	Rogers City Ls.	
			Dundee Ls.	Dundee Ls.
	Onesquethaw	Onondaga: *Paraspirifer acuminatus* Zone		
			Detroit River Group	Detroit River Gp.: Anderdon Ls., Lucas Dol., Amherstburg Dolomite, Sylvania Ss.
		Amphigenia Zone	Bois Blanc Formation	Bois Blanc Fm. (SE. Mich., only)
Lower Devonian	Deerpark	Oriskany Ss.	Garden Island Formation	
	Helderberg	Helderberg Group		

Table 5. Correlation of the Devonian rocks of New York, northern Michigan, and southeastern Michigan and northwestern Ohio (Ehlers et al., 1951).

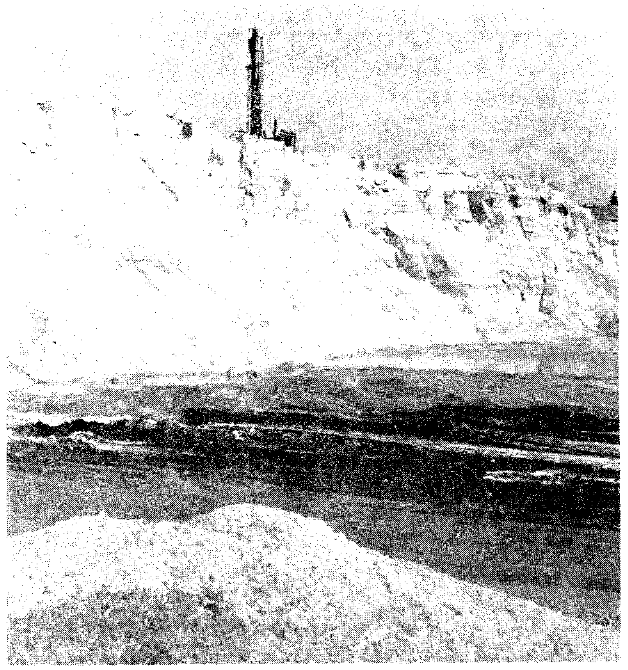

Figure 6. Operations of the Ottawa Silica Co., Rockwood. Blasted sand from face on center and left. Drill on stripped, upper bench.

6. Bed of the Raisin River near Grape:

   a. "At ford"
   b. Opposite claim 275

   (Sherzer, 1900, p. 53)

The specific Ohio localities are described by Carman (1936):

1. France Stone Company, near Silica, 3 miles southwest of Sylvania, Lucas County.

   a. W½ Section 17, T9S, R6E.
   b. NW¼ Section 20, T9S, R6E.

   (Ehlers et al., 1951, Figure 1)

2. Holland Quarry of France Stone Company, center, Section 29, T2N, R10E, about 2 miles southwest of Holland, Lucas County.

3. Metzger Ridge Quarry, SE¼, Section 1, T6N, R9E, about 8 miles southwest of Maumee, Lucas County.

4. Falls of the Maumee River, SW corner, Section 25, T6N, R9E, about 11 miles southwest of Maumee, Lucas County.

Subsurface Distribution and Characteristics

Enyert (1949) and Landes (1951) have shown that in the subsurface the Sylvania forms an arcuate trough which has a maximum depth of about 350 feet. This trough was eroded in pre-Sylvania time in a terrain developed on Bois Blanc and Bass Islands rocks.

In the subsurface of the Lake Erie environs and in southeastern and central Michigan the Sylvania is chiefly a sandstone, but dolomitic sandstone and dolomite also are present. In wells of five Michigan counties a persistent chert bed has been logged 20 to 50 feet above the base of the formation.

Along the northwest axis of the subsurface trough thickness variations in the Sylvania define two sub-basins. The southernmost basin has its center under eastern Washtenaw County where a maximum thickness of 393 feet has been logged in the Ypsilanti Development Company's Fred Voorhees No. 1 well in NE¼ NE¼ SE¼ Section 32, T2S, R7E, Superior Township, Washtenaw County (State Permit No. 3828). The northernmost has its deepest part in eastern Gladwin and western Clare Counties where at least 294 feet of interlayered sandstone and sandy dolomite were penetrated by The Pure Oil Company's D. G. Thompson No. 1 well in C-N½ NW¼ SE¼ Section 3, T20N, R3W, Franklin Township, Clare County (State Permit No. 9590). Landes (1951) extends the northern sub-basin northwestward through the Michigan basin to terminate probably in Crawford, Kalkaska, Wexford, and Lake Counties. Briggs (1959, Figure E) presents a slightly different subsurface picture. He shows the sandy facies of the Sylvania continuing a much shorter distance northwestward, to about the middle of the Southern Peninsula. According to Briggs this sandy tongue is fringed both on the northeast and southwest by belts of sandy dolomite.

At least one tract in the "outcrop area" in Monroe County has been drilled specifically for evaluation as a glass sand. In 1957, 24 holes were drilled in a tract of 420 acres in Sections 19 and 20, T5S, R10E, and in April 1977 a single new hole was drilled in the same tract. From the logs of these drill holes the following major units can be recognized:

1. Overburden: clay, sand, and gravel of Pleistocene age, averaging slightly over 30 feet in thickness.

2. Dolomite and dolomitic sandstone of the Amherstburg Formation. This grades downward into the upper part of the Sylvania, and the exact contact is difficult to locate precisely. On the tract much of this formation has been eroded to varying depths, with thicknesses of the remnants ranging from about 4 to 20 feet. In about one-third of the holes it apparently is absent.

3. The Sylvania Formation, 20 to 70 feet thick. The formation appears to be appreciably thicker under the western part of the tract. The average thickness is 40 feet.

4. Dolomite. Barely penetrated in most of the drill holes. Locally cherty.

Geology at Rockwood

Stratigraphy

The Rockwood Quarry, which presents the best available exposure of the Sylvania, has been studied in detail by Del Greco and Heinrich (1973). Four subunits which are present throughout the quarry exposures are readily recognizable in the southern pit but are less sharply defined in the northern pit. The units, from the base upward, are described as follows:

Unit A: At the bottom it is an off-white, friable sandstone which includes lenticles of somewhat more consolidated sandstone. Individual sand grains are subrounded and range in size from coarse to medium. The sandstone of this unit contains very little other than quartz and a very few pink feldspar grains. Individual beds are 0.05 to 0.1-foot thick, separated by at least 20 darker bands about ⅛ inch in thickness. These brownish bands represent essentially the only visible internal structure of this unit (Figures 7, 8).

Unit B: This unit, which is 9 to 10 feet thick, is much more strongly consolidated than Unit A and weathers to a somewhat darker brownish hue. It contains very few of the thin dark bands, and these commonly show cross-bedding and truncation (Figure 9). No accessory pink feldspar grains were noted; only clear or milky quartz grains were seen. These are in the coarse to medium size range, and are rounded to well-rounded. Conspicuous dark, carbonaceous bands occur at the base, 4 to 5 feet above the base and at 7 feet above the base.

Unit C: This unit is a very well-consolidated, hard rock compared to the other units (Figure 10). Bands and lenses with high carbonate cement content are common. It also contains numerous bands of high carbonaceous content, some of which contain an appreciable percentage of very fine-grained sand-sized or even silt-sized particles. This unit contains the highest amount of carbonaceous material.

Unit D: Unit D is almost an exact duplicate of Unit B. It consists of very white, friable sandstone.

At the base of Unit A an unconformity separates the Sylvania from the underlying Bois Blanc Limestone. This surface, which is gently undulating and serves as the bottom of quarrying operations, is marked by major concentrations of black carbonaceous material, locally in pockets in the top of the limestone in lensoid masses over an inch thick. The carbonaceous material, which appears to be identical with that in bands and disseminated in the Sylvania itself, is black, soft, and friable, crumbling readily into fine flakes.

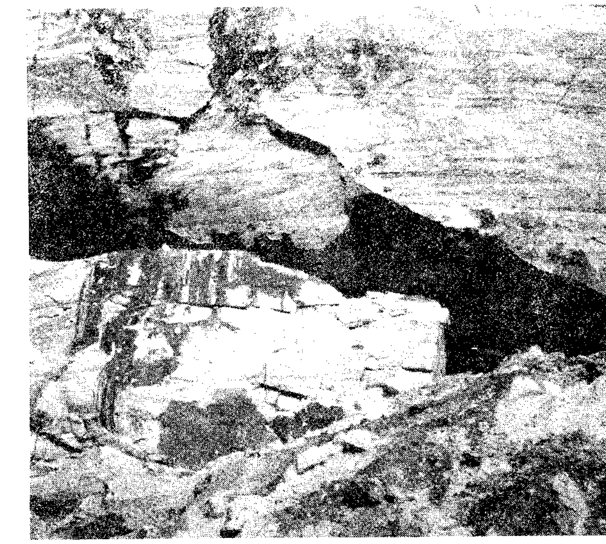

Figure 7. Unit A, Sylvania Sandstone, Rockwood.

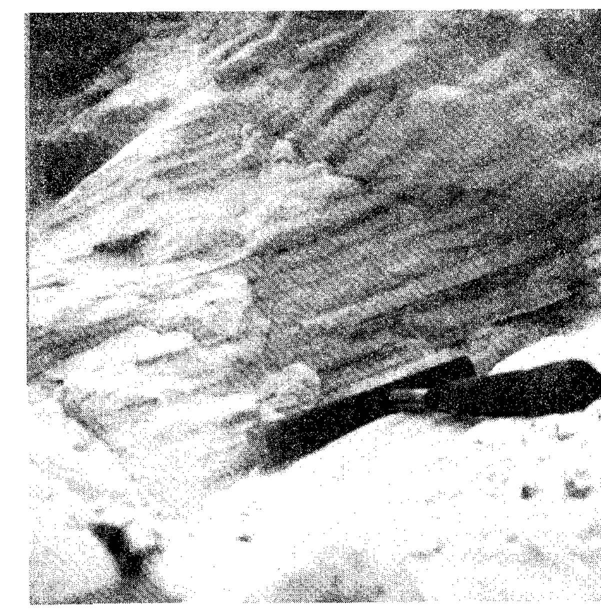

Figure 8. Small-scale banding, Unit A, Sylvania Sandstone, Rockwood.

Structures

Small-scale primary sedimentary structures are conspicuous in many of the quarry-face exposures. These include: cross-bedding

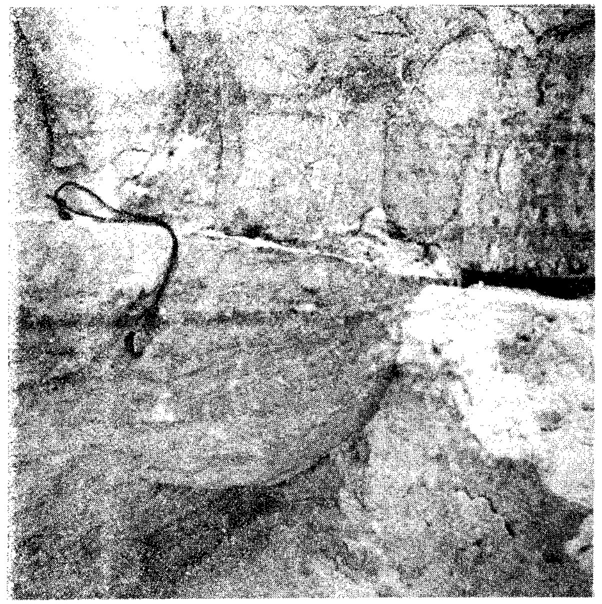

Figure 9. Cross-bedding in Unit B, Sylvania Sandstone, Rockwood.

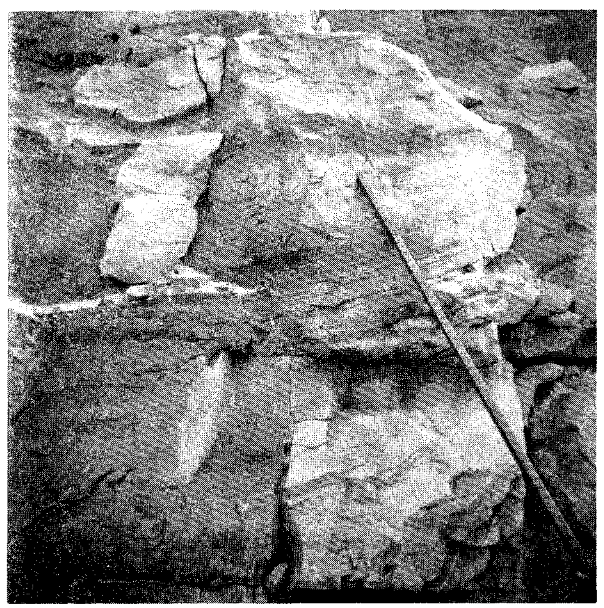

Figure 10. Well-consolidated sandstone, Unit C, Sylvania Sandstone, Rockwood.

(abundant), ripple marks, rip-ups, small-scale unconformities, and worm (?) burrows. Secondary structural features are vugs with crystals, crystal casts, joints, and faults with small-scale strike-slip displacements.

The most conspicuous of the structures is the cross-bedding which is usually defined by thin films or layers of black carbonaceous detrital material. The cross-bed sets vary greatly in thickness from 0.3 foot to 3.4 feet. Dips range from 5° to about 30°, with an average of about 20°, and the preferred dip is to the northwest. This coincides with the regional dip and with the direction of thickening of the formation. In the northern part of the quarry there are many northeasterly-dipping sets. These include tangential and torrential types, but the tabular types are most common. Torrential crossbeds are generally on an erosional base.

Common in some zones are rip-ups and pseudobreccias representing a disruptive environment (Figure 11). None of these disrupted zones forms a well-defined layer throughout the quarry. Less extensive rip-up zones and individual rip-ups are common at several levels in the unit. Disruptive characteristics increase in abundance to the north and east.

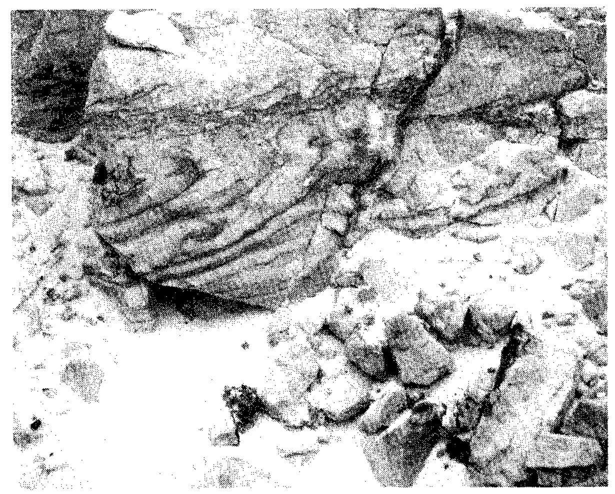

Figure 11. Rip-up zone, Sylvania Sandstone, Rockwood.

Burrows are extremely common and widespread throughout the quarry (Figure 12). They are most obvious in the whiter layers but also occur in some of the brown bands. The burrows are more or less vertical and almost invariably have their upper surface at one of the black carbonaceous layers (Figure 13). Burrows cut across the cross-beds and contain material possessing slightly different texture and color compared to the sand surrounding them. A common difference is that the amount of carbonate cement in the burrow material is somewhat greater than in its surrounding sandstone.

Vugs with calcite crystals are common in an apparently irregular distribution. Less common but not rare are vugs containing both calcite and celestite crystals. Some of the calcite occurs as "nail-head" crystals. These vugs range in size from very tiny holes to crystal-lined cavities over a foot long. A vug is recorded that measured 22 x 15 x 8 inches containing celestite crystals 2¼ x 5 inches in size (Heinrich, 1976). Vugs are

Figure 12. Sandstone bed with extensive worm burrows, Sylvania Sandstone, Rockwood.

Figure 13. Bottom view of worm-burrowed bed, showing ends of burrows (light spots) and abundance of carbonaceous debris at base of layer, Sylvania Sandstone, Rockwood.

most common in those sections of the sandstone with a high percentage of carbonate cement. Larger ones are most commonly found along or adjacent to thicker layers rich in black carbonaceous material. Frequently the vugs are localized on the bottom surface of a cross-bed set. Vugs are more common in the south quarry.

Crystal molds, rectangular in shape and usually small, are common. No trace of the original mineral has ever been found. Stylolites are common in the more dolomitic parts of the sandstone.

Petrology

General

The Sylvania is a supermature quartz arenite. It is weakly to moderately cemented locally, and strongly cemented in some layers by carbonate, chiefly dolomite. In some places it is slightly orthoquartzitic; and silica becomes an important cementing agent in some places. The chief impurity, beyond dolomite, is finely macerated carbonaceous trash. The assemblage of heavy accessory detrital minerals is severely restricted in number of species and in total amount.

Grain Characteristics

The sandstone is well sorted. Mechanical analyses by Grabau and Sherzer (1910) are presented in Table 6, and similar data in histogram form are given by Carman (1936) for the Sylvania in Ohio.

Grain size distribution maxima vary considerably both vertically and horizontally. According to Hatfield et al. (1968) the modal, mean, and median sand grain sizes are each very near 0.25 mm, and in most samples 90 to 98 percent of the grains lie between 0.1 and 0.5 mm in size. Enyert (1949) found no marked general grain-size frequency variations along the strike. There appears to be a tendency for sands at any one locality to be coarser in the upper part of the section when compared to those from the lower part of the formations. He also noted that in the well of the International Salt Co., Inc. (Parcel B-1, Private Claim 49, Melvindale, Ecorse Township, Wayne County, Michigan), an inverse relation existed between grain size and percentage of carbonate cement. The higher the percentage of carbonate, the smaller the quartz grain size.

Grabau and Sherzer (1910), in studying grain shapes, commented (pp. 77-78) ". . . not only the corners and edges are rounded but the body of the granule approaches the sphere or ellipsoid." A typical sample of flint-grade glass sand is shown in Figure 14. In general the larger grains are well rounded, whereas the smaller sizes show a tendency toward greater angularity, a relationship that stems from the fact that the smaller-sized grains more commonly have had their detrital shapes modified via secondary enlargement by silica cement.

Grabau and Sherzer (1910, p. 78) also noted the characteristic surface feature of many grains: "The surfaces of the Sylvania granules, except those secondarily enlarged, do not show the vitreous luster of quartz fragments but, under the microscope, are seen to be roughened and pitted, and to present the appearance of frosted glass." This frosting and pitting were attributed by Grabau and

No.	Sand No. 10 sieve 1.80 mm mesh	On No. 20 0.80 mm mesh	On No. 30 0.50 mm mesh	On No. 40 0.42 mm mesh	On No. 50 0.35 mm mesh	On No. 80 0.18 mm mesh	On No. 100 0.16 mm mesh	On No. 200 0.08 mm mesh	Through No. 200 0.08 mm mesh	Average size of grain determined by the aspirator method
	Toll's pit	%	%	%	%	%	%	%	%	mm
1	One ft. down	0.05	0.40	3.50	9.05	58.78	16.52	9.80	1.90	0.2454
2	6 ft. down	0.00	1.55	9.42	19.98	51.70	6.25	6.25	4.85	0.2385
3	11 ft. down	0.00	0.55	2.10	18.18	65.72	7.05	4.65	1.75	0.2841
4	16 ft. down	0.00	0.00	3.40	29.03	61.52	1.95	2.10	2.00	0.2967
5	21 ft. down	0.00	0.00	2.85	6.31	76.83	8.36	4.20	1.45	0.2660
6	26 ft. down	0.00	1.80	1.95	4.05	42.46	31.92	13.37	4.45	0.1810
	Rockwood									
7	4 ft. down	0.00	0.40	7.65	40.50	50.60	0.50	0.25	0.10	0.3950
8	15 ft. down	0.00	0.60	0.60	2.35	70.45	16.60	9.10	0.30	0.2392
9	20 ft. down	0.00	0.35	6.65	34.10	53.70	2.30	2.25	0.65	0.3497
	Detroit salt shaft									
10	Near top	0.00	1.00	7.51	11.51	43.20	19.52	16.11	1.15	0.2448
11	440 ft. down	0.00	0.10	3.00	15.35	64.93	8.35	6.85	1.40	0.2513
12	450 ft. down	0.00	0.65	6.90	15.95	59.70	11.10	5.30	0.40	0.3071
13	460 ft. down	0.00	0.85	7.55	14.45	44.90	18.70	12.20	1.35	0.2766
14	460	0.00	0.75	7.23	16.00	47.35	16.16	11.65	0.82	0.2760

Table 6. Mechanical Analysis of the Sylvania Sands (Grabau and Sherzer, 1910)

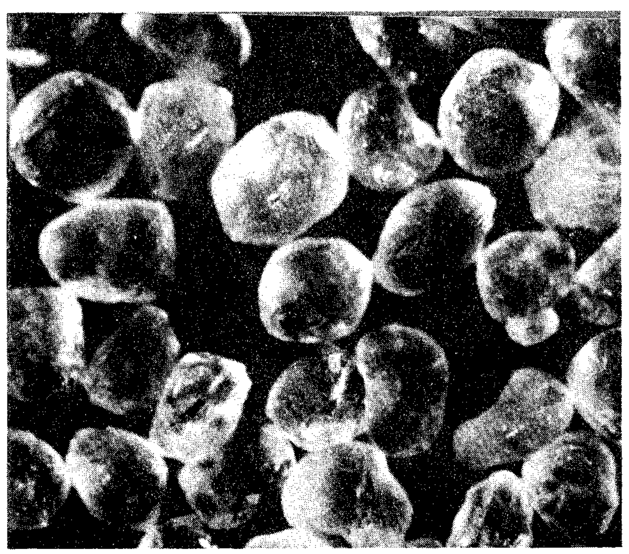

Figure 14. Glass-sand product of Ottawa Silica Co., Sylvania Sandstone, Rockwood. Compare with Figure 15. Both figures approximately 60x.

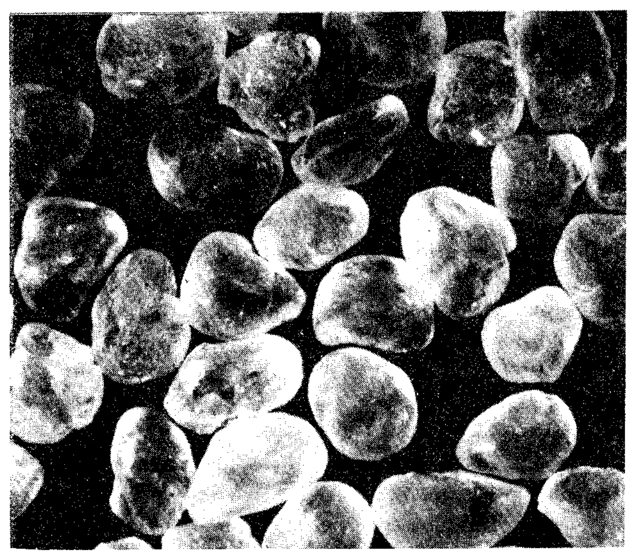

Figure 15. Glass-sand product of Ottawa Silica Co., St. Peter Sandstone, Ottawa, Illinois. This sandstone is regarded as the parent of the Sylvania Sandstone.

Sherzer (1910) to eolian transportation and abrasion. In addition, however, Briggs (1959) observed that some frosted grains have a superimposed polish, an important bit of evidence supporting the concept of a genetic duality in the sand environment. Fabric analyses by Hatfield et al. (1968) show that preferred orientation of the long axes of sand grains is within 15° of the cross-bed azimuth of the unit from which the sample was obtained (for 19 out of 25 thin sections).

Throughout the Rockwood Quarry the sandstone is highly quartzose. Whatever cement is present is most commonly dolomite and the amount tends to increase upward. Silica and very minor calcite are only local cements. The quartz grains average 0.25 mm, and at any one quarry locality there is a tendency for the grains to become coarser upward in the section.

Accessory Minerals

Enyert (1949) made a detailed study of the accessory minerals and their distribution. His data are reproduced in Table 7. Of the species he lists, celestite, anhydrite, pyrite, anatase and fluorite are authigenic, and limonite is supergene.

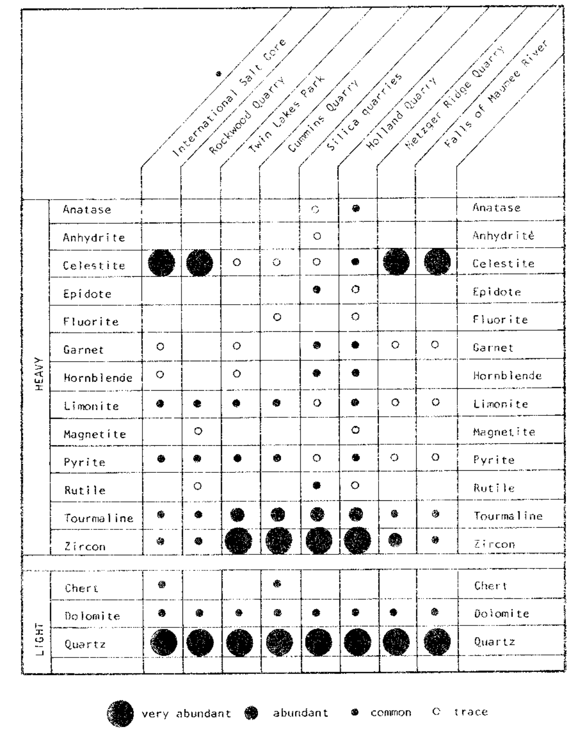

Table 7. Heavy and light accessory minerals of the Sylvania (Enyert, 1959).

The only persistent detrital accessories are zircon and tourmaline which also were the only ones noted on the study of the sandstone at the Rockwood Quarry (Del Greco and Heinrich, 1973). Hatfield et al. (1968) found only zircon and tourmaline.

A more varied suite is reported by Alty (1933), but, unfortunately, only three of the well cores she used are now regarded as having penetrated the Sylvania. Alty (1933) noted some unusual colorless authigenic tourmaline overgrowths on dark detrital tourmaline grains in Detroit River rocks.

The total percentage of accessory minerals is small. Enyert's data (1949) includes both the detrital and authigenic species.

Mineralogy of the Carbonaceous Material

The black carbonaceous material which is concentrated as flakes in both the horizontal layers and dipping foreset cross-beds forms relatively thick "pure" lenses at the basal unconformity. This material is in sufficiently large pieces that they can be studied via the electron microprobe. Whereas the accessory mineralogy of the sandstone is relatively simple, the mineral assemblage in the carbonaceous lenses is unexpectedly complex. It includes: 1) native sulfur: abundant; some encloses dolomite rhombs; some enclosed spheroids of ?; 2) pyrite; 3) rutile; 4) corundum; 5) dolomite; 6) apatite: one grain noted; 7) zircon; 8) tourmaline; 9) quartz; 10) potash feldspar - two types, one fluoresces red, the other blue-gray, 11) plagioclase: andesine?; 12) sericitic muscovite; 13) Fe- Ti-rich mica; and 14) illite.

The carbonaceous material, which serves to cement this assemblage, could not be dissolved or dissociated by hydrochloric acid; nor were any relict organic structures discernable within it.

Cement

Whatever cement is present is overwhelmingly dolomitic. Minor calcite occurs locally. Some pre-carbonate silica cement in oriented authigenic quartz overgrowths tend to favor the smaller-sized quartz grains. The amount of dolomite is highly variable, even at any one locality. Enyert's (1949) results are:

1. Rockwood Quarry — 5% dolomite (1.3 - 6.12%)
2. Twin Lakes Park — 8% (5.27 - 12.90%)
3. Cummins Quarry — 60.15%
4. Silica Quarries — 14% (8.15 - 22.18%)
5. Holland Quarry — 10% (5.81 - 14.90%)
6. Metzger Ridge Quarry — 58.16%
7. Maumee River Falls — 48.95%
8. International Salt Co. Well — 6% (2 - 11%)

It would thus appear that the content of dolomite increases southward, but it must be pointed out that the values for localities 4 through 7 are based mainly on samples from only the upper part of the Sylvania, which, in general, is more dolomitic than the middle and lower.

In the drilled tract the core logs report considerable dolomite, the content of which varies markedly. Here dolomite is reported as:

1) minor to subordinate cement in sandstone; 2) hybrid dolomitic sandstones; and 3) interlayered beds of dolomite.

Chemical Composition

Very few analyses and partial analyses of the Sylvania Sandstone are available. (Table 8).

	Percent	
	Crude	Washed
SiO_2	96.50	99.70
$CaCO_3$	1.50	0.08
$MgCO_3$	1.04	0.22
Fe_2O_3	0.00	--
H_2SO_4, loss & n.d.*	0.76	--
ignition loss	0.20	

*not determined

Table 8. Chemical composition of Sylvania Sandstone, Grabau and Sherzer (1910); Poindexter and Newcombe (1928).

Poindexter and Newcombe (1928) also state (p. 134) that ". . . it is possible under careful supervision to obtain carload lots of glass sand which average 0.015 percent iron oxide, and some analyses running as low as 0.001 percent iron are reported." In general the sand of the Sylvania has been famous for its very low Fe_2O_3 content, ranging, in washed form, from 0.02 to $<$ 0.01.

The sand on the drilled tract also is very low in iron, less than 0.02 percent Fe_2O_3. It averages higher in dolomite, $\sim$ 4 to 5 percent, than the material from the Rockwood Quarry.

Economic Considerations

The Sylvania qualifies as one of the premier glass sands of the world because of the following factors:

1. Chemical and mineralogical composition. It is exceedingly low in Fe_2O_3, Al_2O_3, and alkalies and refractory heavy minerals. Dolomite and carbonaceous material are the chief impurities. The latter is removable by washing. Dolomite can be removed partly by washing, but some sections of the Sylvania will have to be beneficiated by flotation to bring the dolomite down to acceptable levels.

2. The deposit is favorably located with respect to glass production plants in Michigan, Ohio and Canada.

3. Large reserves are present.

The chief problem inhibiting long-continued production in the area involves restriction of quarrying operations by local zoning ordinance. In addition to glass sand, other products include abrasive sand and silica flour.

Origin

The paleoenvironment of the Sylvania has been discussed by Grabau and Sherzer (1910), Carman (1963), Briggs (1959), Hatfield et al. (1968) and Del Greco and Heinrich (1973). Grabau and Sherzer (1910) first developed the theory of eolian deposition. Their model postulated derivation of the sand from some source area to the northwest, probably an outcrop area of the St. Peter Sandstone, and the wind transportation of the material across the then arid intervening area (now part of Michigan). They were led to the conclusion of eolian deposition by several features displayed by the unit in southern Michigan, such as the exceptionally well-rounded grains, the uniformity of grain size, extreme purity, and extremely well-developed cross-bedding. Carman (1936) pointed out that the Sylvania Sandstone in Ohio does not have many of these eolian features. Instead, it displays some undeniable indications of marine deposition. The prominent bedding is replaced by the characteristic bedding of aqueous deposits. Fossils that are common in the sandstone and in the transition beds above it represent marine organisms. Only in a few local areas in Ohio is prominent cross-bedding found. This cross-bedding may be an indication that eolian processes were important in these areas.

Carman's (1936) interpretation is that the Sylvania Sandstone is younger in Ohio than it is in Michigan and that it was deposited in two distinct phases or steps. First, an eolian deposit developed in southeastern Michigan and western Ohio. Then the advancing Detroit River sea overran eolian sand and reworked it, later redepositing it under marine conditions. Thus, the Sylvania would represent a deposit at the margin of an encroaching sea. Briggs (1959) gave a good generalized description of the dual origin mechanism. According to his description the Sylvania is primarily a body of marginal sand at the leading edge of a transgressing boreal sea. The sea may well have reworked the sand but its main function was to serve as an agent of immobilization. Sand was swept southeasterly from Wisconsin by the wind. Water then acted as a sink and held the sand, preventing further wind drifting. Eventually, some carbonate deposition would bind the sand.

According to Summerson and Swann (1970) the Sylvania is not unique but is one of many such formations from the period ranging from the Middle Precambrian to the Upper Devonian. Under this scheme the Devonian was the last

episode in the series before sands from another source were introduced, causing an end to the closed system of clastic sedimentation that dominated the lower Paleozoic. The same detrital material first derived from the Precambrian rocks of the Canadian Shield and other sources had been trapped in the depositional and erosional cycle, with very little input from outside the system. In the Devonian, Cambro-Ordovician rocks of Wisconsin were eroded and sand was picked up by winds. Wind transport would be relatively undisturbed until gentle upward changes in topography associated with the arches to the southeast stopped the sand movement. Dune buildups and some sheets of sand formed in front of these obstructions. Successive marine invasion immobilized the sand, causing some reworking and mixing with carbonate. The area of maximum deposition would probably have been a beach area with an oscillating shoreline. Thus the provenance area of the sand was to the northwest and the paleoslope also was toward the northwest (Hatfield et al., 1968). Here is a case where direction of the source area is not indicated by the paleoslope. Thus, the Sylvania is at least a third-cycle sandstone from reworked St. Peter Sandstone, which accounts for its super-maturity.

Thus, the main points in the genetic model are:

1. The environment was of high energy in a beach area (i. e., both marine waves and river currents) of a transgressive sea, with a shoreline oscillating over a zone 20-30 miles wide.

2. Much, if not most, of the sand was transported to the beach area by winds and there reworked.

3. The paleoslope of deposition was northwestward away from the Findlay Arch.

4. The source of the sand grains is believed to have been mainly Devonian outcrops of Ordovician St. Peter Sandstone to the northwest. The original source of much of the St. Peter sand was pre-Croixan sandstones and quartzites along the southern margin of the Canadian Shield. Thus, the St. Peter is at least a second-generation sandstone, and the Sylvania is at least a third-generation sandstone.

MARSHALL SANDSTONE

Grindstone Industry

Although today grindstones are collected as antiques, suitable for lawn decorations, in the late 1800's they were generally and widely used in agriculture and industry for sharpening metal tools. Grindstones from Huron County, Michigan, were sold throughout the United States and in some foreign countries. The stones range from a five-pound "kitchen stone", to somewhat larger scythe stones, to large factory "wheels" weighing nearly 9,000 pounds and more than seven feet across. The largest stones had faces 14 inches across. Stones shaped from the Marshall sandstone (the sandstones are most likely those in the upper part of the Coldwater shale) in Huron County were regarded as the most valuable found in the United States, and this "Lake Huron bluestone" set the standard for the abrasive-stone industry. Although in 1892 the quarries produced 10,000 tons of grindstones and 12,000 gross of scythestones, demand continued to exceed the supply.

The grindstone quarry industry, one of the earlier industries developed in Huron County, was started by A. C. Peer in 1850. Production in the latter part of the 19th century came mainly from two quarries: those of the Cleveland Stone Company in Sections 24 and 25, T19N, R13E and that of the Huron Grindstone Company in Section 23, T19N, R13E, both at Grindstone City. However, much of the sandstone along the shore of Lake Huron to Section 30 had been worked over by the turn of the century, the waste stone having been discarded into the old workings which were subsequently built over. Quarries near Bayport, worked before the 1890's exposed several layers of fine- to coarse-grained sandstone, six to ten feet thick, of quality similar to that at Grindstone City.

The Marshall Sandstone at Grindstone City was termed a grit owing to the angularity of its quartz grains. The most uniform bed, in the lower part of the Marshall, was about 15 feet thick, homogeneous or with obscure cross-bedding. In some cases cross-bedding prevented production of larger-sized grindstones. The sandstone locally also contained thin conglomerate beds ("peanut conglomerate") and scattered pebbles, the presence of both of which resulted in much waste stone. The stone was regarded as particularly valuable because it did not glaze with usage. This behavioral property resulted from the fact that the sharp quartz particles were set in a cement of clay, detrital muscovite and siderite which wore away at a rate just fast enough to prevent the rock surface from polishing. Because of this, a new crop of sharply angular grinding edges was continuously supplied to the abrasive surface. Thus, the unique character of the stone resulted from the combination of uniform grain size, angularity of the particles, and degree of cohesion of the matrix.

Waste material also was used locally as a building stone and for gravestones. It had a pleasing blue to bluish-gray color. However, Lane (1900, p. 206) states, "It is a much better grindstone than building stone."

In 1912 the following grindstone producers were listed:

1. Eureka Grindstone Company, quarry at Austin;

2. John Holland, quarry at Caseville;

3. Cleveland Stone Company quarries at Grindstone City and Port Austin.

4. The Wallace Company, quarry at Eagle Mills.

The sandstone also was quarried on a small scale in Sanilac County, in NW¼, Section 17, T14N, R13E, where the rock was thin-slabby and suitable only for small grindstones. Cleveland Stone and Wallace also continued to produce scythestones, and in 1913 only these two companies continued in production of both grindstones and scythestones. Both operations continued to World War I but ceased during the war. In 1923 the Cleveland Stone Company resumed operations. At that time production was relatively small, Michigan ranking far behind Ohio (the leader) and West Virginia in the production of grindstones. Production apparently ceased entirely in the early 1930's.

Napoleon Sandstone

Previous Work

The Napoleon Sandstone was named and identified as a stratigraphic unit by W. H. Taylor (1839) and was first described in detail by A. Winchell in 1861 as consisting of (descending):

1. Shaley, micaceous sandstone - 15 ft.
2. Sandstone (Napoleon Sandstone, *sensu strictu*), locally saline - 78 ft.
3. Shaley, micaceous sandstone - 15 ft.
4. Shale - 10 to 64 ft.

No detailed studies were made between the late 1800's and the 1930's. In several Annual Reports of the Michigan Geological Survey, beginning about 1916 and continuing for several years, the quarrying of the sandstone is reported with the remark that the Marshall sandstone contains "iron carbonate" which alters to limonite, resulting in an "unsightly yellow color" on the building stones.

In the early 1930's a petrographic study of the Marshall Formation (which includes the Napoleon), based on the examination of drill cores from numerous wells, was made by Stearns and Cook (1932) and by Stearns (1933). Stratigraphic studies were completed by Thomas (1931), Monnett (1948) and McGregor (1953, 1954). The paleontology of the Marshall has been documented by Driscoll (1961). Quarries in the Marshall Formation (Napoleon member) in southwestern Michigan are listed and described by Squire (1972). The peculiar discoidal sedimentary structures that occur in the Napoleon and formerly were regarded as fossils by some collectors, were described and genetically identified by Dorr and Kauffman (1963) as sand-fillings of whirlpool scour-cavities.

A geological and petrographical study of the Napoleon Sandstone was conducted by the writer in 1976. The purpose of this study was to determine the economic potential of the unit. Field work in Jackson County consisted of detailed examination of quarry exposures and the collection of a series of hand specimens, subsequently examined petrographically.

General Geology

The Napoleon Sandstone is the upper of two units in the Marshall Formation:

Marshall Formation	Napoleon Sandstone
	Marshall Sandstone (also called Lower Marshall Sandstone)

The unit is of Early Mississippian age (Osagian). The Marshall overlies the Coldwater Shale and, in turn, is overlain unconformably by the Michigan Formation, which contains evaporite rocks, thus accounting for the saline brines that occur locally in the Marshall. The Marshall Formation occurs mainly in central-southern Michigan and is known chiefly from subsurface occurrences. It is not present in southeastern Michigan.

The deposition of the marine Antrim and Coldwater shales of Early Mississippian time was followed by a major reduction in the seas which caused much of southern Michigan to become a near-shore and beach area, where the sandstones and siltstones of the Marshall Formation were deposited. The high-energy, near-shore environment is documented by the presence in these rocks of ripple marks, cross-bedding and toroids.

Fine sands dominate in the lower Marshall, becoming medium sand in the upper (Napoleon). The formation thickens toward the south.

The Napoleon, the upper member, is described as a white to light gray sandstone, non-fossiliferous and medium- to coarse-grained. In contrast the lower member, the lower Marshall Sandstone, is usually described as being characteristically fossiliferous and finer grained than the Napoleon. However, as has been pointed out by Monnett (1948) and by Squire (1972) the members may be difficult to distinguish because:

1. Fossils are found from time to time locally in the Napoleon member.

2. Many strata in the Lower Marshall are unfossiliferous.
3. Many coarse-grained sandstone beds in the formation occur below fine-grained sandstones.

For these reasons Monnett (1948) decided that the traditional bisection of the Marshall into upper and lower members was inadvisable and unfeasible; nevertheless, usage of the two subdivisions has continued.

Quarries

The Napoleon sandstone is exposed in the following quarries:

1. Napoleon quarries. Two operating quarries are just east of Napoleon in Jackson County on Austin Road. Ray's Stone Quarry, on the south side of the road is in NE¼ NW¼, Section 6, T4S, R2E, and Jude's Quarry, north of the road is in SW¼ SE¼, Section 31, T3S, R2E. (Figure 16).

Figure 16. Jude's Quarry in Napoleon Sandstone, Napoleon.

2. Stoney Point Quarry, Jackson County, in NE¼, Section 31, T4S, R2W, Hanover Township.

3. Hughes Quarry, Marshall, Calhoun County, in NW¼ SE¼, Section 25, T2S, R6W, Marshall Township.

4. Quarry, Emmett Township, Calhoun County. Near line between NE¼ and NW¼, Section 22, T2S, R7W, just north of the Kalamazoo River.

In addition, Napoleon Sandstone is exposed in a road cut at the intersection of 11 Mile Road and D Drive North in NE¼ NE¼, Section 26, T2S, R7W, Emmett Township, Calhoun County (Squire, 1972).

Geology

Stoney Point Quarry: A thickness of about 20 feet of Napoleon Sandstone is exposed in beds ranging from an inch to about a foot in thickness, averaging about two inches. Monnett (1948) studied the petrography of the rock and found 95 percent quartz grains, the rest chiefly feldspar and mica, no carbonate, but some limonite.

Hughes Quarry: Exposed is about eight feet of green-tan sandstone in two-inch layers. This is the type locality of the Marshall (Winchell, 1861).

Emmett Township Road Cut: Squire (1972, p. 13) reports ". . . a ten-foot section of tan to greenish-tan beds one-half to four inches thick. The beds dip slightly to the northeast, and appear to be very similar to those exposed in Hughes' Quarry at Marshall".

Emmett Township Quarry: The quarry, 100 yards across, exposes over 25 feet of the Marshall (Squire, 1972). The upper 15 feet consists of 1- to 2-inch layers of tan rock with some green or gray beds. A few thicker layers display cross-bedding. On the lower part of the exposure the rock is darker and occurs in beds that range up to 30 inches thick. As in the Napoleon quarries, these lower thicker beds do not split nearly as readily as the material higher in the quarry walls.

Napoleon Quarries

Ray's Stone Quarry, on the south side of the road, occupies 13 acres, whereas Jude's Quarry, on the north side, is developed over 9 acres. An additional tract of 18 acres, unquarried, adjoins the northern quarry area to the north. Austin road, which separates them, runs along a ridge, and the land slopes away gently both to the south and north.

The western segment of Ray's Stone Quarry (west of the access road) has a quarry-face length of about 250 feet (east-west) and is 250 to 300 feet long (north-south). This section, with a face 15 to 20 feet high, has been largely quarried out. Two quarry faces are east of the southern access road. The first is 400 feet along the face (east-west) and 15 to 20 feet high; the second, to the east, is 60 feet along its face and 10 feet high. Relatively small amounts of stone appear to remain to the present depth of the quarry floor.

In these faces two types of sandstone can be identified. In the upper 12 to 15 feet the sandstone is slabby with definite stratigraphic separation surfaces at 1½- to 2-inch intervals (Figure 17). The surfaces are slightly wavy. The lower 5 feet ± of the face has sandstone in units 4 inches to 2 feet thick.

Figure 17. Quarry face, Napoleon Sandstone, showing slabby separation planes, Napoleon.

In Jude's Quarry, a small old cut lies west of the access road, and a large L-shaped quarry lies east and northeast of the access road. In addition, a bulldozer cut and a small shallow trench occur several hundred feet northwest of the western segment. As in the southern quarry, two types of sandstone are evident: 1) upper 6 to 10 feet of thin-bedded flaggy sandstone; 2) lower 5 to 6 feet of thicker-bedded (8 inches to 1 foot) sandstone.

The sandstone also shows distinct cross-bedding locally. The more massive lower sandstone, which displays primary bedding planes at 8 inches to over a foot, has smaller-scale laminations (color, grain size) at 2- to 3-inch intervals, along which, however, no breaks are developed.

The main stratification of the sandstone is essentially horizontal.

The sandstone varies in color from olive-gray to gray to gray-buff to light buff. Limonite staining is locally prominent, as: 1) limonite-stained thin bands parallel with the bedding; 2) limonite coating on bedding planes; 3) limonite coatings on joints at right angles or steep angles to the bedding; and 4) disseminated patches in the sandstone. Several joints and minor fracture zones in the western segment of the southern quarry are coated with clay.

The following sandstone specimens were collected:

Nap-1 Northeastern corner of eastern segment of Jude's Quarry; at base of upper slabby 6 feet.

Nap-2 Southeastern corner of face of eastern segment of Jude's Quarry from stockpile of thicker bedded sandstone (4- to 6-inch beds).

Nap-3 Center of southern face of eastern segment of Jude's Quarry.

Nap-4 In new lower quarry (6-foot face) adjacent to and just east of access road to Jude's Quarry.

Nap-5 In new lower quarry (6-foot face) adjacent to and just east of access road to Jude's Quarry. Contains disseminated bright green mineral as particles and fracture coatings.

Nap-6 In old quarry west of access road to Jude's Quarry; in lower bench.

Nap-7 Center of face of western segment of Ray's Stone Quarry.

Nap-8 Northwest corner of eastern segment of Ray's Stone Quarry.

Nap-9 Eastern face of eastern segment of Ray's Stone Quarry.

Nap-10 Easternmost cut of eastern segment of Ray's Stone Quarry.

Most samples yield a distinct to strong clayey odor when moistened. All are highly permeable. None show any effervescence with HCl, indicating the absence of calcite cement.

The Problem of the Thin Slabby Bedding

The thin slabby sandstone grades downward into "thicker bedded" sandstone (Figure 18).

Figure 18. Upper slabby sandstone grading downward into thicker bedded sandstone, Napoleon.

This also was noted by Squire (1972) for exposures in the Emmett Township quarry. However, in the thicker bedded sandstone, the smaller-scale laminations are present, but no separation planes have been formed along them. The thickness of the upper unit of slabby sandstone is somewhat variable, from 6 to 16 feet. Since the present main utilization of the rock depends largely on its thin slabby character, it is most important to consider the origin of the slabby separation planes. Genesis of the separation planes is a significant factor in assaying the distribution of this kind of material and the magnitude of its reserves. Three possibilities present themselves:

1. The closely spaced separation planes are primary; i.e., a feature derived from the sedimentary process that deposited the sandstone.
2. The planes are secondary, developed as sheeting from glacial unloading.
3. The planes are secondary, developed by ground water action from meteoric solutions, or by near-surface frost action.

If the first were valid, additional similar material might be expectable at depth. If 2 or 3 is valid, the slabby rock occurs only close to the present topographic surface. Mechanism 1 appears invalid for three reasons: 1) the upper and lower types of sandstone are petrographically similar; 2) the actual bedding units appear to be the same general thicknesses in both types, but only in the upper are actual separations present; and 3) the slabby type *grades* into the lower type.

Mechanism 2 is also unlikely, largely because glacial sheeting types of joints are known only in, and theoretically are only possible in, massive rocks such as granite.

It appears that hypothesis 3 is the most likely to be valid and, if it is, reserves of this type of material can occur only to a maximum depth of about 15 feet below the present surface, and they may end at more shallow depths. Inasmuch as the road follows the topographic high crest that separates the two quarries and the sandstone beds are horizontal, it is possible that lesser thicknesses of the slabby rock occur as the land surface slopes away to the north on the unquarried "reserve" of 18 acres. *This may not be the case if the separation process operated during the present hydrologic cycle.* If it operated, however, in preglacial time, then slabby material may have been appreciably removed by postglacial erosion.

Quarrying in deeper parts of the southern quarry also encountered only "thick-bedded" sandstone.

This problem of near-surface "thin bedding" has previously been noted, and Sherzer (1900, p. 174) states, "In all the quarries in southeastern Michigan it is found that the surface layers are shattered and thin bedded, probably from the enormous pressure of the ice sheet and subsequent action of the frost."

Petrography

The Napoleon rock is a lithic arenite consisting mainly of two types of particles: 1) quartz grains, and 2) micro-fragments of various fine-grained rocks including sericite-quartz-phyllite and schist, biotite-quartz-schist, slate, quartzite and chert. Over 90 percent of the rock pieces are of low- to medium-grade regional metamorphic rocks of pelitic ancestry.

Feldspar, both plagioclase and some perthite, is relatively abundant, as are detrital muscovite and biotite. Leucoxene is very common. Pyrite occurs as cement in concretionary pods, altering to limonite.

The quartz particles are angular to subangular; rounded grains are uncommon. Sorting is poor to fair. No calcite cement was found. The rock appears to be consolidated simply by packing of quartz grains. It is friable and highly permeable. Locally limonite and even some pyrite serve as cement, as do the detrital micas.

The accessory minerals observed include: leucoxene, ilmenite, magnetite, pyrite, biotite, brookite, rutile, zircon, tourmaline, muscovite, plagioclase, perthite, and hornblende.

Other accessories reported in previous studies, but not observed in the specimens studied, are: calcite, siderite, garnet, epidote, and actinolite.

The rock, save for minor fluctuations in the quartz-rock particle ratio, is essentially the same in all parts of the quarry. There appear to be no differences between the slabby and thicker-bedded types.

The Napoleon sandstone is regarded as a marine deposit, formed in shallow water of the inner sublittoral zone. The provenance of the lithic arenite was a metamorphic terrain underlain by low- to medium-grade regional metamorphic rocks of pelitic composition, some quartzites and probably some granitoid bodies. The last supplied the detrital feldspar grains.

In addition to its regular usage as flagstone and riprap, the Napoleon has been employed as aggregate in hot-mix bituminous pavements (Chritz, 1975), with satisfactory performances.

The sandstone is too impure to serve as a glass or abrasive sand directly and too expensive to beneficiate to the quality necessary for these uses. The main impurities are:

1. High iron content in secondary limonite, heavy accessory minerals and green clay minerals (Nap-5).

2. Abundant micaceous rock fragments.

3. Relatively high feldspar content.

Economic Potential

The rock has been tested by Makens et al. (1972) who report:

Compressive strength*	20080	psi
Tensile strength*	1680	psi
Modulus of rupture	3120	psi
Porosity (total)	2.3	%
Permeability*	0.23	md
Absorption* (by vol.)	2.40	%
Abrasion (% wear)	3.86	(100 rev.)
	15.92	(500 rev.)
Specific gravity*	2.94	
Hardness* (scleroscopic)	78	

*average value

No data are presently available as to grain size distributions in this sandstone or if these would meet specifications for glass or abrasive sands. In view of the petrographic evidence of the high impurity of the sandstone, neither chemical analyses nor grain size-distribution determinations can be recommended.

It is amply clear, from these studies, that the only economically viable use for the sandstone is the one for which it is presently employed, namely as semi-shaped slabs.

This conclusion points to the absolute necessity of determining how much slabby sandstone remains on the property. This can best be done by digging some bulldozer trenches at selected sites on the 18-acre reserve to the north.

In the 1890's the Napoleon Sandstone also was quarried at Waverly near Holland in Ottawa County, supplying stone for buildings and foundations in Holland, Muskegon, Grand Rapids, South Haven and Allegan. The uniformly gray stone, free of color mottling and pyrite, is silica-cemented and air-hardened upon exposure. It was described as "... a superior stone for cutting, it being susceptible of the most delicate carving" (Parker, 1893, p. 84). It was locally marketed as "Waverly stone."

IONIA SANDSTONE

The Ionia Sandstone, of Pennsylvanian age, crops out prominently along the Grand River Valley near Ionia and Grand Ledge. Quarried formerly along the river just east of Ionia, it was a popular building stone in many cities of the central part of the Southern Peninsula. The sandstone, mottled in yellow, brown, reds and purple, is cemented by hematite. Although it crumbles rather easily upon initial exposure, it eventually air-hardens sufficiently for building purposes (Poindexter et al., 1939).

PLEISTOCENE AND RECENT SAND DEPOSITS

General

Sand and gravel deposits of glacial origin or ancestry are widespread in Michigan. The genetic relationships between glacial and periglacial processes and the resulting sand deposits have been described concisely by Lewis (1975). In addition to glacial deposits, sand and gravel also occur as stream, dune and lacustrine deposits not related directly to glacial processes.

Sand is of economic importance in two fundamentally different ways: 1) its use as aggregate for which the physical characteristics are usually of lesser importance than the chemical composition, and 2) its use as "industrial sand" - a conglomerate of technical applications in which both physical and chemical properties are closely specified. The term "industrial sand" is applied to those specialty sands that are used in glassmaking, metal casting (molding sands), scouring (abrasive or "blasting"), traction in rail transportation (brake sands), high-temperature furnace linings, and manufacture of metallurgical alloys. In general, industrial sands require combinations of specific chemical compositions, grain size, grain-size distribution and shape. The specifications for glass sands have been described in the section on the Sylvania Sandstone. An excellent publication that summarizes information on the specifications, geology, distribution, economics, mining, and processing of industrial sands in Michigan is *Michigan's Industrial Sand Resources* (Lewis, 1975).

Some glacial sands and gravel prove to be excellent aggregate material. Commonly the minerals in such deposits are chemically unweathered and the grains lack surface coatings, both highly desirable features. Weathered, fissile, or fractured particles are quickly broken down during freeze-thaw cycles; and particle surface-coatings can prevent the formation of strong bonds between the aggregate and the cement. Particles of soft fractured rocks commonly are absent from glacial deposits because of comminution and removal during ice transport. Particles originally coated by clay, iron oxide, and calcite usually experience enough grinding during transport to remove all traces of these coatings.

Compositionally, however, many sand and gravel deposits fail to be pure enough for use as concrete aggregate. The only common, chemically deleterious constituents are some kinds of chert. Where present, the chert reacts chemically with the cement, causing a volume increase that often fractures the concrete. When such chert is present in the aggregate, its abundance must not exceed 1 percent, or the aggregate cannot be used for the manufacture of concrete.

For a detailed discussion of the problem of grading gravel for use as concrete aggregate, see Kneller (1964).

If glacial sands are to be utilized for special industrial purposes, they commonly must be beneficiated. Some Michigan glacial sands have been used for molding and core sand and for refractory purposes without beneficiation. Sands of potential glassmaking quality are known from dunes found along the eastern shores of the Great Lakes. These sands, however, require beneficiation before their chemical composition will satisfy the strict requirements for glass sand (see section on Dune Sands).

Often sand and gravel companies supply several different size grades of their product. Accordingly, it is usually to their advantage to work deposits that have relatively poor sorting. Kames and valley train deposits commonly exhibit wide particle-size ranges, so that most of the aggregate grades can be obtained from them. Sand and gravel transported greater distances tend to be better sorted, and thus are less desirable as a source for aggregate.

An unusual and useful method of increasing the particle-size range of outwash sands in Sangamon County, Illinois, has been reported by Hester (1970). These sands provided good "torpedo" sand for use as an aggregate in concrete. But there were insufficient fines in the deposit to profitably produce blend sand for asphalt. This deficiency was overcome when examination of adjacent dunes (derived from the outwash) showed that their particle-size range fell within the limits of those for blend sand, thus providing a sand source that did not require sizing.

Geology

Surficial and largely unconsolidated sand deposits in Michigan are of highly diverse origin. Table 9 is a genetic classification of these deposits.

STREAM DEPOSITS	LACUSTRINE DEPOSITS	DUNE DEPOSITS
Channel	Deltas	Coastal
Terrace	Beaches	Inland
Flood plain	Nearshore	
Alluvial fans	Lake bottom	

GLACIAL DEPOSITS	
NONSTRATIFIED	STRATIFIED
Ground moraine	Ice-contact deposits
End moraine	Kame and kame-moraine complexes
Glaciofluvial deposits	Ice-channel fillings
Channel	Outwash cones and fans
Terrace	Outwash deposits
Glaciolacustrine deposits	Valley train and valley fill
Beach and bar	Outwash plains
Lake bottom	
Deltas	

Table 9. Genetic classification of sand deposits of Michigan.

Economic Geology

In 1976 Michigan ranked fifth in the United States in the production of sand and gravel, producing almost 47 million short tons valued at over $76 million. Of this, nearly 5½ million short tons (nearly $21 million) was industrial sand.

Important factors other than geological that influence the economic importance of construction sand and gravel deposits are (Gere, 1977):

1. Production fluctuates with the state of the economy, particularly with the health of the road-building and general construction industries.

2. Because of the bulky nature of sand and gravel, transportation charges become a major factor in total construction costs. Thus these commodities are obtained, wherever possible, from source pits closest to the construction site.

3. Maximum consumption of sand and gravel is in urban areas, which are built over to the maximum extent and complexly zoned in patterns that preclude sand and gravel mining operations.

Gere (1977) lists all of the recorded sand and gravel producers in Michigan, along with data on the types of operations and counties in which they operate. The importance of the construction sand and gravel mining industry to the economic well-being of the State is indicated by the fact that this list includes 332 producing companies, many with operations at more than one site and in two or more counties. Despite the fact that these construction materials are relatively low-priced mineral commodities, their production constituted nearly 5 percent of the value of all mineral production in the State in 1975. Some 28 counties each produced over 500,000 tons of sand and gravel.

Gere (1977) also has compiled a useful list of State-owned sand and gravel pits which are periodically leased and worked by various operators. Additional sand and gravel pit locations are frequently established by lease on federally owned lands.

A more comprehensive listing of active and inactive, privately and publicly owned sand and gravel pits is published by the State. The list is arranged by county, includes county maps showing pit locations, and abrasion and soundness test results are given when available. Copies of the *Aggregate Source Inventory* may be obtained for $12.00 plus postage and sales tax, prepaid, from: Publications Unit, Contract Section, Department of State Highways and Transportation, P. O. Box 30050, Lansing, Michigan 48909.

Pleistocene Lake Sands

In addition to their employment as fill, concrete and construction sands, several Michigan Pleistocene sand deposits have been investigated for more specialized applications. One such deposit is a lake bed sand, which has been sampled in two places, 9 and 16 miles west of Port Huron in St. Clair County. One locality (A) is just north of M-21 near the center of Section 3, T6N, R16E, about one mile west-southwest of Wadhams. Locality B is in the west-central part of Section 17, T6N, R16E, 3 miles to the southwest. Deposit A appears to be almost on the boundary between the Lake Warren moraine and the sand lake beds of glacial Lake Warren, whereas deposit B is in lake bed sands.

On deposit A several shallow holes have been dug and several wells have been drilled to 100 feet. The pit from which a sample was taken is in a drainage ditch on the north side of the expressway and originally was several feet deep. The sand is gray-brown, with abundant dark specks. Probably this material was completely disturbed during expressway construction, at which time material just to the east of the pit was removed to a depth of 18 feet. A second hole several hundred feet northwest went to four feet and revealed one foot of black organic debris and three feet of reddish brown sand, silty and clayey in texture. Sand piled at the well drilling sites is reddish with a scattering of gravel in particles up to an inch long, poorly sorted and poorly rounded. An excavation for a power pole on Lapeer Road 1/2 mile west of Wadhams shows similar pebbles in the sand. Many pebbles are white limestone and are poorly rounded.

Microscopic study of the sand shows it is very impure mineralogically, containing high percentages of both heavy and light accessory minerals. Also, it is poorly sorted, and grain shapes are highly variable. The sand contains about 10 percent calcite. Other accessories include microcline, plagioclase (both abundant), hornblende (abundant), actinolite, garnet, epidote, hypersthene, rutile, ilmenite, sphene, biotite and sillimanite.

In addition micro-rock fragments of chert, limestone, dolomitic chert and fine-grained quartzose metamorphic rocks are abundant.

The quartz grains are of two extreme types: 1) relatively clear, and 2) nearly opaque owing to clouds of minute inclusions. Although much of the quartz grains are suitable for glass sand, cleaning this sand would be a very complex and costly process.

In Deposit B a pit was dug to 16 feet. A three-foot clay bed was encountered at three feet. Wells on the tract are in sand to a depth of 80 feet. The sand pile from this pit contains tan sand, washed white surficially; locally, reddish patches appear. It is slightly clayey and has a sprinkling of gravel. One cobble is 6 inches long; most are an inch or less and consist of shale, slate, limestone and sandstone.

Microscopic study reinforced the megascopic conclusion that the sand is highly impure. It contains a suite of heavy and light accessory species similar to that in the sand from Deposit A.

Neither sand is suitable for beneficiation to glass-sand grade. A chemical analysis of sand from Deposit B supports this conclusion:

SiO_2	90.0%
Al_2O_3	5.0
MgO	1.8
CaO	1.4
Fe_2O_3	0.43
Na_2O	1.1
K_2O	1.06

DUNE SANDS

Molding Sands

The metal casting industry is one of the world's largest consumers of minerals. In

addition to its obvious huge use of metallic minerals per annum which form the castings themselves, some 20 non-metallic minerals also are used extensively, much of them for molds. Today sand and clay in various forms are still the most common minerals used in the foundry industry. In fact, the use of sand molds of one type or another accounts for at least 96 percent of all castings made (Ashby, 1978). Michigan supplies about 90 percent of the foundry sand used in the automotive industry and 40 percent of all the foundry sand used for all purposes in the United States.

Three general categories of silica sand molds are in use:

1. Naturally bonded sand. This is a silica sand containing sufficient clay, as mined, to be formed satisfactorily into molds after milling and tempering with water. The clay content ranges from 10 to 15 percent in finer grained sands to 20 to 25 percent in coarser grained ones. Generally these naturally bonded sands are relatively low in silica, containing relatively high amounts of Fe_2O_3, Al_2O_3, CaO and alkalies, in the form of feldspar and other accessory species. Such sands have fusion points as low as 1300°C. This characteristic renders them unusable in the casting of steel, which is cast at ~ 1650°C. However, they are suitable for most types of iron and non-ferrous applications. The use of naturally bonded sand has been decreasing.
2. "Synthetic green sand". This is a high-silica sand to which a clay such as bentonite is admixed.
3. Chemically bonded sand. These are sands that are bonded in several ways: a) by sodium silicate hardened by passing CO_2 gas through the mold; b) by sodium silicate with organic esters used as a hardening agent; and c) by several different types of resin binders and their catalyst systems.

Naturally bonded sand is usually recycled. Chemically bonded sands formerly were used only once; but today much of the resin-bonded sand is reclaimed. Reclamation of sodium-silicate sands is more expensive. In general the use of both "synthetic green sand" and chemically bonded sands in place of naturally clay-bonded sands leads to a very large increase in the quantities of high-silica sand used by the foundry industry. In turn, increasing costs of transporting waste, difficulties in finding suitable waste-dumping sites, increasing cost of high-silica sand and environmental control regulations governing the discard of phenol-impregnated sands all have led to an increase in sand reclamation and recycling (Ashby, 1978).

In the United States the foundry industry utilizes two general types of sands, classified as (Edwards and Rose, 1974): 1) Lake and Bank sands and 2) silica sands. The Lake and Bank sands contain 92 to 94 percent SiO_2 whereas silica sand has in excess of 98.5 percent SiO_2, usually washed to upgrade it to 99.5 percent or more SiO_2. Included in the Lake and Bank sands are some river sands that are used chiefly for construction purposes.

The foundry industry produces three types of castings:

1. Gray iron foundries. The gray iron castings' largest market is the automotive industry in Ohio, Northern Kentucky, Indiana, Illinois and Michigan. These castings are poured at temperatures ranging from 2400° to 2700°F. Silica sands or Lake and Bank Sands will satisfy the requirements for gray iron castings. From 2.5 to 3 million tons per year of sand are shipped from the State of Michigan for gray iron castings by the Lake and Bank sand producers.

2. Steel castings. Steel castings are used in the heavy construction industry, railroad equipment, power equipment, mining equipment and other equipment requiring high-strength castings. These industries are located in the East, Midwest, and on the West Coast. Steel castings are poured at 2750° to 3000°F. Silica sands are used for steel castings because of their chemical purity, which enables them to better withstand the high thermal shock. Silica sands also are desirable because of the higher reclamation factor.

3. Non-ferrous castings. Non-ferrous castings are bronze and aluminum castings, poured at 1200° to 2000°F. This industry can use either silica sands or Lake and Bank sands or combinations of the two.

The term "Lake sand" applies to sand either dredged from Lake Michigan or dug from dunes bordering that lake chiefly in Michigan and Indiana, and has become a standard for the industry. It is a curious coincidence that Michigan has produced two world-national "Lake" standard mineral products. In the early history of mining native copper on the Keweenaw Peninsula, Michigan copper metal was referred to as "Lake (Superior) copper" against which synthetically produced copper metal was compared. "Bank sand" is quartz sand with up to 5 percent clay (Wilborg, 1975).

In addition to bulk chemical and mineralogical characteristics, the physical characteristics of molding sands are also important. The interrelationships of grain properties and molding sand quality have been summarized by Edwards and Rose (1974, p. 7-8):

> The physical characteristics of sands are important to foundrymen because the shape of the sand grain relates to its surface area. Sands are divided into the following four general shapes: 1) angular, 2) subangular, 3) rounded, 4) compounded.
>
> Subangular and rounded sands are generally preferred by foundries. The amount of surface area for any particular mesh size is increased progressively when comparing rounded, subangular, and angular sands. Thus, rounded grain sands require the least amount of binder. However, angular sands have a certain unique characteristic and that is, they appear to have the best thermal shock resistance due to their packing characteristics and their interlocking strength.
>
> Packing characteristics of sands are as follows: 1) rounded grain: highest density packing characteristics; 2) subangular: moderate density packing characteristics; 3) angular: least density packing characteristics, but maximum interlocking. The so-called compounded sand grain is the least desirable sand grain because during the mixing process when the binder is being applied to the sand grains, the compound grains will separate from each other and make the bonding characteristics more difficult. Also at high temperatures these same grains will fracture or separate themselves thus creating fines within the foundry sand system, which is undesirable.
>
> Surface area figures covering the various foundry sands mined throughout the United States and used by the foundries are given. The surface area figures were obtained by using the 50 mesh sieve fraction, that is -40 + 50 sand and this was done for uniformity as well as the fact that most foundries purchase a sand containing the 50 mesh sieve fraction.
>
> The surface area figures obtained are as follows and these figures are based on the theory that 1.0 equals a perfect sphere:

STATE	COEFFICIENT OF ANGULARITY
Michigan	1.11
Arkansas	1.14
Wisconsin	1.21
Nevada	1.21
Illinois	1.22
Oklahoma	1.27
Texas	1.31
West Virginia	1.36
New Jersey	1.47
Tennessee	1.49
South Carolina	1.59

Further information on Michigan molding sands and the Michigan molding-sand industry is to be found in Brown (1936), Lewis (1975), Bourne (1975) and Gere (1977).

Michigan molding sand companies producing from dune deposits on the east side of Lake Michigan are listed in Table 10 (Gere, 1977).

Not quite all the molding sand produced in Michigan comes from nearshore on inland Lake Michigan sand dunes. Some molding sand is produced from sands dredged from Saginaw Bay and from a deposit in Tuscola County.

Conversely, dune sand products are not used exclusively as molding sands. Some find application as blast, engine, furnace and, rarely, glass sands.

Geology

Michigan sand dunes traditionally are grouped into two categories: coastal dunes and inland dunes. Coastal dunes occur mainly along the eastern shore of Lake Michigan from the Indiana line to the Straits of Mackinac (Figure 19). Others are found along Great Lakes' shorelines in St. Clair, Alger, Luce and Houghton Counties (Kelly, 1971). Inland dunes, as far as 30 miles or more from present shores of the Great Lakes, are best represented by those of the eastern half of the Northern Peninsula, those of the Saginaw Bay region, and those east of Lake Michigan chiefly in Mason, Newaygo, Oceana, Muskegon, Ottawa, Van Buren, and Berrien counties.

Figure 19. Sand dunes along Lake Michigan, Grand Haven.

Coastal dunes tend to be generally free of clay and silt, to have a common range of grain sizes and have sand that is more rounded than grains from other types of sand deposits. Inland dune sand is characterized by a slightly higher silt and clay content, smaller more

Construction Agg. Corp. P. O. Box 6830 Ferrysburg, Michigan 49409	Plant: Stationary Uses: Molding	SE¼ NW¼ Sec. 17, T8N, R16W Ottawa County
Martin Marietta Corp. Industrial Sand Div. 110 E. Main Street Rockton, Illinois 61072	Plant: Stationary Uses: Glass, molding	NW¼ Sec. 18, T6S, R19W Berrien County
McCormick Sand Corp. P. O. Box 506 2875 Lincoln St. Muskegon, Michigan 49443	Plant: Portable Uses: Molding, glass, blast	SE¼ Sec. 16, T11N, R16W Muskegon County
Manley Brothers of Indiana, Inc. P. O. Box 67 Chesterton, Indiana 46304	Plant: Stationary Uses: Molding, furnace, engine	SW¼ Sec. 5, & NW¼ Sec. 6, T6S, R19W, Berrien County
Nugent Sand Co., Inc. P. O. Box 506 2875 Lincoln St. Muskegon, Michigan 49943	Plant: Dredge, stationary Uses: Molding, engine, blast	NE¼ Sec. 3, T9N, R17W Muskegon County
Sand Products Corp. 2489 First Nat'l. Bldg. Detroit, Michigan 48226	Plant: Portable Uses: Molding	NE¼ Sec. 17, T15N, R18W Oceana County
Sargent Sand Co. 2840 Bay Road Saginaw, Michigan 48605	Plant: Stationary Uses: Engine, metallurgical	NE¼ Sec. 29, T19N, R18W Mason County
Standard Sand Co. P. O. Box 290 Grand Haven, Michigan 49411	Plant: Stationary Uses: Molding, engine	E½ SW¼ Sec. 2, T6N, R13W Ottawa County

Table 10. Molding sand producers in Michigan.

angular grains, and a bulk composition that differs slightly from that of coastal dune sand (Lewis, 1975). The best developed inland dunes are 30 to 40 feet high, whereas coastal dunes commonly attain a height of over 100 feet. Inland dunes, which appear as ridges, small hills and knolls on ancient lake beds and outwash plains, are older. Not being subject to the intense wind and wave action that affects coastal dunes, they usually are well stabilized with a cover of vegetation. Coastal dunes, unless also so anchored, are very unstable and migrate in the direction of prevailing winds.

A third type of deposit, the coastal sand strip, occurs along all of Michigan's Great Lakes shorelines. These low, wind-formed ridges border present shorelines and locally extend inland. The youngest type of wind deposit, they are considered by some geologists to represent embryonic dunes. They also are silt- and clay-free but usually contain higher percentages of carbonate as limestone and dolomite particles (Lewis, 1975).

Sand dunes along the shore of Lake Michigan came into existence as the result of interaction of four fundamental factors: 1) an adequate sand supply, 2) current and wave action, 3) fluctuating lake water levels, and 4) strong onshore winds (Drexler, 1969).

Headlands, generally composed of unconsolidated glacial drift, yield material to the lake via breaker erosion. In addition, material may also be obtained from older glacial lake beds and minor amounts are supplied by present rivers. The present topography of the east shore of Lake Michigan was formed during deglaciation near the end of the Wisconsin glacial activity. This shore is considered to be unique among those bordering the Great Lakes in that it has a large number of morainic headlands, a factor in the abundance of dunes along this coast (Scott, 1942).

After loose sand particles enter the shore zone, currents transport them along the coast away from the headlands. As currents lose velocity when passing into deeper water or into bays that are protected from waves and wind, they deposit part of their sand load.

Thus beaches grow at the heads of bays, and spits or bars extend across the mouths of bays. With a drop in water level, bars are exposed for drying, wind erosion and redeposition.

A beach maintains itself in equilibrium as long as the amount of sand brought in at one end exactly equals the amount removed at the opposite by the same current. If excessive sand is received, the beach either must grow lakeward to form a terrace, or the extra sand migrates away from the shore to form dunes. According to Scott (1942) and Olson (1958) the most important process that links shoreline sand deposition with dune growth is continued, but slight fluctuations of the lake level. As summarized by Drexler (1969) the process operates as follows (p. 8):

> Lakeward of any shore line for varying distances are long, linear sags and swells in the lake bottom parallel to the shore. Waves generate these undulations which are called *low and ball* structures. If the lake level along a shore drops fairly rapidly, or so that the lows and balls are not destroyed by breaking waves, sand may begin accumulating on the lake side of the elevated ball structures just as on an elevated bar. If the former ball structure grows high enough before lake level returns to normal, the beach will shift to the lakeward side of this barrier. Dry sand from the new beach now blows to the crest of this linear barrier where vegetation fixes most of it. Once distinctly capped by wind blown sand, and elevated accordingly the hump acquires the name *foredune*. This dune should continue to grow vertically as a long linear ridge until the vegetation that binds the newly added sand dies. With the vegetation removed, blow-out depressions soon pit the windward side of the foredune with the wind-excavated sand collecting as a small, curved dune to the lee. One method of destroying a vegetation cover would simply require that lake level rise until waves could attack the foredune's base. Repeated foredune development and destruction extend the small blow-out dunes landward and increase their height and volume. When large enough and properly curved, these are called *parabolic dunes*.

Because parabolic dunes do not migrate in the strict sense, their arms always remaining attached to source shore, ones of older age can be correlated with former, now elevated beach levels that once fed them sand (Tague, 1946).

Foredunes have two different bedding sets: 1) on the windward side beds dip 10^o to 20^o toward the wind direction; 2) to the lee of the crest beds dip 15^o to 25^o away from the effective winds. Dunes lying to the lee of the foredune crest retain the windward-dipping low-angle beds, but to the lee the beds are sand-avalanche layers dipping 30^o to 35^o toward the lee. Parabolic dunes contain only avalanche bedding (Olson, 1958).

Composition

Major impurities of dunes include: soil zones, marl and peat lenses, zones of buried vegetation, thin shale plates ("fly sand"), carbonate root pipes and fulgurites. Where younger dunes migrate onto older ones, a fossil soil layer containing organic debris and residual limonite-hematite concentrations separates the two.

Because the bulk of the parent material for the dunes was glacially derived, the accessory mineral fraction of the dunes contains fresh feldspars and ferromagnesian species that normally would have decayed under a nonglacial regime. The suite of accessory minerals recorded for Lake Michigan dune sands includes: orthoclase, microcline, tourmaline, garnet, zircon, hornblende, epidote, calcite, magnetite, ilmenite, and leucoxene. The feldspar content is usually several percent and Bourne (1975, p. 4) reports " . . . that Lake Michigan dune sands [consist] of 80 percent quartz, 18 percent feldspar and 2 percent miscellaneous", which doubtless represents a maximum. All the accessory species save calcite undergo less thermal expansion than does quartz, and feldspars and the other accessories increase the dimensional stability of the sand at temperatures at which the molds are filled by molten metal.

Chemical analyses for the significant elements resulted in the following representative ranges, expressed in percentages:

SiO_2	87-94	Na_2O	0.30-0.61
Al_2O_3	2.6-6.2	K_2O	0.90-1.8
Fe_2O_3	0.34-1.40	ZrO_2	0.003-0.009
TiO_2	0.06-0.28	Cr_2O_3	0.004-0.07
MgO	0.20-0.80	SO_3	0.01-0.06
CaO	0.5-3.0	Org. mat.	0.06-0.70

The iron is chiefly in the iron oxides and mafic silicates. Magnetic removal, chiefly of ilmenite and lesser magnetite, can reduce the Fe_2O_3 content by 65 percent and also will bring down the alumina content by about one-third. Without flotation beneficiation however, dune sands, even after magnetic treatment, generally still contain too much Fe_2O_3 to be used as a glass sand, even for amber glass. Schemes for mixing magnetically beneficiated dune sand with equal amounts of Rockwood Sylvania sand for amber glass sand have been suggested. Although lake dune sands may well be beneficiatable to glass-sand grade chemically and their grain-size distributions also are suitable for glass sand, it is unlikely that they will ever be used on a large scale for glassmaking raw material, largely because of the preeminent position they occupy in the foundry sand industry. The uniqueness of Lake sand is that it combines the requisite chemical composition and mineralogical composition (quartz and feldspar) with a grain-size distribution that does not necessitate grading of the sand. The total of the fractions for the +70 and +100 mesh sizes is as high as nearly 90 percent and is reported to average over 50 percent. Detailed grain-size analyses of typical Michigan dune sands are presented by Lewis (1975, Table 4).

Future

According to Bourne (1975), foundry sand operators own less than 5 percent of the sand dune acreage along the shoreline of Lake Michigan. Private ownership is 66 percent and public ownership 29 percent. A survey by the National Industrial Sand Association indicated that the companies have an estimated 20 to 30 years' reserves at the present rate of mining. Because of the intense competition for lake shore acreage for residential and recreational purposes, acquisition of additional reserves is difficult and expensive. In addition it is anticipated that the production rate will rise 20 percent by 1980.

Ultimately these problems will lead to increased reclamation of used foundry sand and the substitution of sand from non-dune deposits, which will require more complex (and expensive) preparation. One possibility is to explore for offshore sand deposits within Lake Michigan itself. Recent studies in western Lake Michigan off the Wisconsin shore have indicated that combinations of geological and geophysical techniques can be used successfully in prospecting for offshore sand and gravel deposits (Nebrija et al., 1978).

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Factors for converting from METRIC to U. S. Customary and U. S. CUSTOMARY to Metric

When You Know	(Symbol)		Multiply By		To Find	(Symbol)
LENGTH						
millimeters	(mm)	x	0.039	=	inches	(in.)
centimeters	(cm)	x	0.394	=	inches	(in.)
meters	(m)	x	3.281	=	feet	(ft.)
meters	(m)	x	1.094	=	yards	(yd.)
kilometers	(km)	x	0.621	=	miles	(mi.)
inches	(in.)	x	2.540	=	centimeters	(cm)
feet	(ft.)	x	30.480	=	centimeters	(cm)
yards	(yd.)	x	0.914	=	meters	(m)
miles	(mi.)	x	1.609	=	kilometers	(km)
AREA						
square centimeters	(cm^2)	x	0.155	=	square inches	($in.^2$)
square meters	(m^2)	x	10.764	=	square feet	($ft.^2$)
square meters	(m^2)	x	1.196	=	square yards	($yd.^2$)
square kilometers	(km^2)	x	0.386	=	square miles	($mi.^2$)
square inches	($in.^2$)	x	6.452	=	square centimeters	(cm^2)
square feet	($ft.^2$)	x	0.093	=	square meters	(m^2)
square yards	($yd.^2$)	x	0.836	=	square meters	(m^2)
square miles	($mi.^2$)	x	2.590	=	square kilometers	(km^2)
MASS (weight)						
grams	(g)	x	0.035	=	ounces	(oz.)
kilograms	(kg)	x	2.210	=	pounds	(lb.)
ounces	(oz.)	x	28.350	=	grams	(g)
pounds	(lb.)	x	0.454	=	kilograms	(kg)
VOLUME						
milliliters	(ml)	x	0.0352	=	fluid ounces	(fl. oz.)
liters	(l)	x	2.113	=	pints	(pt.)
liters	(l)	x	1.057	=	quarts	(qt.)
liters	(l)	x	0.264	=	gallons	(gal.)
cubic meters	(m^3)	x	35.314	=	cubic feet	($ft.^3$)
fluid ounces	(fl. oz.)	x	28.383	=	milliliters	(ml)
pints	(pt.)	x	0.473	=	liters	(l)
quarts	(qt.)	x	0.946	=	liters	(l)
gallons	(gal.)	x	3.785	=	liters	(l)
gallons	(gal.)	x	0.0283	=	cubic meters	(m^3)
TEMPERATURE						
Fahrenheit	(^oF)		(^oF-32)/1.8	=	Centrigrade	(^oC)
Centigrade	(^oC)		(1.8^oC+32)	=	Fahrenheit	(^oF)


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