

With or Without Salt—A Comparison of Marine and Continental-Lacustrine Diatomite Deposits

Chapter D of
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By Phillip R. Moyle and Thomas P. Dolley

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With or Without Salt—a Comparison of Marine and Continental-Lacustrine Diatomite Deposits

By Phillip R. Moyle and Thomas P. Dolley

Abstract

Diatoms in sedimentary deposits of marine and continental, especially lacustrine, origin have similar nutrient (for example, phosphate, nitrate, and silica) and light requirements; however, their geologic ranges and physiographic environments vary. Marine diatoms range in age from Early Cretaceous to Holocene, and continental diatoms range in age from Eocene to Holocene; however, most commercial diatomites, both marine and lacustrine, were deposited during the Miocene. Marine deposits of commercial value generally accumulated along continental margins with submerged coastal basins and shelves where wind-driven boundary currents provided the nutrient-rich upwelling conditions capable of supporting a productive diatom habitat. Commercial freshwater diatomite deposits occur in volcanic terrains associated with events that formed sediment-starved drainage basins, such as the Basin and Range Province, particularly in Nevada. Marine habitats generally are characterized by stable conditions of temperature, salinity, pH, nutrients, and water currents, in contrast to lacustrine habitats, which are characterized by wide variations in these conditions. Marine deposits generally are of higher quality and contain larger resources, owing to their greater areal extent and thickness, whereas most of the world's known diatomites are of lacustrine origin. Both types of deposit are commonly mined by open-pit methods and subjected to processing designed to remove organic matter, CO₂, pore water, and inorganic contaminants in order to produce purified products. The highest quality diatomites, predominantly from marine sources, are used in filtration, although both types of deposit produce filter grades, and additional end uses include fillers, additives, absorbents, and abrasives.

Introduction

Diatomite, an earthy, very fine grained siliceous sedimentary rock, commonly light in color, is composed primarily of opaline frustules (walls or skeletons formed of secreted silica) from single-celled aquatic plants called diatoms. Also known as diatomaceous earth or diatomaceous silica, deposits of diatomaceous rock occur globally and may be of either marine or continental origin. Continental deposits are primarily of lacustrine origin, although fluvial, paludal, or estuarine depos-

its are also known. Large deposits with commercial grades, generally referred to as diatomite, are uncommon. Just as societal end uses of this important commodity are a function of its physical and chemical properties, so these properties are a consequence of various conditions and processes, ranging from the original nature of the organisms and their habitats, their depositional environment and diagenetic processes, modern tectonic settings, and weathering environments. This chapter examines specific aspects of diatomite—from the original life forms and their habitats, depositional environments, and chemical and physical properties, to mining and societal end uses—noting the similarities or differences between marine and nonmarine types of deposit. Mitchell's (2002) demonstration of a few simple, low-cost tests for selected physical and chemical index properties to identify high-quality diatomite in Thailand points out the importance of understanding the characteristics of both marine and lacustrine deposits. Here, we emphasize diatomite of lacustrine origin, as in Shenk's (1991) descriptive deposit model 31s.

Diatomite is white if pure, commonly buff to gray in place, and rarely black. It can be further described as chalk-like, soft, friable, very finely porous, or very low in density (floating on water until saturated), and the frustules essentially are chemically inert in most liquids and gases. Diatomite also has a low thermal conductivity, owing to its high pore volume, and a high fusion point. Combinations of physical and chemical properties of high-grade diatomite make it suitable for many specialized applications, especially for filtration, its principal use. The Greeks used diatomite 2,000 years ago as a lightweight building material and in ceramic pottery (Breese, 1994). Much later, it was used as an absorbent to stabilize nitroglycerine in the manufacture of dynamite, beginning in 1867 (Harben and Kuzvart, 1996; Harwood, 1999). Society has discovered many additional uses for diatomite, such as a filler in such products as paints and dry chemicals, as an absorbent for industrial spills and in pet litter, as an insulator in sawn and molded shapes, as a mild abrasive in polishes, and as a silica additive in cement and other products. Some diatomite deposits, such as those hosted by the Middle to Upper Miocene Monterey Formation and the Upper Miocene to Lower Pliocene Sisquoc Formation in the California Coastal Ranges, may also contain significant petroleum sources or reservoirs (Harben and Kuzvart, 1996; Krebs, 1999). The broad geographic and temporal (Cretaceous or older to Holocene) ranges of diatoms also make them important tools as biostratigraphic markers for

chronologic dating and lithologic correlation in oil and gas exploration (Krebs, 1999), as well as indicators of marine and continental paleoenvironments (Stoermer and Smol, 1999; Wallace, 2003).

Marine and Continental-Lacustrine Diatomite Deposits

Diatoms

Diatoms are single-celled golden-brown algae, assigned to the class Bacillariophyceae (Barron, 1987, p. 166). They occur as two morphologic types based on their symmetry, either centric (also called radial or circular) or pennate (also called axial or elongate). The frustules are characterized by ornate, highly sculptured walls of silica with species-specific intricate patterns and symmetries (Wetherbee, 2002) that are used for taxonomic classification. Diatoms have adapted to various marine and continental aquatic conditions, particularly to planktonic or benthic environments. Some of the similarities and differences between lacustrine and marine diatoms and their habitats and environments of deposition, discussed in this and the following sections, are summarized in table 1. Marine environments favor planktonic diatoms because diatoms flourish in the widespread photic zone—less than 100 to 200 m deep (Barron, 1987; Boardman and others, 1987). Most planktonic diatoms are centric and are the primary nutrient producers in the photic zone. Depending on nutrient supply, turbulence, and illumination in the photic zone, diatoms can occupy various benthic habitats (Bradbury and Krebs, 1995) in shallow ocean margins, but they are rare in deep-sea sediment. Barron (1987) noted that lakes support both planktonic and benthic diatoms but that benthic diatoms dominate in streams and soils. He further described a group of marine tychopelagic diatoms that are intermediate between planktonic and benthic forms.

As many as 20,000 marine and continental diatom taxa may exist worldwide, according to Bradbury and Krebs (1995), who also noted that in North America and Europe are more than 1,000 common freshwater diatom species, with species endemic to specific ancient lakes typically ranging in abundance from 10 to 30 percent of the taxa.

The silica (opaline) in the cell walls of diatoms allows them to be well preserved in the fossil record relative to microorganisms that lack silica. Barron (1987) reported that more than 90 percent of photic-zone-produced diatom frustules dissolve in the silica-undersaturated marine environment before they reach the sea-floor-bottom sediment, whereas diatom frustules coated in organic matter or encapsulated in fecal pellets are protected from dissolution. Bradbury and Krebs (1995) noted that unaltered diatoms are not likely to be recovered from below a burial depth of 1,524 m; however, Krebs (1999) stated that the formation of calcareous concretions early in the burial or diagenetic process can preserve frustules.

Habitat and Environments of Deposition

Diatoms, both marine and nonmarine, require three conditions to sustain life: an aqueous environment, light, and a continuous supply of nutrients and minerals. Although these conditions are far from unique, satisfaction of all three conditions controls sustained diatom viability and production and, thus, the distribution and size of deposits. Such nutrients as phosphates and nitrates return to the water column when the organism dies and decays on the sea floor or lake bottom. In contrast, silica incorporated into the diatom frustules is permanently removed from the water if it is not dissolved while passing through the water column (Harben and Kuzvart, 1996). Therefore, a continuous supply of silica is needed to refresh the diatom-productivity zone for both marine and continental environments. Although marine environments range from the deep oceans to the continental shelf and near-shore conditions, the requirement for light and nutrients restricts viable environments to the uppermost 100 to 200 m (Barron, 1987; Boardman and others, 1987). Furthermore, most marine forms are stenohaline—that is, they tolerate only a narrow range of salinity (Sverdrup and others, 1970). Thus, favorable conditions are limited to environments with stable salinity—from areas along continental margins that support upwelling of deeper, generally colder, nutrient-rich water, to a near-surface photic environment where wind-driven currents disperse and recirculate nutrient-depleted surface waters to the open ocean. Western continental margins with submerged coastal basins and shelves (Harben and Kuzvart, 1996) and wind-driven boundary currents, such as selected sections of the California, South American, and Southwest African coasts (Barron, 1987), are examples of areas that provide the nutrient-rich upwelling conditions capable of supporting diatom habitat. In addition to continental margins, Sverdrup and others (1970) noted that an accumulation of more than 50 volume percent diatom frustules in a 1,500-km-wide band of ooze is present along the 60th Parallel in the South Pacific Ocean (table 1), where conditions in the photic zone favor diatom productivity.

Nonmarine diatoms have the same nutrient (phosphate, nitrate, and silica) and light requirements as marine organisms, but they have inhabited a wide variety of freshwater aquatic environments, including lakes, ponds, rivers, streams, and springs (Barron, 1987; Bradbury and Krebs, 1995) since the Eocene. Commercial freshwater diatomite is most commonly associated with lakes, where thick deposits of significant areal extent can accumulate. These deposits generally are associated with volcanic terranes and events that formed sediment-starved drainage basins, such as basin-and-range extension. In Nevada, these basins subsequently filled with freshwater, thus promoting the growth of diatoms (Bradbury and Krebs, 1995). Volcanic processes, such as hot springs, provide a supply of silica needed for skeletal development (Breese, 1994). Continental diatoms can be of the planktonic, benthic, or epiphytic (attached) type; however, planktonic varieties dominate lacustrine environments, and pennate benthic species prevail in fluvial systems (Barron, 1987;

Table 1. Summary comparison of diatoms, their habitats, and factors affecting the formation of marine and continental-lacustrine diatomite deposits.

[Where information spans both marine and continental-lacustrine deposits, we were unable to determine different characteristics for the specific factor]

Factor	Marine deposits	Continental-lacustrine deposits
Diatoms and habitat-----	Primarily planktonic forms, with lesser benthic and tychopelagic forms; benthic forms rare in deep-sea sediment.	Planktonic and benthic forms in lakes, but planktonic dominant. Benthic forms dominant in streams and soil.
	As many as 20,000 total combined marine and continental taxa worldwide. Estimated 1,000 common freshwater species; 10 to 30 percent lacustrine species endemic.	
	Primarily continental margins with cycle of upwelling, nutrient-rich currents and surface currents that disperse nutrient-depleted water in upper 100–200 m; also deep-sea plankton.	Primarily small lacustrine systems associated with volcanism that dams fluvial systems to form lakes; require continuous supply of nutrient-rich/silica-rich freshwater in low-alkaline lakes. Also occur in slow fluvial systems, ponds, swamps, and soil.
	Stenosaline-----	Euryhaline; not excessively alkaline.
	Stable temperature, salinity, pH, nutrients, and water currents.	Widely varying temperature, salinity, pH, nutrients, and water currents.
Depositional environment-----	High diatom productivity; long duration; minimal clastic and biogenic dilution; water column allows diatoms to reach bottom.	High diatom productivity; long duration but shorter than marine; minimal clastic and biogenic dilution; periodic volcanism.
Dilution-----	Dilution by terrigenous sediment near continental margins or by such biogenic forms as radiolarians during deposition.	Dilution by introduction of excess clastic sediment and volcanic ash into basins.
Diagenesis and preservation-----	Limited marine sediment cover compacts and removes water, and leaching removes excess organic matter thus increasing quality. Excess compaction may crush frustules, and deeper burial (>600 m, >50°C) may recrystallize silica.	Limited clastic sediment or volcanic cover compacts and removes water, and leaching removes excess organic matter, thus increasing quality. Excess compaction may crush frustules, and deeper burial (>600 m, >50°C) may recrystallize silica.
	Preservation primarily due to silica in frustules. Also, cover by younger marine sediment protects diatomite deposit when uplifted and exposed to weathering and erosion.	Preservation primarily due to silica in frustules. Also, cover by terrigenous sediment or volcanic flows protect diatomite deposit from weathering and erosion.
Geologic timespan-----	Early Cretaceous to Holocene-----	Eocene to Holocene.
Optimum period of deposition----	Miocene-----	Miocene, especially middle Miocene.
Distribution in western North America.	California Coast Range but primarily at Lompoc in San Bernardino County, Calif.	All the Western United States, but largest deposits in Nevada; additional major deposits also in Idaho, Oregon, and Washington.

Bradbury and Krebs, 1995). Barron noted that temperature, salinity, pH, nutrients, and water currents vary much more widely in nonmarine than in marine environments. For example, nonmarine diatoms are euryhaline—that is, they tolerate a wide range of salinities (Sverdrup and others, 1970) relative to the stenosaline marine diatoms described above; however, lacustrine diatoms do not thrive in alkaline water (Barron, 1987).

Dilution also plays an important role in the formation of diatomite deposits. A common, but serious, disadvantage of near-shore marine environments is that they may be subject to rapid and voluminous input of terrigenous sediment from adjacent continental margins, thus diluting the concentration

of diatoms on the seabed. In addition, Boardman and others (1987) noted that some biota, such as radiolarians, are commonly associated with diatoms; thus, biogenic dilution factors may also be present. Therefore, the formation of commercial quantities and grades of diatomite in marine environments is favored by a low influx of both terrigenous and biogenic sediment. The favorable physical conditions and nutrient supply described above must also be sufficiently continuous and persistent to accumulate thick, widespread deposits of commercial value. Marine diatomites deposited along stable, long-lived marine shorelines and in tidal areas with good water quality (low clastic input, adequate nutrients and silica, and stable salinity) and clarity generally form in a few large,

high-grade deposits suitable for multiple uses at all market levels, including filtration (Breese, 1994). For example, the Miocene Monterey Formation, a marine diatomaceous unit, as much as 2,000 m thick, composed of biogenic silica, carbonate, detrital sediment, and volcanic ash, is exposed extensively for nearly 800 km along the California Coast Ranges (Barron, 1987). The formation hosts one of the largest commercial diatomite deposits in the world near Lompoc, Calif., where diatomite is mined from a section as much as 300 m thick (Cressman, 1962).

Postdepositional Processes

Once deposited, siliceous diatoms are more resistant to dissolution than other types of biogenic matter; however, the deposits are subject to diagenesis, burial, and exposure, all of which can have significant effects. Diagenesis may preserve a deposit, enhance its quality, or completely destroy it, depending on the type and severity of the process. A sediment cover can preserve the deposit by protecting it from erosional processes; in addition, a sediment cover can compact the diatomite and remove excessive water from the diatomaceous materials. Leaching may remove organic matter and other biogenic materials from the diatoms and enhance the deposit quality (table 1). Barron (1987), however, observed that deeper burial and related increasing temperature can cause recrystallization of frustules and destruction of some of their useful physical properties. He described a progression of rock-property changes, associated with burial depths ranging from 600 to 1,500 m, that transition from biogenic silica to opal-CT at 50°C and then to quartz at about 80°C. The lithified final products of this diagenetic process, porcellanite and chert, have significantly lower porosity and higher density than those associated with commercial diatomite.

Uplift of both lacustrine and marine deposits exposes them to weathering and erosional processes. Marine deposits are best preserved by postdeposition cover by younger marine sediment. Volcanic flows covered and protected many continental lacustrine deposits (table 1), particularly in the Great Basin, Columbia River Basin, and Snake River Plain in the Western United States.

Temporal Distribution

Marine diatomites have been associated with upwelling and other favorable environments since at least 66 Ma, when diatomaceous silica became a significant component in Cretaceous marine sediment (Heath, 1974; Barron, 1987). Boardman and others (1987) also mentioned a fossil record of diatoms that extends from the Cretaceous to the Holocene; however, Bradbury and Krebs (1995) cited evidence of marine diatoms in sediment as old as Early Cretaceous or even Jurassic. Clearly, our level of knowledge on this subject is evolving. The oldest (middle Eocene) continental diatoms apparently evolved from marine ancestors during the early

Tertiary or Late Cretaceous (Bradbury and Krebs, 1995). Bradbury and Krebs (1995) also noted that the Miocene was a time of both marine and continental diatom productivity, rapid evolution, and environments favorable for preservation (table 1).

Chemistry and Contaminants

The chemistry of commercial diatomite deposits is dominated by the siliceous composition of the diatom frustules, which are formed by biologic secretion, or precipitation, of amorphous silica (Cummins, 1960; Durham, 1973) (see subsection above entitled "Diatoms"). Frustules in living diatoms or of Holocene age resemble amorphous soluble silica gel, whereas fossil frustules resemble opaline silica and have a lower solubility than younger ones (Kamatani, 1971). Chemical analyses of bulk diatomite samples typically range in SiO₂ content from 70 to 90 weight percent and reportedly as high as 97 weight percent in marine deposits (Cummins, 1960; Durham, 1973; Breese, 1994). The chemical and bulk physical characteristics of marine and continental diatomite deposits are summarized in table 2.

Combined H₂O content in the frustule opaline structure ranges from 1.9 weight percent in some marine species to 9.6 weight percent in some lacustrine species (Breese, 1994). Diatomite contains abundant free water, ranging from 10 to 60 weight percent H₂O. Additional major components from several world-class deposits include 2 to 10 weight percent Al₂O₃ and small, but varying, amounts of Fe, Ti, P, Ca, Mg, Na, and K oxides (Cummins, 1960; Durham, 1973). In the same samples, CO₂ and organic-matter contents range from less than 1 to more than 17 weight percent (table 2; Cummins, 1960, LOI, table 1).

A wide range of contaminants are associated with diatomaceous sediment. Chert, manganese nodules, phosphates (for example, vivianite), radiolarians, silicoflagellates, sponge spicules, ostracods, and bivalves, as well as volcanic rocks, are more likely associated with marine deposits (Shenk, 1991; Breese, 1994). Marine deposits may also contain silanol (Si-OH bonded) and siloxane (Si-O-Si bonded) on the surface of the siliceous materials (Kadey, 1967). Lacustrine-fluvial deposits more likely contain varying common terrigenous components, such as volcanic ash, quartz, mica, and feldspars, as well as such biogenic materials as fossil leaves, fish and reptile bones, peat, marl, and tufa (Breese, 1994). Contaminants common to both types of deposit include clays, gypsum, calcite, and, less commonly, salt, pyrite, and sulfur (table 2; Shenk, 1991; Breese, 1994).

Physical Properties

Marine diatomite deposits are generally thicker and of greater areal extent than lacustrine deposits (Bradbury and Krebs, 1995). Additional distinct differences in physical properties between marine or lacustrine deposits are not identified;

Table 2. Summary comparison of chemical and bulk physical characteristics of marine and continental-lacustrine diatomite deposits. [Where information spans both marine and continental-lacustrine deposits, we were unable to determine different characteristics for the specific factor]

Factor	Marine deposits	Continental-lacustrine deposits
SiO ₂ content of diatomite (wt pct)-----	70–97	70–90
H ₂ O content of frustules (wt pct)-----	Relatively lower; as low as 1.9 in specific marine species.	Relatively higher; as high as 9.6 in some lacustrine species.
H ₂ O content of diatomite (wt pct)-----	10–60	
Contaminants (codeposited and diagenetic).	Chert, manganese nodules, phosphates (e.g. vivianite), radiolaria, silicoflagellates, sponge spicules, ostracods, bivalves, clay, gypsum, calcite, salt, pyrite, sulfur, and fish bones.	Quartz, mica, feldspars, and marl, and biogenic materials such as peat, vegetal material, reptile and fish bones, clay, gypsum, calcite, salt, pyrite, and sulfur.
	Many others, such as clay, gypsum, calcite, salt, pyrite, sulfur, and fossil fish bones, may be common to both.	
Areal extent of deposits-----	More extensive-----	Less extensive.
Thickness of deposits-----	Thicker-----	Thinner.
Frustule physical properties-----	Size: 0.75–≤1,000 μm, mostly 10–150 μm.	
	Voids, 10–30 volume percent.	
	Specific gravity, 1.9–2.35.	
	Hardness, 4.5–6.0 Mohs.	
Bulk density (in place) (g/cm ³)-----	.320–0.640	
Bulk density (dry powder) (g/cm ³)----	.080–0.256	
Bulk density (wet powder) (g/cm ³)----	.160–0.480	
Bulk hardness (Mohs)-----	~1.5, owing to friability	
Thermal properties-----	Low conductivity; melting point, 1,400–1,750°C	

however, we provide a general overview because the industrial uses of diatomite are a direct function of these properties (table 2).

Diatomite frustules are microscopic in size, ranging in diameter from 0.75 to 1,000 μm (1 mm), mostly from 10 to 150 μm (Breese, 1994). The opaline silica that composes frustules ranges in specific gravity from 1.9 to 2.35, about twice that of water (Cummins, 1960); however, the best known characteristics of diatomite, imparted by the complex-shaped frustules with 10 to 30 volume percent voids, are its low bulk density and high porosity. The bulk density of diatomite ranges from 0.320 to 0.640 g/cm³ (Cummins, 1960), about half that of water. Diatomite can absorb 1.5 to 3 times its

weight of water (Durham, 1973). The apparent density of dry diatomite powder (or diatomite product) ranges from 0.080 to 0.256 g/cm³ and of wet diatomite powder from 0.160 to 0.480 g/cm³ (table 2; Cummins, 1960; Durham, 1973).

Diatomite's low thermal conductivity is due to its abundant pore volume and its melting point, which ranges from 1,400 to 1,750°C (Durham, 1973). These properties probably led the Greeks to use it as a lightweight building stone and in ceramic pottery 2,000 years ago (Breese, 1994). The hardness of massive diatomite is only about 1.5 Mohs, owing to its friability, and so it is easy to quarry. Diatomite frustules themselves range in hardness from 4.5 to 6.0 Mohs (table 2; Cummins, 1960).

Table 3. Summary comparison of economic factors of marine and continental-lacustrine diatomite deposits.

[Where information spans both marine and continental-lacustrine deposits, we were unable to determine different characteristics for the specific factor]

Factor	Marine deposits	Continental-lacustrine deposits
Number of deposits-----	Fewer-----	Greater.
Size of deposit-----	Larger-----	Smaller.
Production-----	Large-----	Medium to small.
Mining method-----	Open pit.	
Milling and processing-----	Careful crushing and grinding to preserve frustules; hot-air transport and classification; natural, calcined, and flux-calcined varieties.	
Postprocessing properties-----	Reduced H ₂ O, CO ₂ , and organic-matter contents; calcined variety is pink because of Fe oxide; flux-calcined variety changes color to white.	
	Increased hardness, from 4.5 to 6.0 Mohs.	
	Increased specific gravity, from 1.95 to 2.3.	
	Primarily filtration; also fillers, additives, absorbents, and abrasives.	Primarily fillers, additives, absorbents, abrasives; also filtration.

Mining, Processing, and Other Economic Factors

Although diatomaceous silica is a relatively common sedimentary rock, large economically minable deposits with commercial grades, referred to as diatomite, are uncommon to rare (Harben and Kuzvart, 1996). Factors that determine the economic viability of high-grade diatomite deposits, whether marine or lacustrine, include the areal extent, thickness, and continuity of the deposit; the number and uniformity of beds; the dominant diatom species; and the degree of selective mining required. Marine and continental-lacustrine diatomite deposits have much in common with respect to deposit quality and mining, beneficiation, and end uses; however, they also exhibit some key differences. Kadey (1975) noted that most of the world's known diatomites are of lacustrine origin but that marine deposits are generally larger. For example, the marine deposit at Lompoc, Calif., is the largest single producer of diatomite in the United States, although the cumulative production from the several smaller lacustrine deposits in the Western United States is considerably greater (Dolley and Moyle, 2003). Furthermore, Harben and Kuzvart (1996) observed that marine deposits are considered to be of superior quality, owing to their higher diversity in the size and shape of diatoms. No additional significant differences in mining or processing of marine or lacustrine deposits are noted; the economic factors of marine and continental deposits are summarized in table 3.

Diatomite's physical properties—its low bulk hardness, low bulk density, and friability—make surface or near-surface high-grade marine and continental-lacustrine deposits amena-

ble to open-pit mining. Depending on the geologic configuration of a deposit, this low-cost, bulk-tonnage mining method generally consists of selectively grading large volumes of ore from exposures of high-grade rock, lifting the select high-grade material with scraper-loaders or loading it onto truck haulers, and transporting to a processing plant (Breese, 1994; Harben and Kuzvart, 1996). At some deposits where basalt, chert, or other contaminants are interbedded with the diatomite, coarse contaminants must be selectively mined or screened out at the minesite before shipment to the plant. Although open-pit mining is the dominant method, Harben and Kuzvart (1996) noted that a few foreign operations utilize underground methods to mine diatomite, for example, the Sig deposit in Algeria, as well as underwater dredging, such as at Lake Myvatn in Iceland.

Crushing and grinding of crude diatomite are accomplished in a series of careful steps designed to preserve the diatom skeletal (frustule) structure, an important attribute of most products. Dolley and Moyle (2003) present a generalized diagram of a typical diatomite-processing plant, and Harben and Kuzvart (1996) briefly described the processes. Where possible, heated air is used to dry and transport diatoms through the beneficiation process, including separation of diatoms from denser and coarser contaminants and classification of diatoms into different sizes. Selected grades of natural diatomite may be calcined in a kiln at 870–1,093°C, volatilizing such contaminants as organic matter, CO₂, and pore water to produce a pink granular material. CO₂ and organic-matter contents range from less than 1 to more than 17 weight percent (Cummins, 1960, LOI table 1) in some deposits. Calcining also recrystallizes 40 to 60 weight percent

of the silica in the frustules to cristobalite for such specific end uses as special filter grades. Diatomite may also be flux-calcined by the addition of soda ash or salt flux to the kiln at 1,148°C to produce a white grade wherein the Fe oxides are converted to a clear glassy phase. Calcining and flux calcining increase the hardness from 4.5–5.0 to 5.5–6.0 Mohs and the specific gravity from 1.95 to 2.3 (Harben, 1999). Natural, calcined, and flux-calcined diatomites can be sorted by size and other properties to yield a wide range of products.

In general, processing costs are lower if H₂O and organic-matter contents, as measured by loss on ignition, are lower because less energy is required to remove these contaminants (Benton, 1983). The cost to process some medium-grade lacustrine diatomites, suitable for such lower-end uses as absorbents and fertilizer, can be prohibitive at a loss on ignition as high as 20 weight percent (Breese, 1994) because of the high energy required to volatilize the water and organic matter. At a loss on ignition of more than 5 weight percent, marine diatomite becomes too expensive to heat-treat for such high-grade uses as filtration. For example, an accounting at the Lompoc, Calif., marine diatomite mine shows that mining accounts for 10 percent, processing for 60 percent, and packaging and shipping for 30 percent of the total costs (Benton, 1983). Any increase in processing cost due to excess H₂O content could make parts of a deposit uneconomic.

Filtration-grade diatomite is produced from both marine and some lacustrine deposits; however, lower grades of lacustrine deposits generally limit end uses to abrasives, fillers, fertilizer and pesticide, polish, catalyst material, insulating brick, and absorbents (Breese, 1994). The greatest demand for high-grade ore of marine origin is as a filter product, used in processing beer, wine, and liquor, sugars, and pharmaceuticals; however, low-purity marine or lacustrine diatomite with increased contaminant contents may be processed for such lower-end uses (Breese, 1994) as fillers or additives.

Summary and Recommendations

Although we have discussed many of the characteristics of diatomite deposits and identified important differences between those of marine or lacustrine origin, we did not obtain detailed data that distinguish between marine and lacustrine deposits for some important factors (tables 1–3). On the basis of descriptions of depositional environments, several differences between marine and continental-lacustrine diatomite deposits are apparent. Marine deposits form over broad areas on the ocean floor, whereas lacustrine deposits form under areally limited, specialized environmental conditions. Furthermore, marine deposits are generally thicker and represent longer periods of geologic time than lacustrine deposits. In addition, the physical, chemical, and environmental conditions of marine diatomaceous systems clearly vary less widely than those of lacustrine systems.

We lack detailed data that distinguish between specific numbers and varieties of taxa, as well as the physical proper-

ties and some chemical properties of marine and nonmarine diatomite deposits; additional research is warranted on these topics. We also lack data that differentiate specific deposit parameters, such as diatom size and shape and frustule density and trace-element chemistry, which may affect milling and processing methods, as well as products and end uses. Many of these factors are important from an economic perspective with regard to the national diatomite resource base.

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