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Title:	<i>F. L. Kadey, "Diatomite", Industrial Rocks And Minerals, Volume I, Society Of Mining Engineers, New York, 1983.</i>

Diatomite

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Diatomite is a siliceous, sedimentary rock consisting principally of the fossilized skeletal remains of the diatom, a unicellular aquatic plant related to the algae. Thus, it has been formed by the induration of diatomaceous ooze, and consists mainly of diatomaceous silica, a form or variety of opal which is first formed in the cell walls of the living diatom. Diatomaceous silica is not generally regarded as a synonym or the equivalent for diatomite, although it has been so used at various times. Accurately, diatomaceous silica is the preferred name for the principal mineral component of which the rock, diatomite, is composed. The terms diatomaceous earth and kieselguhr are used as synonymous with diatomite. The designations tripoli, tripolite, infusorial earth, etc., were used at one time but are now obsolete. With the changing nomenclature, these terms that were at one time correct when proposed and used for generations would be considered incorrect if used today in the light of current knowledge. The designation diatomite is reserved for those accumulations of diatomaceous silica that are of sufficient quality, size, and minability to be considered of potential commercial value.

Processed diatomite possesses an unusual particulate structure and chemical stability that lends itself to applications not filled by any other form of silica. Foremost among these applications is its use as a filter aid, which accounts for over half of its current consumption. Its unique diatom structure, low bulk density, high absorptive capacity, high surface area, and relatively low abrasion are attributes responsible for its utility as a functional filler and as an extender in paint, paper, rubber, and in plastics; and as an anti-caking agent; thermal insulating material; catalyst carrier; and chromatographic support; polish, abrasive, and

pesticide extender to name a few representative applications.

The United States is the principal producing country, although diatomite is found in numerous other locations.

Geology

Composition and Morphology

Diatomaceous silica qualifies as a mineral of organic origin in much the same way that aragonite and collophane do. The silica of the fossilized diatom skeleton closely resembles opal or hydrous silica in composition ($\text{SiO}_2 \cdot n\text{H}_2\text{O}$).^{4, 12, 203} The silica is of acute biological significance, not only for the cell wall component, but also for the basic life process.^{45, 51} Without silica, cell development ceases.³¹ In addition to bound water, varying between 3.5 and 8%, the siliceous skeleton may also contain, in solid solution, or as part of the SiO_2 complex, small amounts of associated inorganic components—alumina, principally—and lesser amounts of iron,^{46, 49, 55} alkaline earths, alkali metals, and other minor constituents.^{59, 63, 67} Boron is reported to be an essential element for diatom growth.^{52, 58} Since diatomaceous silica is not pure hydrous silica but contains other intimately associated elements, there is good reason to consider it a distinct type or variety.⁴ Associated with the diatomaceous silica, and integrated as part of the diatomite, may be variable amounts of organic matter, soluble salts, and particles of rock-forming minerals that were syngenetically deposited or precipitated with the diatom frustules. Sand, clay, carbonate, and volcanic ash are typical common contaminants. Other contaminating minerals may be present, such as feldspar, mica, amphiboles, pyroxenes, rutile, zircon—the result of weathering, then transporting, and subsequent redeposition of surrounding land masses. Commercial diatomite may also contain fragments and particles of

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1976, "The Parameters on Diamond Bits," pp. 82-89. Use of Diatomite, p. 166. "Abundance of Diatomite," p. 157, No.

Properties of Diatomite (Johannes), p. 5-9.

Industrial Applications and Applications, ME Preprint, New York, 8 pp. "Diatomite," p. 199.

1961, "The Diatomite," p. 199.

Mechanical Properties of Diamonds," p. 199.

The Diamond," p. 199.

other such organisms as silico-flagellates, radiolaria and siliceous sponges.

In a commercial diatomite, silica makes up the bulk of the chemical composition; usually over 86% and as high as 94%. Alumina and iron generally are at least 1.5 and 0.2%, respectively. This includes not only that believed to be incorporated as part of the skeleton but iron and alumina associated with many of the contaminants. Lesser amounts of other elements, a small part of which may be secreted in the diatom skeleton, comprise the balance of the total chemical composition. The manner in which many of these elements are associated is not presently known. Table 1 illustrates the chemical composition of diatomites from various areas.¹ Although diatoms appear amorphous under the light microscope, X-ray studies show untreated diatomite to have a broad halo in the region of the principal cristobalite peak, thus it has been referred to as "micro-amorphous."⁴ The main X-ray line is an approximation and not identical with α -cristobalite.⁶⁶ Some researchers have reported β -cristobalite to be prevalent.⁷¹ The crystalline impurities produce their own X-ray lines; hence they furnish an identification of their nature, to a greater or lesser degree, depending on the amounts present. The ultimate hardness of the diatom skeleton is between 4½ and 5 on the Mohs' scale. After calcination or flux calcination, the Mohs' hardness is increased to 5½ to 6. The friability, or the propensity of the skeleton to break down, rather than to abrade, renders a measurement of hardness meaningless without also a consideration of the particle size.¹⁷² The specific gravity ranges from 1.95 to 2.3. In calculating settling velocities, bulking values, etc., an apparent specific gravity of 2.0 for natural milled powders and of 2.3 for flux calcined powders is generally used.¹³⁷ Refractive index is variable between about 1.40 and 1.46 for natural earth, and increases to 1.49 for flux calcined diatomite.

Taxonomically, diatoms are divided into two broad categories: Centricae (discoid) and Pennatae (elongate to filiform). The study of the various intricate shapes and structural patterns of individual siliceous skeletons is as old as the use of the light microscope itself. Each form consists of two valves that are bound together by a connecting band or girdle. In the living diatom, these encase the cell contents.

Each siliceous valve is punctated by a system or pattern of openings that are arranged in a

consistent and orderly design (Figs. 1-3). Furthermore, each valve appears to consist of an inner and an outer platelike surface, separated by ribs that result in a chambered interior. The structure of each surface is different in that the nature of the openings from each surface into the chamber is not necessarily the same. It is on the basis of the valve structure that diatoms are classified. The openings in the skeleton, classified by diatomists and divided into primary, secondary, and in some species, tertiary structures, are believed to simply support the membrane of the living diatom through which the nutrients pass by the process of osmosis. The valves vary between approximately 5 and 1000 μ in diameter, or maximum dimension, depending on the genus (Fig. 4). Most species fall within the range of 50 to 150 μ . It is not within the scope of this chapter to dwell further on the botanical aspects of the diatom, although a few of the numerous references on the subject are included in the bibliography for the interested reader.

Suffice it to say that outside the realm of mining and commerce, the diatom has its own nomenclature and scientific entity, the study of which distinguishes it as a source of enjoyment for amateur and professional microscopists alike; and as a scientific tool in the fields of limnology, stratigraphic correlation, and other similar noncommercial applications.^{3, 75, 82, 95, 194} Certain properties of diatomite—physical and chemical—may be visualized as primary or fundamental in nature. The nature and configuration of the skeletal structure, specific gravity, refractive index, hardness and friability, and composition are a few. These are the properties that determine secondary or derived properties which also endow diatomite with the attributes that set it apart from other sources of silica. It is an accurate generalization to state that the skeletal structure or configuration of the diatom is the principal primary property that controls most of the derived or secondary properties. Low bulk density, low wet or cake density, and high surface area may be visualized as examples of derived or secondary properties. The loose weight and wet density, for example, are a function of, and depend on, the skeletal structure and specific gravity. The particle size and shape on which bulk and wet cake density depend can be altered to a degree by milling; but ultimately, they are determined by such primary properties as structure, density, and friability. Certain properties

TABLE 1—Chemical Composition of Natural Diatomites from Various Localities (Oven-Dried Basis)

Constituent	Lompoc, CA	Maryland Calvert Formation	Nevada	Idaho	Kenya Soysambu	Japan Niigata Earth	Russia Kamy- shov Urals	Spain Alba- cete	Mexico Jalisco	Algeria (Primo Grada)
Silica (SiO ₂), %	89.70	79.55	86.00	89.82	84.50	86.0	79.92	88.60	91.20	58.40
Alumina (Al ₂ O ₃), %	3.72	8.18	5.27	1.82	3.06	5.8	6.58	0.62	3.20	1.66
Iron Oxide (Fe ₂ O ₃), %	1.09	2.62	2.12	0.44	1.86	1.6	3.56	0.20	0.70	1.55
Titanium (TiO ₂), %	0.10	0.70	0.21	0.07	0.17	0.22	0.48	0.05	0.16	0.10
Phosphate (P ₂ O ₅), %	0.10	—	0.06	0.13	0.04	0.03	—	—	0.05	0.20
Lime (CaO), %	0.30	0.25	0.34	1.26	1.80	0.70	1.43	3.00	0.19	13.80
Magnesia (MgO), %	0.55	1.30	0.39	0.54	0.39	0.29	0.98	0.81	0.42	4.57
Sodium (Na ₂ O), %	0.31	1.31	0.24	1.03	1.19	0.48	0.65	0.50	0.13	0.96
Potassium (K ₂ O), %	0.41	—	0.29	0.22	0.91	0.53	0.72	0.39	0.24	0.50
Ignition loss, %	3.70	5.80	4.90	4.02	6.08	4.4	4.91	5.20	3.60	17.48*
Total	99.98	99.71	99.82	99.35	100.0	100.05	99.23	99.37	99.89	99.22

* Includes 13.9% CO₂.

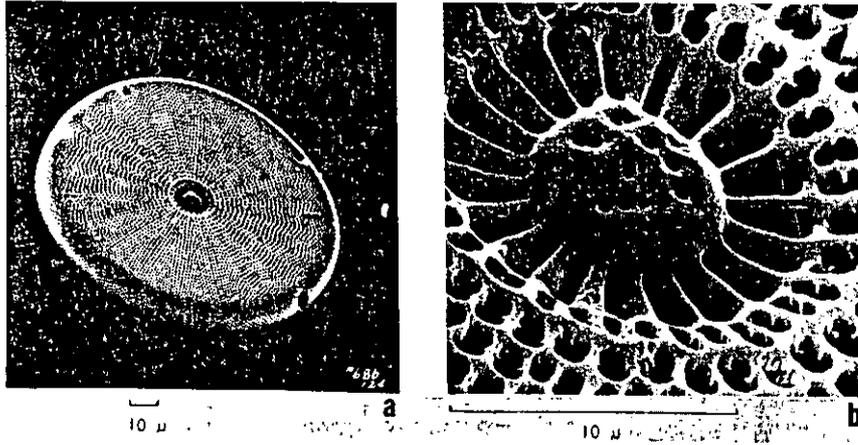


FIG. 1—Scanning electron micrograph of *Arachnoidiscus ornatus*, Lompoc, CA.

FIG. 4—Electron micrograph of *Coscinodiscus* valve. The structure includes a larger opening approximately 3 μ occurring in the center of the valve. The secondary structure is a meshlike opening 0.5 μ diam throughout the other plates. The ridges of undissolved secondary structure are seen in a vertical line in the secondary

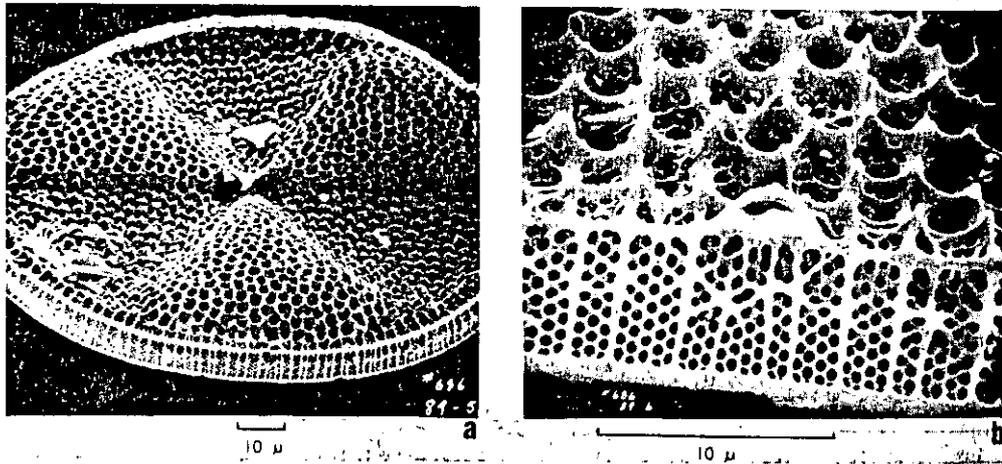


FIG. 2—Scanning electron micrograph of *Actinoptychus undulatus*, Lompoc, CA.

as pH, water can be modified and deposited syr

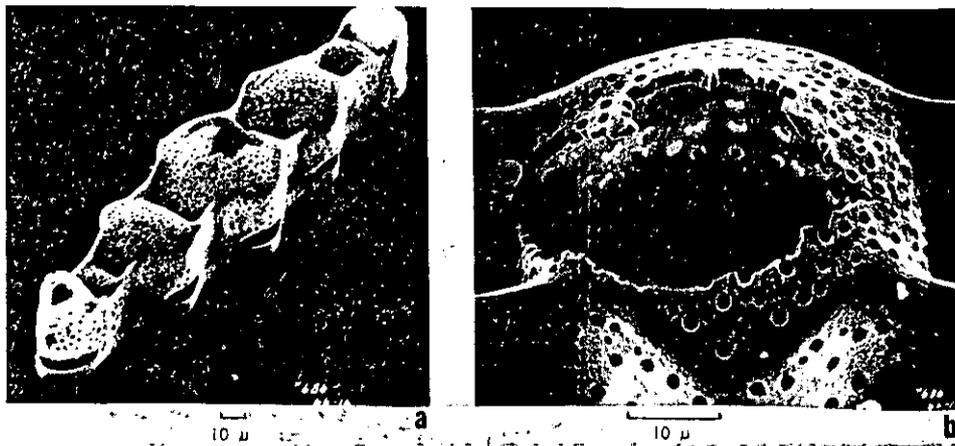


FIG. 3—Scanning electron micrograph of *Biddulphia Tuomeyi*, Lompoc, CA.

Mode of Occurrence
The frustule of a diatom, a unicellular algae, of the order Bacillariophyta, is a rectangular block of silica. This group comprises 16,000 species of the diatoms, which form a scum on post-glacial seaweed, or on the sides of whales, and in oceanic ice. They are particularly common in the open sea. The mode of occurrence may be that of a diatom. Furthermore

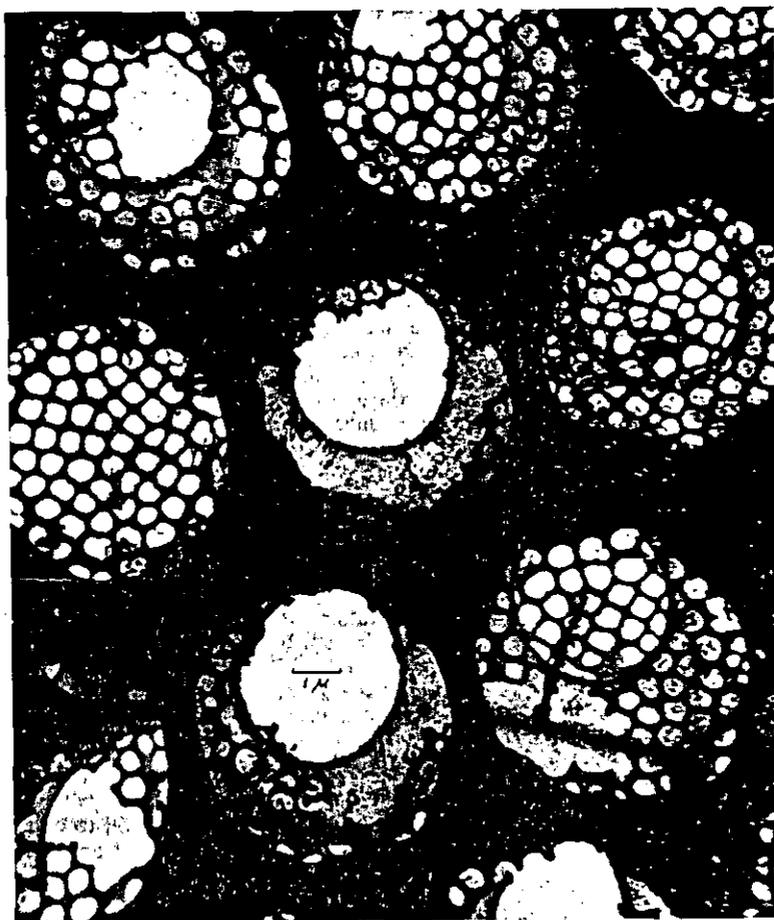


FIG. 4—Electron micrograph of portion of *Coscinodiscus radiatus* valve. The primary structure includes the larger openings of approximately 3μ diam, occurring in one plate of the valve. The secondary structure is the meshlike openings of 0.5μ diam that cover the other plate. Vestiges of undissolved tertiary structure can be seen in a very few of the secondary openings.

as pH, water solubility, and abrasiveness can be modified by extraneous material that was deposited syngenetically with the diatoms.

Mode of Occurrence and Origin

The frustule or siliceous skeleton of the diatom, a unicellular or noncellular microscopic alga, of the class Bacillariophyceae, and the order Bacillariales, serves as the ultimate building block of which diatomite is composed. The group comprises over 300 genera and 12,000 to 16,000 species. In living form, accumulations of the diatom may be seen as the iridescent scum on ponds, the slippery gelatinous film on seaweed, on the bellies of certain species of whales, and other such varied habitats as oceanic ice floes, hot springs, moist soil, and particularly as masses of planktonic colonies on the open sea. Their natural function appears to be that of a food for other organisms of the sea. Furthermore, their role in controlling the geo-

chemical balance of silica in marine and in lacustrine waters is scientifically recognized.^{36, 37, 48, 68, 90}

Environmental conditions for growth include at least the five following major requirements:

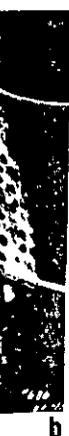
1) Large shallow basins (preferably 35 m or less in depth) for deposition, so that photosynthesis can occur. With regard to lacustrine deposits, a shallow lake provides sufficient actinic light for photosynthesis for not only pelagic diatoms, but also for benthonic forms attached to stones and to plants on the lake bottom. In the case of thick deposits of marine diatomites, there is evidence for a down warping of the basin of deposition, thus maintaining fairly shallow water for benthonic species. The open sea is reportedly the best environment for pelagic diatoms.

2) An abundant supply of soluble silica.^{31, 36, 37, 45, 57} There is a worldwide correlation between the existence of thick diatomite deposits and proximity to volcanic ash occurrences.⁷⁶ While volcanic ash does not necessarily have to

1—Scan-
electron
micrograph of
Coscinodiscus
radiatus, Lom-
bardi, CA.



A.



A.

accompany diatom deposition, some mechanism for increasing the silica content in marine and lacustrine bodies beyond the present day norm is necessary for the formation of commercially thick deposits. There are numerous examples wherein marine and nonmarine deposits meet this condition. Typical of these are at Lake Myvatn, Iceland; in the state of Jalisco, Mexico, where the deposits border the ancient shores of Lake Atotzilco; and those occurrences bordering Lake Rotorua, New Zealand; in Nevada the late Miocene Virgin Valley beds in Humboldt County, and the early Pliocene Esmeralda formation in Nye and Esmeralda Counties; the Payette formation in Idaho and Eastern Oregon. These all are associated with volcanism. Deposits of marine diatomite exhibit a similar correlation; the late Miocene-early Pliocene Sisquoc formation which comprises the Lompoc, CA diatomite; the middle and late Miocene Monterey formation of the Coast Ranges; and the middle Miocene Tremblor formation east of Coalinga, CA, are examples of diatomites associated with contemporary volcanism. Particles of volcanic ash are a common contaminant of some diatomites.

3) An abundant supply of nutrients. In most lakes that are nontoxic to diatom proliferation the supply of nutrients is often more available than is the supply of silica.

4) The absence of toxic or growth-inhibiting constituents in the water. Although few lakes contain toxic water in the usual sense, many in which the rate of evaporation exceeds inflow during long periods of the year build up concentrations of soluble salts to the point of inhibiting diatom growth.^{47, 60, 191}

5) A minimum supply of clastic sedimentary materials. While this, per se, is not a requirement for diatom growth, low nondiatomaceous contamination is paramount for the development of a commercially suitable deposit.

The effect of temperature, light, pressure, and other factors on diatom growth has been discussed.^{34, 50, 64, 195, 204, 209} In addition to its unique siliceous skeleton, the living form has a nucleus, it produces certain protoplasmic substances by the process of photosynthesis, and incidental to its metabolism, it manufactures oil and vitamins. The rate of reproduction of diatoms varies with the species from between two or three times a day to once a week; and one diatom may have 100 million descendants in 30 days.^{199, 200, 209} Deposition of the skeletal remains occurs after it has served its natural function. Thus, given the right conditions of environment and geologic location, tremendously thick deposits of diatomaceous ooze may build up on the floor of the containing body of water.

Potassium-argon dating of volcanic minerals and glass in North Pacific sediments has established Tertiary sedimentation rates of from less

than 1 mm per 1000 years for deep sea red clay, to 1 cm per 1000 years for calcareous-siliceous ooze nearer the continent.^{51, 80} In comparison, the rhythmic banding seen in Lompoc, CA diatomites suggests a rate considerably faster than that—probably of the order of 1 mm or more per year. Gross has calculated a sedimentation rate of 4 mm per year for a 25% diatom-75% silt sediment, deposited in Sannich Inlet, B.C.¹⁰⁵

After deposition, such subsequent geologic forces as consolidation, burial under what will later be overburden, regional uplift, and partial erosion come into play to expose, yet protect, the deposit for later discovery and exploitation.

Because of the delicate nature of the diatom skeleton, deposits of diatomite to be useful to industry cannot undergo any great degree of regional metamorphism or chemical alteration. For this reason, geologic conditions that have not resulted in an appreciable degree of consolidation or of cementation are preferable. When orogenic forces are excessive, the resulting metamorphosis produces opaline cherts, porcelanites, and similar more indurated materials of noncommercial interest.

In place, diatomite is soft and "punky," and has a chalklike appearance. Color may vary from snow white in a pure, well bleached and dry deposit, to olive green or darker where substantial organic remains are still present and where moisture content is high. It may exhibit stratification, caused by either, or both, sedimentation of particularly flat beds or a preponderance of discoid diatoms, or by seasonally rhythmic deposition of clay and other impurities. On the other hand, it may be massive and show no stratification. It may be so loosely consolidated that when handled, a field sample will readily break down to a powder, or it may be hard enough to crack "brittley" when struck with a hammer. In addition to induration through consolidation, precipitation of carbonate for example, or "baking" by volcanic flows can destroy an otherwise good deposit. The better quality diatomite is lightweight, usually possessing a block density between 20 and 34 lb per cu ft.

Classification of Deposits

The various species of diatom thrive in either a marine or a lacustrine environment. Some forms live in brackish waters. Identification of the diatoms from an unknown deposit label it as having been laid down in either one environment or the other. It is, therefore, to be ex-

pected that a classification deals of freshwater added to the whether depo or bog origin because the di marine enviro those that live association of as seen by m serves to diffe water, but als deposit locati ple may have semblages, lii individual loca differences rei out, diatomite produce a r: uses to whic merically, m world are of ever, those o merous, tend

FIG. 5—Mi
marine diat
blage from
CA.

pected that a major criterion of deposit classification deals with whether it is of marine or of freshwater origin. Some investigators have added to the environments just mentioned, whether deposits are of modern lake, marsh, or bog origin.⁵ These criteria are important because the diatom assemblages associated with marine environments are quite different from those that live only in freshwater habitats. The association of forms or the diatom assemblage, as seen by means of the microscope, not only serves to differentiate marine origin from freshwater, but also in many cases, to identify the deposit location from which an unknown sample may have come (Figs. 5-9). Diatom assemblages, like fingerprints, are specific to individual locations. Because of the structural differences related to origin, as has been pointed out, diatomites have a range of properties and produce a range of effects in the numerous uses to which they have been applied. Numerically, most of the known deposits in the world are of lacustrine origin. Generally however, those of marine origin, although less numerous, tend to be larger.

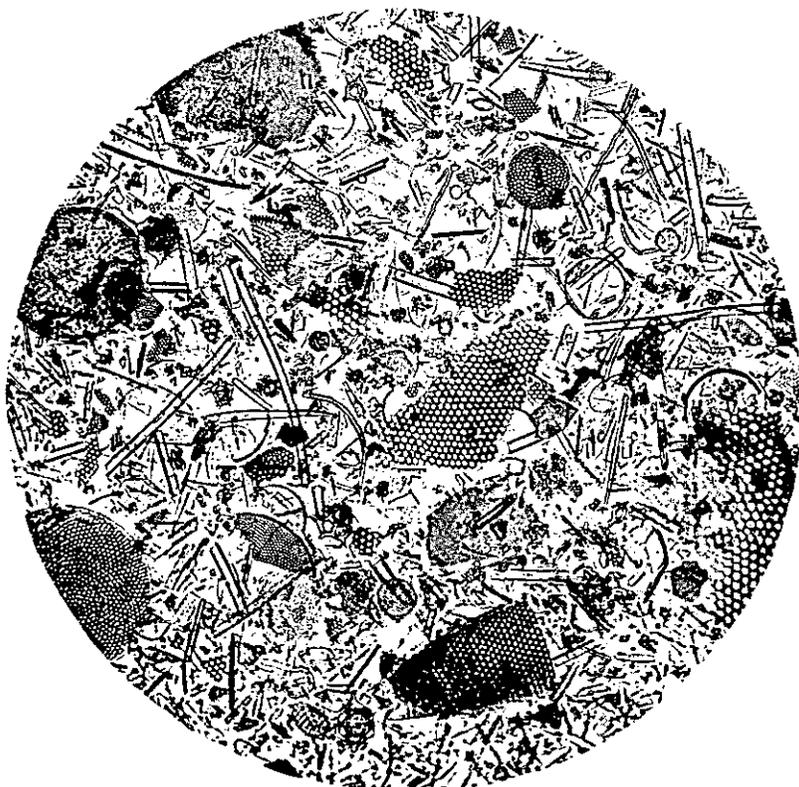
Distribution of Deposits

The occurrence of diatomaceous silica is widespread throughout the world. Although algae appeared quite early in geologic history, commercial deposits are generally restricted to sedimentary formations of Tertiary and of later age, and further limited ecologically by those conditions for formation that have been previously described. However, when one considers the numerous other limiting factors that must be taken into account before an occurrence qualifies as a commercial deposit—quality, minability, location, and size—then the numbers are few indeed. While a good portion of the California coast could be considered "diatomaceous in character," an area of hardly more than four square miles contains diatomite of high quality, commercial value.

North America

United States: Occurrences of diatomite have been reported from just about all of the east and the west coastal states, and indeed, from

FIG. 5—Micrograph of marine diatom assemblage from Lompoc, CA.



100 μ

FIG. 6—Micrograph of lacustrine diatom assemblage from Carlin, NV.



100 μ

many bordering these states in the interior of the country. Commercial production, however, has been limited to a few of these. First American production was from Maryland, where from 1884 until 1930, marine diatomite was extracted from the Fairhaven member of the middle Miocene Calvert formation.^{129, 215} This diatomite outcrops along the banks of the Patuxent, Rappahannock, and Potomac rivers; and in cliffs along Chesapeake Bay. It is contaminated with varying amounts of loosely held silica sand, most of which can be removed in processing. More intimately held montmorillonite, illite, and kaolinite are also present. Removal of the clay on an experimental basis has been attempted with little practical success, for other than low quality applications.¹²⁹ Today, the remains of a diatomite enterprise of bygone years can be seen at such places as Kaylors Landing, MD, lying idly and in ruins. The largest and most uniform deposits in the world are to be found in the vicinity of Lompoc, CA (Fig. 10). The diatomite sequence of commercial significance is of the order of 1000

ft thick and is part of a thicker diatomite series of marine origin belonging to the Sisquoc formation of late Miocene or possibly early Pliocene age. Although the Lompoc diatomite may have been known since the time of the Spanish Conquistadors in the 1760s, it was not recognized as such until over a century later, and first mining was not started until about 1890.² The strata at Lompoc, which present a good example of rhythmic bedding, are mined by the Filtration and Minerals Div. of Manville International Corp. principally from a broad pitching syncline with related smaller anticlines and synclines. Quarries located at strategic places on the flanks and nose of the major syncline, and related structures, permit extraction of crude from various parts of the stratigraphic column, thus allowing for blending of crude types to fit the product demand. The Dicalite Div. of Grefco, Inc. also produces from an area in the general Lompoc district.

Diatomite was mined by the Dicalite Co. from a deposit in the Palos Verdes Hills near Los Angeles starting in the 1930s, but that de-

FIG. 7—Miocene bog diatom from Palos Verdes Hills, Bra

posit is now of commercial importance. Other deposits are found in other parts of the country where diatomite is mined in various forms. In Cyprus Industrial Minerals Division mine diatomite and at Clair Tertiary or are close to in moisture Dicalite Division deposit near Palos Verdes in southern Washington lacustrine diatomite. Division of Wisconsin there was produced. Minor Oregon¹¹⁵ that have produced in Idaho and

FIG. 7—Micrograph of bog diatom assemblage from Pernambuco, Brazil.



100 μ

posit is now depleted.²³⁰ A massive embayment of commercial freshwater diatomite in Shasta County has been outlined by Grefco, Inc. There are other minor operations in California.²²⁰ Second to California in production is Nevada, where diatomite from freshwater deposits is mined in two principal areas. In addition to Cyprus Industrial Minerals Co., the Fibers and Minerals Div. of Eagle-Picher Industries, Inc. mine diatomite from deposits near Lovelock and at Clark, near Reno. These are of late Tertiary or Pleistocene age. The beds at Clark are close to the surface and are relatively low in moisture. Diatomite is also mined by the Dicalite Div. of Grefco from a freshwater deposit near Basalt, about 60 miles from Tonopah in southwestern Nevada. In the state of Washington, diatomite is produced from a lacustrine deposit near Quincy by the Kenite Div. of Witco Chemicals Corp.⁷ At one time, there was production from a deposit at Kittitas, WA. Minor production has been reported from Oregon¹¹⁵ and from Arizona.¹¹⁶ Other states that have produced diatomite in the past include Idaho and Utah. A mixture of carbonate and

freshwater diatomite in western Kansas was mined by the Delore Div. of NL Industries until 1977. Florida has bog and lake bottom deposits near Pensacola and in central Florida that have received exploratory attention in the past. Noncommercial bog and lake deposits are well known in Maine, New Hampshire, Massachusetts, and New York. Some of these were operated on a small scale in earlier years.

Canada: Production in Canada at present is limited to freshwater Miocene deposits near Quesnel, B.C., where Crownite Diatoms Ltd. and Pacific Diatomite Ltd. produce a fertilizer grade product. Eastern Canada has well-known occurrences in Nova Scotia and New Brunswick that are not profitable to exploit at the present time.

Mexico: Diatomite occurs in several states in Mexico, and among these are Tlaxcala, Colima, Jalisco, Michoacan, and Mexico. Some production has been known since 1927. Good quality earth is mined near Catarina in Jalisco (Fig. 11) by Diatomita San Nicolas, S.A. de C.V. Filter aids and fillers from this operation are shipped to Latin America, Europe, and Aus-

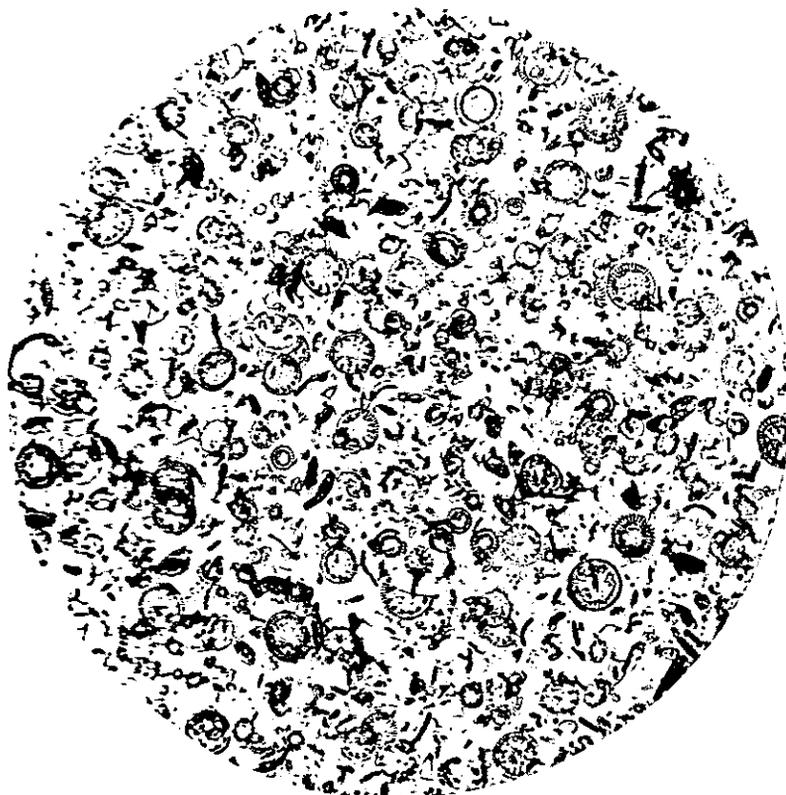


FIG. 8—Micrograph of lacustrine diatom assemblage from Elche de la Sierra, Spain.

100 μ

tralia. Other commercial deposits are exploited at Zacapu and at Tuxpan by Kieselguhr de Mexico in Michoacan. Production has been reported at Magdalena and Cocula in Jalisco,² at La Blanca in Tlaxcala, at San Martin Texmelucan in Puebla, and at Ixtlahuaca in the state of Mexico.

Europe

The most significant European sources of diatomite are freshwater Tertiary and Quaternary deposits located in the Massif Central area of southern France. Deposits at Collandres, and at Saint-Bauzile (Ardeche) in the Privas area, are worked by Soc. CECA (Carbonisation et Charbons Actifs). A deposit near Murat, mined by Manville de France, is processed into filter aids. The Lüneburger-Heide deposits of Western Germany were the first commercially mined deposits in the world, but have declined in importance in recent years. Some production is, however, reported from Tagebau and from Unterluss by Kieselguhr Industrie GmbH. In Italy, commercial deposits are located at Arcidosso and Santa Fiora and mined by Winkel-

mann Mineraria S.p.A. at Castel del Piano, all near Monte Amiata. Diatomiti Italiane A.P.E.S. S.p.A. operate further south in the Viterbo area, and Diatom S.p.A. mine a deposit at Castiglione in Teverina. Medium grade diatomite is mined in the area of Tombolia in northern Italy. Good quality Spanish diatomite is mined from lacustrine deposits between Hellin and Elche de la Sierra by Manville Española S.A. in the southeastern part of the country. Some of these deposits were mined from underground galleries for over 50 years, but in recent years have been converted to open pit operations. Some of the earth is a remarkably white color, but chert lenses and carbonate beds necessitate highly selective mining methods. There are other, low quality occurrences in Spain, including a marine occurrence near Almeria. In Iceland, a diatomaceous ooze of Holocene Age is dredged from Lake Myvatn and pumped in slurry to the processing plant by Kisilidjan, H.F., where the volcanic ash is removed by hydroclones. The resulting slurry, after pumping to settling ponds, is dewatered and dried with geothermal steam prior to flux

FIG. 9—Micrograph of lacustrine diatom assemblage from Iceland.

calcining. This diatomite has been known since the 19th century and is mined by the Kieselguhr works in the lake basin of Iceland, U.K. It is not suitable for use as a filter aid, but is used mostly for

An unusual occurrence of diatomite is the diatomite of Moler. This diatomite is mined because of its use as an insulator. It is found over 200,000 years old elsewhere in the world. It is used for insulating of Tertiary and Quaternary Fur and Moler diatomite of recent years.

There are several other diatomite deposits. Although little production is reported, 300,000 tons per year exist near Iztapalapa, Mexico. In Anatolia, Turkey

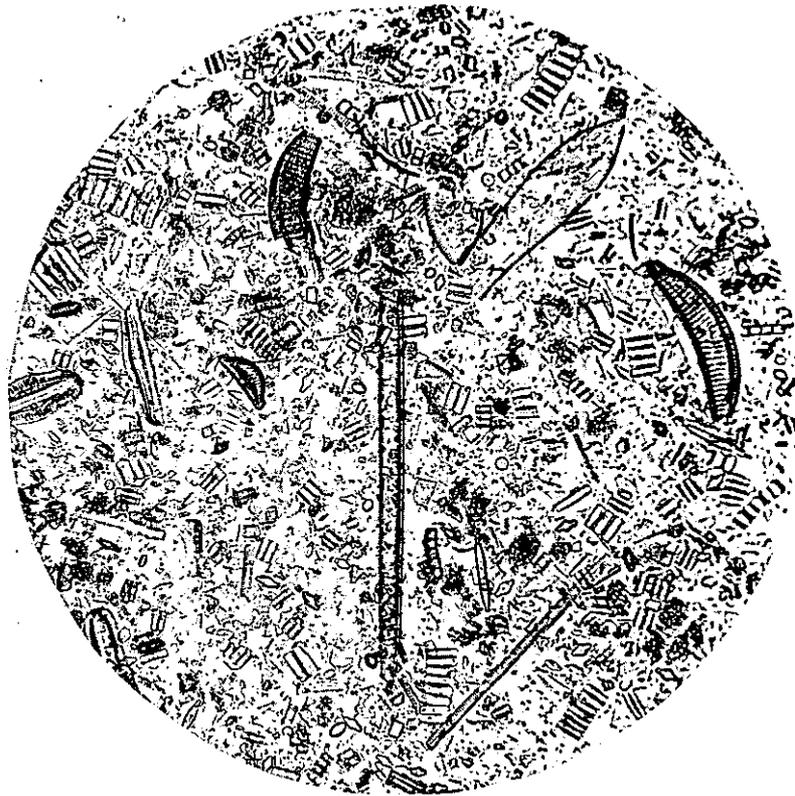


FIG. 9—Micrograph of modern lake diatom assemblage from Myvatn, Iceland.

calcining. The diatomite of Skye, Scotland, has been known for some time.⁹² Some diatomite is mined by Cape Insulation Ltd., from a wet lake basin deposit near Kendal in Westmoreland, U.K. The earth is dark in color and is not suitable for filter aid manufacture. It is used mostly for thermal insulation.

An unusual, but commercially viable deposit, is the diatomite-clay mixture of Denmark called Moler. This earth is not suitable for filter aids because of the iron oxide and clay content, but over 200,000 tpy is produced and exported elsewhere in Europe for fertilizer coating and for insulating. Moler is of marine origin and of Tertiary age and occurs on the islands of Fur and Mors in northern Jutland. Some diatomite of good quality has been produced in recent years in southern Denmark.

There are numerous deposits in the USSR. Although little information is available, production is estimated to be of the order of 300,000 tpy. Freshwater diatomite deposits exist near Prilep, Yugoslavia, and in central Anatolia, Turkey. Romania reports 45,000 tpy

production for fertilizer coating from a lacustrine deposit near Adamclisi. Small unproductive deposits occur in many other European countries.

Africa

Impure diatomite, suitable only for insulating materials, is mined by Marico Mineral Co. from a deposit in the Ermelco District, Transvaal, and by Witdraai Kieselguhr Co. from a deposit in the Prieska District, near Postmasburg, Cape Province.

East Africa produces both filter aid and filler grade products from deposits near Gilgil, Kenya. These deposits, mined by East African Diatomite Industries Ltd., were deposited in Pleistocene lakes in the Rift Valley. Several other smaller deposits are not of current economic interest.

Marine deposits of Miocene age occur near Sig (formerly St. Denis-du-Sig) in Algeria. These are mined by Sonarem, a government agency, from underground galleries and a large



FIG. 10—Aerial view showing extent of Manville diatomite quarries at Lompoc, CA.

portion of the production is shipped to France and Italy. There is a marked similarity in appearance between the Algerian and Lompoc diatomites when viewed under the microscope. The diatomite from Algeria however, is characterized by a noticeable amount of carbonate contamination, and is deficient in many of the diatom types that, in the Lompoc earth, provide a better balance for filtration. Numerous, intensely folded, thin beds occur near Mosteganum, Algeria.

South America

Production of the order of several thousand tons per year is mined from small, scattered deposits in Rio Negro Province in Argentina. Much of the earth occurs under a basalt cap, which necessitates mining from galleries and in one instance as an open pit operation after blasting away the basalt. There are also small impure occurrences in San Juan province near Calingasta, and in remote parts of Salta Prov-



FIG. 11—View of one of the Diatomita San Nicolas quarries at Catarina, Jalisco, Mexico.

ince. There are also occurrences in Brazil. The most developed are reported in Peru, Chiclayo, and in Colombia, Cúcuta, and other Latin

Asia

There is a marked increase in the demand of diatomite in Asia. The most developed markets, existing in China, India, and Japan, are well known. The demand in Australia and New Zealand is increasing, principally because of the increasing need for diatomite in the pulp and paper industry. The most developed diatomite deposits in Asia are in the Philippines and the Malay Peninsula.

Elsewhere, diatomite occurs in one reason for its use. Furthermore, diatomite deposits are found in various parts of the world.

Reserves

Present reserves of diatomite are estimated to be in excess of 100 billion tons. The most important reserves are in the United States, Mexico, and the Philippines. The reserves in the United States are estimated to be in excess of 100 billion tons. The reserves in Mexico are estimated to be in excess of 10 billion tons. The reserves in the Philippines are estimated to be in excess of 10 billion tons.

Keeping reserves of diatomite suitable for use is a problem because of its softness and its tendency to erode in road construction. One way to solve this problem is to use diatomite in the form of a concrete aggregate.

ince. There are numerous bog deposits in Brazil. The states of Ceará and Bahía contain the most deposits, although eight other states are reported to have smaller impure occurrences. Peru has occurrences at Pisco, Piurá, Chiclayo, and Arequipa; and Chile has deposits of high brightness earth at Arica and Chiloe. In Colombia, diatomite occurs at Tunja and Antioquia. Diatomite occurs to a lesser degree in other Latin American countries.

Asia

There is considerable potential for development of deposits in the Far East. Japan has a growing industry based on its own marine and lacustrine deposits operated by Showa Chemical Co. Deposits, possibly suitable for local markets, exist in Indonesia and in Korea. China has commercial deposits about which little is known. There are several small deposits in Australia and in New Zealand, but for filter aid quality, these countries depend on imports, principally from the US. The pressure from increasing transportation costs, however, is lending motivation to the exploration and possible development of shallow mediocre quality bog deposits in Western Australia near Perth and Geraldton.²²⁸

Elsewhere in the world are numerous other occurrences of diatomaceous silica which, for one reason or another, have not been exploited. Furthermore, accumulations of diatomaceous ooze are forming today that will constitute the deposits of "tomorrow."

Reserves

Present reserves are estimated to be adequate beyond the year 2000. Presently known deposits are stretching beyond forecasted depletion through the efforts of research and development in finding methods to process lower grade crude. Other deposits that are currently considered marginal by virtue of quality, minability, or accessibility will undoubtedly take on new importance should the present reserves begin to dwindle.

Exploration

Keeping in mind the previously described limiting criteria for formation, prospecting for diatomite entails reconnaissance of potentially suitable terrain. Because it is usually soft and easily eroded, white "showings" in stream banks or in road cuts should be investigated.

One would surmise that gravimetric survey-

ing would be fruitful in the search for diatomite horizons in conjunction with higher density beds. So far, however, no successful operations of this kind have been reported. Geophysical refraction seismic surveys have successfully outlined the depth of shallow fresh water diatomite basins. This works particularly well where the soft (low velocity) diatomite is underlain by higher velocity basalt (C.M. Smith, Grefco, Inc., personal communication).

Geochemical methods so far have not been adapted to the prospecting for, nor exploration of, diatomite. However, narrow pass-band infrared imagery (3-4 and 4.5-5.5 micrometers) has been used to recognize diatomite from aircraft by its thermal characteristics.⁷⁹ Changes in vegetation have been noted over diatomite-bearing areas of bog deposits, and this might indicate the possible application of geobotanical techniques in prospecting.

When carried to the point of development, exploration of diatomite deposits is pursued in stages. After an occurrence has been recognized through prospecting, usually, the first step in exploration consists of a preliminary sampling of all visible outcrops. The nature of the material is noted and recorded by measuring the attitude of the beds, and by observing all other visible structural and stratigraphic features. Sampling intervals are divided into visible increments if bedding, textural, and color changes or stratification are evident. If thick enough and no visible divisions are apparent, the stratigraphic interval spanned by each sample should be no more than 150 cm for each channel cut. In this way, nonvisible characteristics—diatom assemblage, chemical changes, etc.—may be noticed and characterized during testing of the samples. In subsequent exploration stages, the 150-cm interval may be reduced, if required. Evidence of staining, degree of consolidation, judgment of color, bedding, and stratification, etc., are all field characteristics that are important, and which should be noted. Pending favorable results from the laboratory evaluation of the samples, the next stage of exploration is planned to delineate the reserves within the area and to further assess the quality. With horizontal beds under relatively thin overburden and in areas of gently rolling topography, the digging or augering of vertical exploratory shafts to expose the entire stratigraphic column has proven highly satisfactory. In countries with low labor rates and in locations where mechanical equipment is difficult to maintain, hand-dug shafts up to 50 m in depth have many advantages. When these are of the order of 1 to 1½ m in diam, ingenious "bird

cage" types of sampling platforms, lowered by windlass into the hole from a tripod arrangement, have been used to support a geologist, who logs the hole and collects samples from the wall of the shaft. Whether hand-dug or machine-bored with a large auger, these openings in the deposit have the advantage that the structure and nature of the beds may be noted and correlated from hole to hole. Where overburden is minimal or nonexistent, holes dug by backhoe have been used. While these have the advantage of the speed of excavation that is provided by mechanical equipment, depth is limited to about 6 or 7 m at the most.

Core drilling in diatomite is specialized and requires special equipment and experienced drilling crews. Little, if any, good quality diatomite will produce satisfactory core with a diameter of less than 10 to 15 cm. Any formations that will, are usually too highly consolidated to be of much commercial value. A 10-cm core if possible to obtain, however, provides the amount of material that is required for testing. Where any amount of topographic relief is present, trenching by bulldozer on hill-sides will expose the bedding and will permit subsequent channel sampling. The opening of trenches by bulldozer across the bedding of dipping strata will remove overburden and expose the strata for sampling.

The positioning of drill holes, shafts, or trenches to adequately cover a deposit, depends upon a number of factors. Sample positions are most commonly arranged systematically in a grid to cover the area to be explored. The distance between sample locations is dependent, among other things, on the lateral variation in important properties or characteristics of the diatomite. Where important properties are thought or known to change rapidly with lateral extent, holes must be placed more closely together than when a high degree of uniformity is experienced in preliminary study. (Sample holes, on as close as 30-m centers, have been used.)

The advantage of two and three-stage exploratory programs is that exploration can begin with a relatively economically wide spacing of sampling locations. Upon testing of the samples from such a stage, a judgment can be made whether, because of unfavorable findings, the program should be aborted, or if a subsequent program is needed in which the hole spacing is reduced. Subsequent stages of exploration consist of additional specialized sampling and of the selection of bulk samples for plant scale trials. Whereas the foregoing methods are

suitable for dry deposits, specialized techniques must be developed for bog deposits and for those occurring under lakes or ponds.

In the case of shallow lakes, sample locations are marked with survey poles driven into the ooze. Peat bog samplers that extract a 30 to 60-cm incremental sample have been designed with long shafts so that a sample can be extracted from as much as 8 m below the surface. These may be used from a boat or raft that is floated into position and anchored. Some preliminary field testing can be incorporated into the exploratory phase of deposit evaluation. Field examination of samples by portable microscope can reveal considerable information. Other obvious field aids include an HCl test for carbonate, a grit test by grinding the crude between teeth, and the noting of appreciable water-solubles by taste.

Evaluation of Deposits

A preliminary idea of quality can be gained from the foregoing field observations. The most obvious recognizable property is color. The higher the brightness of a diatomite, the more attractive its potential as a filler is likely to be. Another property that is evident in the field is block density. A low block density is indicative, among other things, of freedom from contaminating solids, such as sand and clay. Diatom type and degree of consolidation are also reflected in block density. A low degree of consolidation is desirable. Highly consolidated diatomites are difficult to mill and result in degradation of the skeletal structures. As previously mentioned, the most useful tool in the field is a portable microscope. When performed by an experienced operator, microscopic examination in the field can be used to ascertain diatom constitution and contaminants, to direct the course of exploration, to provide a stratigraphic correlation, and to eliminate the shipping of useless samples to the testing center.

While much useful information can be collected in the field, and can lead at that point to a firm recommendation by the geologist to *not* consider the deposit further, the ultimate judgment of quality, however, is formed from the results of usually extensive testing in the laboratory. The chemical analysis of a diatomite, while useful to some extent, is not an effective criterion in predicting the performance for most applications. It is to be expected of course that the lower the percent of nonsilica components, the better—to be sure their absence is essential in many cases. However, simply the indication

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of high SiO_2 content alone is not a sufficient sign of a suitable crude. Chemical purity, then, is an attribute that becomes more important only after other indications of suitability have been ascertained. The properties that are measured in the laboratory are designed to reflect the performance of the finished product in a specific, or similar grouping, of applications. The milling of the crude in the laboratory must, of course, simulate the treatment that it would receive in plant equipment. Such properties as microscopic constitution, loose weight, wet density, screen size, brightness, abrasion, water absorption, filtration flow rate and clarity, pH, and resistivity, and in specialized cases, porosity and acid soluble iron, calcium, and trace elemental content are just a representative few of the many characteristics that are of importance in various applications and which must be evaluated in the laboratory. Special applications generate the need and the design of additional special and often relatively expensive testing methods.

Preparation for Markets

Mining

By and large, the most economical and indeed the only method of extraction used in the United States is quarrying or open pit mining. In Europe, Africa, South America, and parts of Asia, commercial deposits are mined underground as well. In Iceland, the deposit at Lake Myvatn is dredged from beneath about 1 m of water and pumped in slurry form to the processing plant 2 km away.

In the larger open pit quarries of the western United States, nearly all use power equipment. Since blasting is not ordinarily required, only bulldozers, front-end loaders, and trucks are required to extract and transport the crude to the mill. In the Manville Celite® operations at Lompoc, bulldozer-rooter combinations loosen the consolidated strata which are loaded into diesel-powered bottom-dump trucks by Euclid belt loaders, by diesel and electric shovels, and by front-end loaders. The result is an endless procession of conveyance from the quarries to strategically located stockpiles over vertical storage shafts. These are connected to the processing plant through an underground transportation system, which permits considerable flexibility in the blending of various crudes at the mill.

In smaller American operations, diesel-powered scrapers convey the earth to stockpiles where front-end loaders are used to fill

the trucks for transportation to the mill. Where hard contaminants or thin strata are encountered, power shovel application may be required.

Although some operations outside the United States are carried on by large companies and use modern mining methods, diatomite mining in many parts of the world is still, for the most part, a small or family owned operation, often from underground tunnels and galleries, and of pick and shovel and wheelbarrow magnitude. Where the climate will allow, the ore is spread on the ground or on drying platforms, and the moisture reduced to less than 20%. Rotary dryers are often used rather than simultaneous milling-drying processes.

At the Manville Lompoc deposit, extensive sampling and testing precede the mining operation for quality control. Selective mining then consists of separating "critical horizons" which are sent to waste. In many smaller deposits, such as are prevalent elsewhere in the world, selective mining of narrow beds by hand to separate chert lenses and carbonate inclusions is widely used.

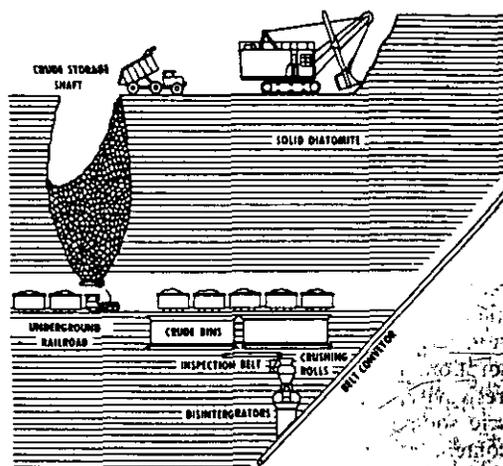
The attitude of the beds, their thickness, the distribution of intercalated impure horizons, and thickness of overburden all have a bearing on the method of mining that is best to use. Underground mining of horizontal beds consists simply of following each stratum as far into the deposit as is economical. Then recovery of part of the remaining approximate 44% that is required to support the roof is removed on the way out, if the mine is ever depleted to that extent.

Underground mining of inclined beds becomes increasingly difficult with increased dip. Depending on topography and on the arrangement of galleries, exploitation may not be economically feasible for any appreciable distance. Open pit quarrying is obviously preferable to underground mining because of lower mining costs and greater rates of recovery. When the beds are dipping gently, open pit mining offers considerable flexibility in that quarries can be located where beds of a particular quality outcrop, thus allowing for blending of several crude types. Horizontal beds in rolling topography offer similar advantages.

Milling and Processing

Because of the high moisture content of the crude and other processing losses, it is highly desirable to have the mill as near as possible to the mine. Under unusual conditions, however, crude diatomite has been trucked considerable

FIG. 12—Schematic representation of the mining, transporting, processing, and packaging of Celite diatomite powders. Reprinted by special permission from Chemical Engineering.



distances to a plant. The Manville Lompoc plant, for example, is adjacent to the quarries, whereas the Manville Española S.A. plant at Alicante, Spain, is situated over 100 miles from the source of crude.

Since the particulate shape and structure of the diatom skeleton is the physical property that most distinctly sets diatomite apart from other forms of silica, and for which its uniqueness is most responsible, great care is taken during milling and processing to preserve this structure. Such size reduction methods commonly used in the processing of other industrial minerals, as ball milling or grinding, would destroy the delicate structure and would render it useless for such applications as filtration or as a flattening agent in paint (Fig. 12).

Since crude diatomite commonly contains as much as 40% moisture, and in many cases over 60%, primary crushing to aggregate size is followed by a simultaneous milling-drying as the suspended particles of diatomite are carried in a stream of hot gases. Passage of the suspended particles in the hot gases through a series of fans, cyclones, separators, and a baghouse results in the separation of the powder into various sizes, in the removal of waste impurities, and in the expulsion of the sorbed water. Ratios of over three tons of crude in place, to one ton of filter aid product, are not unusual. Diatomite products, so processed without further treatment, are bagged or handled in bulk as "natural" milled products.

When the adjustment of particle size distribution is required for such applications as fast flow rate filter aids, the heating of the powder to incipient fusion in large rotary kilns, followed by further milling and classifying, results in straight calcined grades. Further adjustment

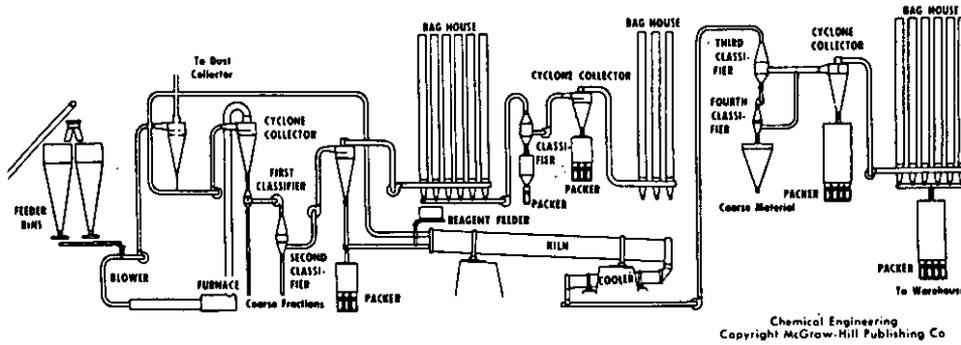
of particle size is effected by the addition of a flux—usually soda ash—before the calcining step. The use of sodium chloride as a flux is still common outside the US, although in this country, its corrosive action is avoided. Such products are referred to as "flux calcined."

It should be pointed out that the term "calcination" is a misnomer when referring to the heat treatment of diatomite. The process is not, in the correct technical sense, one of calcination at all. Rather, it is the agglomeration of fines through incipient fusion or sintering—often with a flux. The incorrectly introduced term has persisted and has become entrenched in the particular nomenclature of the trade; and for historical reasons, its use is being continued here.

Simple calcining without a flux (straight calcining) results in a product with a pink cast. The color is caused by the oxidation of iron in the crude and becomes more intense with an increasing iron oxide content. Flux calcining produces a white product in good quality diatomite, in part believed to be caused by the conversion of the iron to complex sodium-aluminum-iron silicates, rather than to the oxide. A pinkish cast is often observed in flux calcined diatomite, if the amount of flux required for optimum filtration properties is insufficient to complex all of the available iron.

Calcining and flux calcining produce other changes in the diatom particle. Among these are the loss of the combined water that is part of the opaline structure, degradation of the tertiary and secondary structure of the diatom valve through incipient fusion, and conversion of portions of the otherwise amorphous silica to cristobalite (Figs. 13a-d).

Filter aid powders for special uses are pro-



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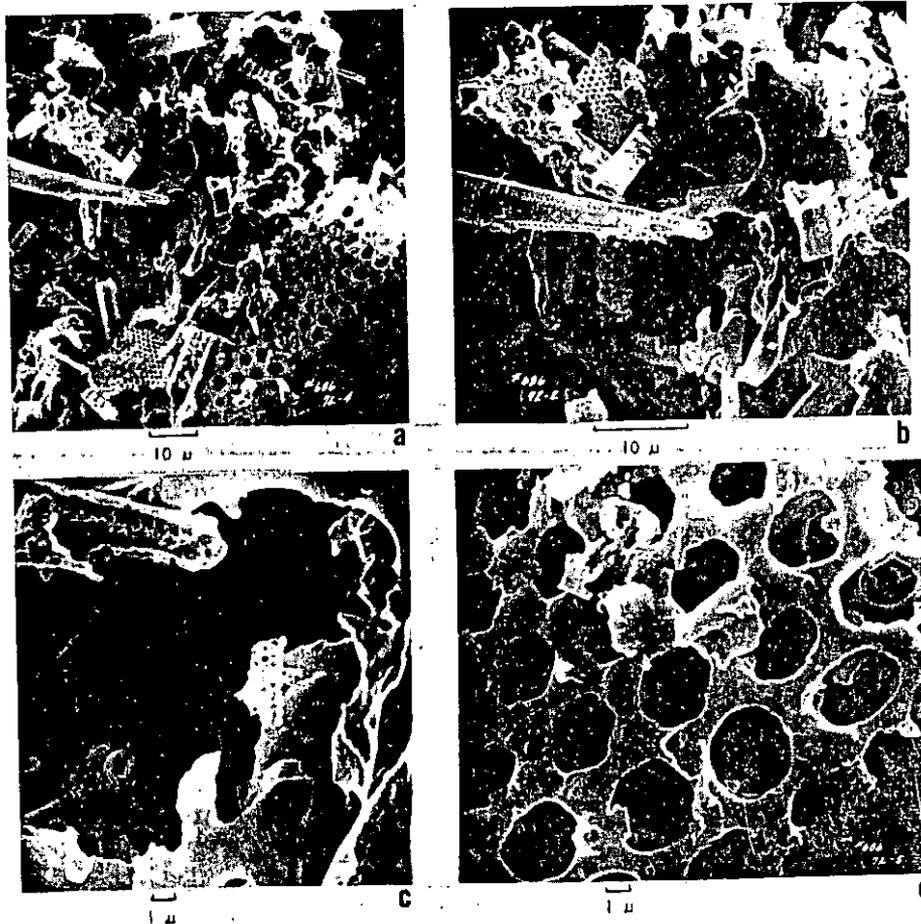


FIG. 13—Scanning electron micrograph of flux-calcined Lompoc, CA, diatomite illustrating agglomeration of fine particles and incipient fusion of siliceous structure.



FIG. 14—An aluminum, pneumatic, dry bulk tanker on semi and full trailers for transporting diatomite powders. These are 1250 cu ft each (8–9 tons) in capacity. Each has its own low pressure air system for unloading to the customer's storage bin.

duced by acid treatment of dried and milled material, in combination with conventional calcination and flux calcination. Specially prepared diatomite aggregates have also been produced for use as supports in gas liquid chromatography by special sizing to close tolerances, followed by acid treatment, and by special surface treatments with silanes or silicones to deactivate the support surface. The application of diatomite in brick and in extruded and aggregate forms has declined in recent years, hence the manufacture of product types in other than fine powders is less important. Special milling and classifying techniques have been employed in the control of particle size distribution for functional fillers. For the efficient control of gloss and sheen in paint, for example, grades of diatomite powders are available in which the nonfunctional fines, as well

as the oversized particles, have been removed during processing.¹⁶¹ This point is treated in more detail later.

While the greater portion of diatomite powders are packaged and shipped in 50-lb bags, or equivalent metric quantities, in recent years progress has been made in the pneumatic bulk handling of diatomite in conjunction with commercial shipments in bulk box cars, in bulk trucks, and in pressure differential special bulk compartmented cars^{137, 161, 216} (Fig. 14).

Testing and Specifications

As is common with most industrial minerals, the testing procedures by which processed diatomite powders and aggregates are evaluated and standardized are designed to quantify an

TABLE 2—Trace Elemental Composition of a Typical Celite® Diatomite Product*

Element	Ppm	Element	Ppm	Element	Ppm	Element	Ppm
Antimony (Sb)	2	Gadolinium (Gd)	<1	Neodymium (Nd)	20	Tantalum (Ta)	20
Arsenic (As)	5	Gallium (Ga)	5	Nickel (Ni)	120	Tellurium (Te)	<2
Barium (Ba)	30	Germanium (Ge)	<10	Niobium (Nb)	5	Terbium (Tb)	<0.2
Beryllium (Be)	1	Gold (Au)	<0.5	Osmium (Os)	<0.5	Thallium (Tl)	<0.5
Bismuth (Bi)	<0.5	Hafnium (Hf)	<0.5	Palladium (Pd)	<1	Thorium (Th)	5
Boron (B)	100	Holmium (Ho)	<0.2	Platinum (Pt)	<2	Thulium (Tm)	0.2
Bromine (Br)	20	Indium (In)	<0.5	Praseodymium (Pr)	2	Tin (Sn)	<1
Cadmium (Cd)	2	Iodine (I)	1	Rhenium (Re)	<0.5	Tungsten (W)	<0.5
Cerium (Ce)	10	Iridium (Ir)	<0.5	Rhodium (Rh)	<0.5	Uranium (U)	5
Cesium (Cs)	5	Lanthanum (La)	10	Rubidium (Rb)	10	Vanadium (V)	200
Chlorine (Cl)	400	Lead (Pb)	2	Ruthenium (Ru)	<1	Ytterbium (Yb)	<0.5
Chromium (Cr)	100	Lithium (Li)	1	Samarium (Sm)	2	Yttrium (Y)	100
Cobalt (Co)	5	Lutetium (Lu)	<0.2	Scandium (Sc)	20	Zinc (Zn)	<10
Copper (Cu)	40	Manganese (Mn)	60	Selenium (Se)	10	Zirconium (Zr)	20
Dysprosium (Dy)	<1	Mercury (Hg)	0.3	Silver (Ag)	<0.5		
Erbium (Er)	<0.5	Molybdenum (Mo)	5	Strontium (Sr)	20		
Europium (Eu)	1						
Fluorine (F)	50						

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* The symbol <, less than, indicates below detection limit of method used. Values are reported in parts per million (ppm).

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attribute required in the performance of a function. Filter aids must produce clarity of varying degree, depending on the fluid to be filtered, and at a reasonable flow rate. A filter aid grade, then, may be subjected to a filtration test that measures flow rate through a filter cake under controlled conditions, as well as the clarity of the resulting filtrate. Since diatomite is purchased on a weight basis, and used on a volume basis, the cake or wet density is also important. To arrive at a suitable product, control of particle size distribution, as reflected in screen analysis is important. In certain filler applications, particle size distribution must be characterized quite precisely with sedimentation and related techniques. Lately, the Coulter Counter has been widely used. Particularly in food processing and conditioning, pH and resistivity of a water slurry are important. Recently, soluble trace elemental analysis to conform with Food Codex methods and limits has become important. Table 2 shows the trace elemental composition of a typical Celite® diatomite. In functional fillers for paper or paint, brightness of the powder, as reflected in a TAPPI or a General Electric brightness; fineness translated into Hegman reading; vehicle demand expressed in oil and water absorption; and abrasion for paper by the Valley Iron method are only a few examples of the properties that must be measured and controlled. These and other properties are the subject of specifications and of quality control procedures by which manufacturer and buyer agree on a product. Most of the tests are well known, whereas others are proprietary and confidential. Often, it is more practical to judge a particular characteristic by comparison against a standard sample. This is common and accepted practice, and is used particularly in evaluating properties that do not lend themselves readily to quantification.

TABLE 3—Domestic Production of Diatomite

Year	Sales, 1000 St	Average Value \$ per Ton
1973	609	59.26
1974	664	76.31
1975	573	80.01
1976	631	87.08
1977	648	98.56
1978	651	111.26
1979	717	125.97
1980	689	146.02
1981	707	152.48

Source: Meisinger, 1982.

The following are specifications and test procedures currently in use by the ASTM:

D 604-42 (reapproved 1975)	Diatomaceous Silica Pigment
D 719-63 (reapproved 1976)	Analysis of Diatomaceous Silica Pigment
C 517-71	Diatomaceous Earth Block and Pipe Insulation

The following military specifications are currently in effect:

MIL-S-15191B	(Oct. 20, 1967) Silica, Diatomaceous (Flattening Extender Pigment)
MIL-D-20550B	(Aug. 8, 1968) Diatomaceous Earth
MIL-F-52637	(Feb. 20, 1969) Filter Aids, Water Purification
52-MA-522a	Diatomaceous Silica Pigment

The following TAPPI specification is current:

T658 OS-77 (1977)	Properties of Diatomaceous Silica
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Production and Consumption

Although affected by changes in the economy, the production of diatomite has shown steady increase through 1974. A sharp drop in 1975 was followed by steady recovery that surpassed 1974, until 1980. According to US Bureau of Mines statistics, the average value per ton has increased steadily. This trend is reflected in Table 3. The breakdown of domestic diatomite consumption by applications is illustrated in Table 4. The exportation of diatomite has increased steadily except for a drop in 1975 that gradually recovered in subsequent years. The trend is illustrated in Table 5.

The United States leads world production; California has remained the predominant producing state, followed by Nevada, Washington, and Oregon. Four companies, Manville International Corp., Grefco, Inc., Eagle Picher Industries, and Witco Chemical Corp., account for approximately 90% of domestic production. Russian production, which is second to that of the United States, tends to run between 45 to 50% of US production. Other major producing countries are France, Germany, and if Moler is considered, Denmark. Minor world production also comes from over 20 other countries. Total world production had not, as of 1980, quite reached 2 million tons, having been of the order of about 1.75 million tons in 1979.

TABLE 4—Domestic Consumption of Diatomite by Principal Uses
(% of Total Consumption)

Use	1973	1974	1975	1976	1977	1978	1979	1980
Filtration	61	60	60	60	59	63	63	66
Fillers	18*	19*	20*	21*	22*	23	21	21
Insulation	4	5	4	5	5	3	3	3
Miscellaneous	17	16	16	14	14	11	11	10

*The US Bureau of Mines included fillers with miscellaneous until 1978. The split between fillers and miscellaneous before 1978 is the author's estimate.

Marketing

The successful marketing of diatomite products by the major producers has depended, to a large degree, on their ability to furnish high caliber technical sales service to the customer. Technically trained sales engineers, supported by research and development organizations, have resulted in the solution of customer production problems with the consequent introduction of a particular diatomite grade to do the job. In technical service to the paint industry, for example, the development of cost saving formulations, through the introduction into the formulation of specially developed extender pigments and diatomite grades for control of gloss and sheen, has been of great help to paint manufacturers. There can hardly be a better foundation on which to base sales effort or to assure product performance. A similar approach in the selection of filter aids to meet a specific requirement, or to solve a unique problem, has entrenched trade or brand names in the minds of users who have come to demand a high degree of quality and of uniformity. While this approach has been of considerable assistance to industry, and has ultimately benefited the consumer, it has made marketing more difficult for minor producers with an inferior deposit or an untrained sales organization to compete in the more sophisticated or demanding applications of diatomite. The small producer, however, supplying to a local, or to a lower grade market has been able to compete successfully. This is particularly applicable to the small foreign producer against American imports.

Diatomite powders are traditionally sold as carload, l.c.l., and warehouse. American exports are to a large degree sold through distributors, as are diatomite chromatographic supports, both domestically and abroad.

Because of its low bulk, freight and containers constitute a substantial part of the cost to the consumer. The precise effect of the cost

of transportation on the diatomite industry is being treated separately in this chapter.

Transportation

The low bulk density of processed diatomite presents unique transportation problems. Since all American commercial diatomite originates in the western states, and the predominant markets are located east of the Mississippi River, a substantial part of the eastern delivered cost consists of freight charges. The price per ton of a California processed filter aid delivered in New York consists, for example, of approximately 33% transportation costs. The successful exportation of American diatomite to Europe, Africa, Latin America, and the Far East has traditionally been dependent on a reputation and a need for superb quality.

With the cost of ocean freight increasing steadily, together with the rising costs of production at home, exports have been under continued pressure from the local sources. For this reason, the motivation for foreign exploration by American companies in the major market areas is apparent. The trend, therefore, toward decreasing exports in future years is to be anticipated. The following are typical current (May 1981) transportation costs (inland plus ocean freight) from Lompoc, CA, to representative foreign ports:

Port	Cost per Mt, \$
Capetown, South Africa	253
Yokohama, Japan	121
Buenos Aires, Argentina	213
Sydney, Australia	282
Hamburg, West Germany	179
Hull, England	181

Uses

Filtration: By far, the widest use for processed diatomite is as a filter aid for the separa-

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TABLE 5—Exports of Diatomite

	Quantity, 1000 St	Value, 1000 \$
1974	186	17,541
1975	147	15,314
1976	149	16,832
1977	152	18,876
1978	153	21,463
1979	170	26,496
1980	173	32,238
1981	160	24,397

Source: US Bureau of Mines.

tion of suspended solids from fluids.²³⁴ About 50% of all processed diatomite is channeled into this application. Indeed, the probability of economic success for a potential deposit is seriously reduced if it cannot be processed into a single, if not a range, of filter aid products. The requirements for filter aid suitability are subtly complex and many. Above all, diatom skeletal constitution and structure, density, and soluble impurities are principal considerations. The part that the skeletal structure plays in a filter aid is of paramount importance. In addition to the space between diatom particles in a filter cake, the interstices and chambers provided within the structure play their part in the trapping of impurities. The relationship and interplay between variously shaped particles in a multi-species assemblage is also important. A single-species assemblage of forms often has less to offer than an association consisting of numerous different species. The balance, for example, between pennate and discoid species found in the marine earth at Lompoc, together with its response to calcination and flux calcination for the increase in flow rate, is unmatched with regard to its flow rate-clarity relationship. Certain lacustrine earths, consisting of a completely different assemblage or of wholly one species, while lacking the advantages mentioned, possess other merits for certain applications. For example, the lacustrine earth mined for some years at Terrebonne, OR, (and now depleted) was a favorable fast flow rate filter aid for rotary precoat filtration in that the filter cake was less susceptible than that made with other earths to cracking on the rotary drum. The need for low density and particularly in filter aids sold for food processing for low solubility content is obvious.

Diatomite is processed into filter aids for all types of food and nonfood processing applications.¹⁴⁹ The selection of the proper grade of filter aid depends on the size of the suspended

particles that are to be removed. It is axiomatic in the use of filter aids that as the particle size, and thus the flow rate increases, the ability of the filter aid to remove small particles of suspended matter decreases.¹³⁷ Conversely, as filter aid particle size and, therefore, flow rate decreases, the ability of the filter aid to remove small particles of suspended matter increases. The factors that govern which end of this flow rate-clarity relationship is to be emphasized will depend very much on the type and the particle size distribution of the undissolved solids being removed. The best filter aid is that grade that will result in the fastest flow rate (or the greatest throughput per dollars worth of filter aid) and yet will provide adequate clarity. The correct clarity must be determined and specified by the filter aid user. The calcination and flux calcination of diatomite powders are performed for the purpose of adjusting particle size distribution through incipient fusion and by agglomeration of the fines and structure to produce a range of flow rates, hence clarities.

The more commonly known applications are the use of processed diatomite powders in the filtration of dry cleaning solvents;¹³² pharmaceuticals;¹³⁷ beer, whiskey, and wine; raw sugar liquors; antibiotics;¹³¹ industrial;¹⁴⁰ municipal,^{141, 152} and swimming pool waters;¹³³ fruit and vegetable juices; lube, rolling mill, and cutting oils; jet fuels; organic and inorganic chemicals; and varnishes and lacquers. Diatomite has also been mixed with asbestos, and with other minerals, and surface-treated and acid-washed to improve its effectiveness in special filtration applications. Table 6 lists the physical properties of some commercial filter aids.

Fillers: The second largest use of diatomite is that employed as a filler. Although natural milled powders were used to some extent in paint, paper, abrasives, and other uses before there were baghouse grades, later filler applications were the result of product development to use the baghouse fines that would otherwise be discarded as a byproduct of the filter aid manufacturing process. In recent years, however, while filler products are usually produced in conjunction with, and as an integral part of the manufacturing process for filter aids, their specifications and properties are tailored to meet the requirements of a demanding filler market. Indeed, the term "filler" was often used as the catchall term for those uses that were not directed toward filtration.

Lately, however, the expression, *functional filler*, has been set apart and reserved for those

TABLE 6—Physical Properties of Some Commercial Filter Aids

Grade*	Color	Density, Lb per Cu Ft		Screen Analysis, % Retained, 150 Mesh	pH	Specific Gravity	Water Absorption	Relative Flow Rate	Typical Applications, Filtration	
		Dry	Wet							
Natural	Filter-Cel	Gray	7.0	15.9	1.0	7.0	2.10	235	100	Vegetable oil catalyst
Calcined	Celite 505	Pink	8.0	21.0	—	7.0	2.15	170	135	Apple juice
	Standard Super-Cel	Pink	8.0	17.2	3.0	7.0	2.15	255	200	Beer and wine
	Celite 512	Pink	8.0	17.9	4.0	7.0	2.15	250	300	Sugar
Flux Calcined	Hyflo Super-Cel	White	9.0	17.2	5.0	10.0	2.30	245	500	Dry cleaning solvents, chemicals, etc. (most widely used filter aid)
	Celite 501	White	9.5	16.9	8.0	10.0	2.30	250	750	Grape juice
	Celite 503	White	9.5	17.2	9.0	10.0	2.30	240	900	Industrial and potable water
	Celite 535	White	12.0	17.6	9.0	10.0	2.30	245	1350	Industrial wastes
	Celite 545	White	12.0	18.0	12.0	10.0	2.30	240	2160	Swimming pools
	Celite 550	White	18.1	21.0	20.0	8.0	2.30	220	2380	Pharmaceuticals
Celite 560	White	19.5	20.0	50.0	10.0	2.30	220	7500	Phosphoric acid	

* Grades listed are Manville registered trademarks.

filler applications in which diatomite produces a desired effect or function that is more than simply the bulking or partial replacement of an otherwise more expensive component in the formulation. The larger part of the total filler market is that in which diatomite serves as a functional filler as defined, rather than as a mineral filler. The following discussion, rather than application-oriented, is designed to highlight those properties of diatomite that are important in its application as a functional filler, as well as an absorbent, mild abrasive, extender, insulation, conditioning agent, and catalytic or chromatographic support. In general, more than one property is important in any application. A key property, supported, however, by others, usually provides the specific function.

Particulate Structure—Much has already been stated regarding the unique nature of the diatom valve and pointing out its difference from other forms of silica. The use of diatomite as a functional filler in paint for the control of gloss and sheen, accounts for a major share of the dollar volume attributed to fillers. The small particles serve to roughen the other-

wise smooth paint film and to produce a flattening effect.^{162, 168} Precise particle size control is required during production of flattening agents, since the extreme fines contribute little to the flattening effect, but because of their absorption do increase the vehicle demand. Particles that are too coarse, on the other hand, will cause surface blemishes and unsightly spots. This is not to say that only the structure is important in this application. Structure is of primary importance, but brightness, absorption, pH, refractive index, and chemical stability are also important.

The unique structure of the diatom valve makes it useful as an antiblocking agent in polyethylene film production. The film is blown as an envelope, and while hot, has a tendency for the surfaces to stick together or "block." If a small amount of diatomite (0.05 to 0.5% by weight) of the right particle size distribution is incorporated into the film, the fine particles sticking through the plastic surface provide a mechanical separation or "antiblocking" effect that keeps the surfaces from sticking.¹⁶⁴

As in the flattening of paint, such other sup-

porting properties of diatomite are of great importance in the manufacture of a

Liquid Aids—The high surface area and high value, however, can absorb water. Specifications are still "dry" in addition of property of liquid carrier and pitch chemical in sulfuric acid through the safer and c

Inertness—exceptionally 94%. Because to most of extremely point of attributes, are responsive and supports in hydrolyst used and the petroleum

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porting properties as absorption, brightness, refractive index, and particle size distribution are important and must be considered in the manufacture of antiblocking agents.

Liquid Absorption—Diatomite powders, because of their high surface area and low bulk value, have a high absorptive capacity. They can absorb up to 2½ times their weight of water. Specially processed diatomite powders are still "dry" and free flowing even after the addition of 50% by weight of water. This property contributes to their application as the liquid carrier in rug cleaners, pesticide carriers, and pitch control in paper manufacture. In the chemical industry, such hazardous materials as sulfuric and phosphoric acids are converted through the use of diatomite to dry powders for safer and easier handling and storage.

Inertness—A high quality diatomite has an exceptionally high silica content—as much as 94%. Because it is essentially silica, it is inert to most chemical reactions and is resistant to extremely high temperatures, with a softening point of about 2600°F. Coupled with its other attributes, inertness and temperature resistance are responsible for its utility as a catalyst carrier and as an insulation. Diatomite catalyst supports are ideal for the nickel catalyst used in hydrogenation processes, the vanadium catalyst used in the manufacture of sulfuric acid, and the phosphoric acid catalyst used in the petroleum industry.

Mild Abrasive—Because it is similar in composition to opaline silica, diatomite has a hardness sufficient to produce abrasion on metal surfaces. However, to this attribute is coupled the fact that the delicate skeletal structure has a friability and particle size that causes it to polish, rather than to scratch.¹⁷² The highly refined (or low contaminant) natural milled product is ideal for incorporation into silver polish formulations, and the slightly increased strength or particle integrity produced by flux calcination makes this type of treatment suitable for producing the more abrasive effect required in automobile polishes.

Reinforcing Effect—The particulate structure produces a semireinforcing effect in such diverse materials as silicone rubber specialties, and in mechanical rubber goods.

Silica Source—Because of its high content of silica and its high surface area, diatomite is a particularly suitable and reactive form of silica in combination with lime for the hydrothermal manufacture of lime-silicate insulations and of highly absorptive calcium-silicate powders.

Chromatographic Support—The use of di-

atomite as a chromatographic support is a unique development, principally of the 1960s, and makes use of and illustrates essentially all the properties that have been previously described.¹⁸⁰ Structure and absorption account for its unique capacity to carry sufficient amounts of the liquid phase.¹⁸⁷ An inert surface is required to keep the support from reacting and interfering with the partitioning ability of the liquid phase. When properly processed and treated, diatomite chromatographic supports satisfy all these requirements.^{184, 187}

Miscellaneous—Other applications that make use of the unusual properties listed above include anticaking agent on ammonium-nitrate prills, match head composition to control after glow, welding rod composition, use in battery box separators, pozzolan and concrete additive to improve workability and reduce bleeding, acetylene containers, and a stabilizer in explosives, drilling mud additive, and as a conditioner of animal foods. Table 7 lists the physical properties of some commercial fillers. The uses of diatomite are also covered in the chapter on "Fillers, Filters, and Absorbents," pages 243-257, Volume 1.

Further Considerations and Trends

Since the United States is self-sufficient, imports of diatomite have been negligible. However, depending on the course of foreign exploration, on processing costs, and on transportation charges, it is conceivable that eastern US markets could be penetrated to some degree by European or African sources.

The presence of eastern US occurrences of diatomite, while not a threat to western supremacy at present, could become competitive. For certain low quality applications, the marine diatomite outcroppings in Maryland and Virginia could have utility. Marked advances in processing are required before this earth could approach the quality of western deposits. The bog deposits of Florida, New England, and New Brunswick, because of their eastern location, are intriguing. Advances in dredging technology and in imaginative processing will be required to upgrade these to commercial potential.

Substitutes

While diatomite possesses properties and characteristics that are unmatched by other forms of silica—indeed by any other type of

TABLE 7—Physical Properties of Some Commercial Fillers

Application:	Paper										Paint				Abrasives				Conditioning Agent				Anti-Blocking Agent		Reinforcing Agent
	Cylinder Machine Production	Fourdrinier Production	High Flattening		Low Luster Stir-In		Silver Polish	Automobile Polish		Buffing Compound	Toxicant Extender	Fertilizer Coating	Polyethylene Celite	White Mist	Rubber										
			Celite 281	Celite 281	Celite 499	Celite 499		Snow Floss	Super Floss							Celite HSC	Celite 209	Celite 379	White Mist	Celite 270					
Brand*	Celite 321A	Celite 305	Celite 281	Celite 281	Celite 499	Celite 499	Snow Floss	Super Floss	Celite HSC	Celite 209	Celite 379	White Mist	White Mist	Rubber											
Loose wt, lb per cu ft	7.0	7.2	8.0	8.0	7.2	7.2	7.1	8.7	10.7	7.2	7.9	8.8	8.6												
Wet density, lb per cu ft	20	22.5	20.0	20.0	19.0	22.0	22.0	26.0	17.0	22.5	19.2	20.8	24.0												
Moisture content, %	4.0	3.0	0.5	0.5	0.1	4.1	4.1	0.1	0.5	4.0	3.3	0.1	0.3												
Retained on 150 mesh, % wt	—	0.1	Trace	Trace	Trace	Trace	Trace	0	5.6	0.1	0.1	Trace	0.1												
Retained on 325 mesh, % wt	8.0	0.4	1.2	Trace	0	0.3	0.1	0.1	19.6	0.4	3.0	Trace	0.7												
Oil absorption, % wt	210	180	145	160	160	190	120	185	185	180	190	160	150												
Color	Gray	Gray	White	White	White	Gray	White	White	White	Gray	Gray	White	Pink												
Brightness, TAPPI	65	63	88	89	89	64	91	86	86	63	59	90	60												
Hegman	—	—	1	1	4	4%	3%	—	—	—	—	5	—												
Sheen	—	—	12	12	15	50	50	50	—	—	—	30	—												
Specific gravity (apparent)	2.0	2.0	2.3	2.3	2.3	2.0	2.3	2.3	2.3	2.0	2.0	2.3	2.2												
pH	6.6	6.2	8.7	8.7	9.5	6.5	9.2	8.9	8.9	6.2	7.1	9.8	6.5												
Resistivity, ohms	3000	3000	13,000	7400	7400	3000	5000	9000	9000	3000	4000	6500	30,000												
Refractive index	1.42	1.42	1.48	1.48	1.48	1.42	1.48	1.48	1.48	1.42	1.42	1.48	1.44												
Surface area, sq. m per g	20-30	20-30	0.7-3.5	0.7-3.5	0.7-3.5	20-30	0.7-3.5	0.7-3.5	0.7-3.5	20-30	20-30	0.7-3.5	4-6												
Porosity, %	65-85	65-85	65-85	65-85	65-85	65-85	65-85	65-85	65-85	65-85	65-85	65-85	65-85												
Particle size range, μ	8-1	4-1	850	850	495	140	375	1900	1900	170	410	390	300												
Valley Iron Abrasion, mg	440	170	—	—	—	—	—	—	—	—	—	—	—												

* Brands listed are Manville Registered Trademarks.

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mineral powder—in certain applications, it has lost some ground to new and different materials. Where for decades it has occupied a place of preeminence in the field of filtration, a relative newcomer has appeared to challenge its position in specific applications—perlite. Perlite, when expanded and milled into a filter aid, has cut into the rotary precoat filtration field. It has taken over some markets for sugar, for alginates, and for pharmaceutical filtration. The percentage of total perlite going into filtration applications has increased steadily to where it was approximately 18% in 1979. Another area where inroads have been made into diatomite's role is in paper fillers and in paint where calcined clay and talc in recent years have partially replaced it. However, some of the major diatomite producers are also in the perlite and talc business.

Tariffs and Taxes

There is no tariff on the importation of diatomite into the United States. In those countries that have a customs tax, the Brussels Tariff designations are generally used. The classifications into which the various grades and types of diatomite are relegated are not uniform among countries, but depend on the interpretation of the responsible customs officials in each country. Of course, the rate of taxation is also variable among countries. In Japan, for example, natural and straight calcined grades are admitted duty free under the Brussels Tariff No. 25-12, which is defined to include "Siliceous fossil meals and similar siliceous earths (for example, kieselguhr, tripolite, or diatomite), whether or not calcined, of an apparent specific gravity of one or less." Flux calcined grades, on the other hand, are taxed 4% in Japan under designation 38-03-2, which applies to "activated carbon (decolorizing, depolarizing, or absorbent) activated diatomite, activated clay, activated bauxite, and other activated natural mineral products." Diatomite catalyst carriers imported into Japan are classed as "Laboratory, chemical, or industrial wares," and taxed 6% under designation 69-09-1.

The European Common Market countries use the designation 25-12-00 for natural and straight calcined products and 38-03-00 for flux calcined products. Some countries insert other figures for the last two digits for further classification. There is still no duty charged against these tariff numbers.

One legitimate point of contention among diatomite producers appears to be the classification of flux calcined diatomite by government

authorities under designation 38-03-2, thus including it with "activated" mineral materials. It cannot be logically argued with any degree of scientific accuracy that the flux calcination of diatomite should be visualized as an *activating* process similar to that of clays or carbon.

Under the Tax Reform Act of 1969, the percentage depletion allowance for diatomite was reduced from 15 to 14%.

Health and Ecology

Considerable expenditures of money and effort by the major producers have been made to control dust both in mines and in plants. Since the calcined and flux calcined grades of diatomite contain cristobalite,⁶ protection of workers against pneumoconiosis through the use of dust control equipment and through education has become common practice. The health of workers with major companies is periodically checked by physical examinations that include chest X-rays. The filtering and optional heating of air of mining equipment cabs is not uncommon among the larger producers. While untreated diatomaceous silica is not known to be hazardous, many in the industry regard all dusts to be a nuisance that should be held to a minimum and the comfort and protection of workers is provided for accordingly. Respirators are usually required of workers in parts of the plant, and environmental control departments periodically monitor the dust count at strategic stations within the processing plants. A modern, large diatomite plant is a model in dust control and cleanliness.

SILICA

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Almost all of the references listed herein, which by no means includes all those available, are dated 1960 or later. The reader is referred to the previous editions of *Industrial Minerals and Rocks* for bibliographic information prior to 1960.

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