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Regional Geologic Setting of Late Cenozoic Lacustrine Diatomite Deposits, Great Basin and Surrounding Region: Overview and Plans for Investigation

Chapter B of

Contributions to Industrial-Minerals Research

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James D. Bliss, Phillip R. Moyle, and Keith R. Long, Editors

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Abstract

Freshwater diatomite deposits are present in all of the Western United States, including the Great Basin and surrounding regions. These deposits are important domestic sources of diatomite, and a better understanding of their formation and geologic settings may aid diatomite exploration and land-use management.

Diatomite deposits in the Great Basin are the products of two stages: (1) formation in Late Cenozoic lacustrine basins and (2) preservation after formation. Processes that favored long-lived diatom activity and diatomite formation range in decreasing scale from global to local. The most important global process was climate, which became increasingly cool and dry from 15 Ma to the present. Regional processes included tectonic setting and volcanism, which varied considerably both spatially and temporally in the Great Basin region. Local processes included basin formation, sedimentation, hydrology, and rates of processes, including diatom growth and accumulation; basin morphology and nutrient and silica sources were important for robust activity of different diatom genera. Only optimum combinations of these processes led to the formation of large diatomite deposits, and less than optimum combinations resulted in lakebeds that contained little to no diatomite.

Postdepositional processes can destroy, conceal, or preserve a diatomite deposit. These processes, which most commonly are local in scale, include uplift, with related erosion and changes in hydrology; burial beneath sedimentary deposits or volcanic flows and tuffs; and alteration during diagenesis and hydrothermal activity. Some sedimentary basins that may have contained diatomite deposits have largely been destroyed or significantly modified, whereas others, such as those in western Nevada, have been sufficiently preserved along with their contained diatomite deposits.

Future research on freshwater diatomite deposits in the Western United States and Great Basin region should concentrate on the regional and local processes that led to the formation and preservation of the deposits. Major questions that need to be answered include (1) why were some basins favorable for diatomite formation, whereas others were not; (2) what postdepositional conditions are needed for diatomite preservation; and (3) what were the optimum process combinations that led to the formation and preservation of economic diatomite deposits?

Introduction

Late Cenozoic lacustrine diatomite deposits are common in parts of the Great Basin region and other Western States (fig. 1); they are second only to large marine diatomite deposits in southern California as a diatomite resource in the United States. Diatomite is or has been mined from lacustrine deposits in all of the Western States, of which Nevada currently is the largest producer.

Sedimentary basins were present in the Great Basin and surrounding regions at various places and times during the past 16 m.y. Many of these basins contained small to extensive lakes, in some of which the conditions favored the formation of thick diatomite deposits in the lakebeds. Other contemporaneous basins in the region contain only little or no lacustrine sedimentary materials or diatomite deposits. In addition, postdepositional processes, such as volcanism, sedimentation, uplift, erosion, and various forms of alteration, varyingly combined to preserve or destroy diatomite deposits and host sedimentary rocks.

Getting from a sedimentary basin in the past to a diatomite deposit in the present requires processes that both formed and preserved the deposit. The focus of the new Industrial Minerals in Lacustrine Environments Task of the Western Industrial Minerals Project (WIMP) is to evaluate these events and processes and to develop a genetic model that can be used for exploration and mineral-resource assessments. This chapter presents a brief overview of Late Cenozoic lacustrine basins in the Great Basin region of the Western United States, and it introduces various processes that may have contributed to the formation and preservation of diatomite deposits. The ideas presented and questions posed here will be evaluated in more detail during the multiyear course of this study.

Regional Geologic Setting

Tectonics

The effects of Late Cenozoic tectonism varied spatially and temporally throughout the Great Basin region. In some parts of the southern and eastern Great Basin, late Oligocene crustal extension continued into the early to middle Miocene.

This extension led to the formation of extensive detachment structures in the Grant, Snake, and East Humboldt Ranges and the Ruby Mountains in eastern Nevada, as well as other structures related to low-angle faulting in southeastern Nevada (Axen and others, 1993). Most of this faulting ceased or was waning by about 15 Ma.

In many parts of the Great Basin region, west-southwestward-directed crustal extension began in the middle Miocene and continued into the late Miocene, possibly as late as 6 Ma (fig. 2; Zoback and Thompson, 1978). This crustal extension created abundant high-angle faults and small to moderate uplifts separated by broad basins. At about 6 Ma, the extension direction shifted northwestward (fig. 2; Zoback and Thompson, 1978; Christiansen and Yeats, 1992). High-angle faults that formed between 6 Ma and the present produced the modern horst-and-graben topography typical of much of the Great Basin.

In western Nevada, right-lateral movement began along the Walker Lane structural zone as early as 12 Ma (fig. 2; Hardyman and Oldow, 1991; Stewart and Perkins, 1999; Schwartz, 2001). This right-lateral movement, in combination with the post-6-Ma northwestward-directed crustal extension, has caused oblique movement along faults in the Walker Lane, in contrast to crustal extension in the regions to the east that produced dip-slip normal faults (Henry and Faulds, 2002).

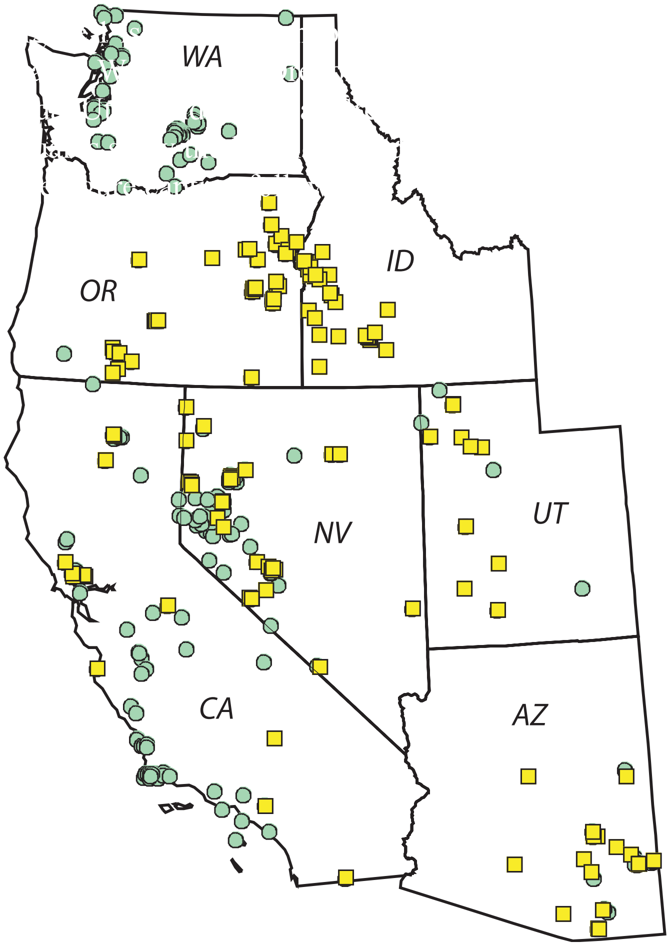

Figure 1. Western United States, showing locations of diatomite deposits. Many of these deposits near the Pacific coast formed in marine environments; more interior deposits formed in freshwater environments. Data from U.S. Geological Survey (yellow squares) and U.S. Bureau of Mines (green circles); diatomite deposits in both data sets are shown by yellow squares only.

Possible topics of study:

- What tectonic environments were most conducive to the formation of lacustrine basins?
- When and where did these basins form in the context of the regional tectonics?
- How did tectonics affect the paleotopography, and how did this effect of tectonics on topography change in space and time?

Volcanism

Two regional volcanic systems (western andesite and bimodal) were active in the Great Basin and surrounding region during Neogene and Quaternary time. Early to late Miocene volcanism related to the early Cascades volcanic arc created the western andesite assemblage. This volcanic arc included stratovolcanoes and shield volcanoes that erupted in the western Great Basin and to the north-northwest beneath the modern Cascade volcanic chain (fig. 2).

Bimodal mafic-felsic volcanism influenced much of the north-central Great Basin (fig. 2), producing widespread mafic flows and more localized rhyolite domes and tuffs. Volcanism began about 17 Ma with the eruption of the voluminous and regionally extensive Steens Basalt in the northwestern Great Basin, the Columbia River Basalt Group in eastern Oregon and Washington, and other mafic flows elsewhere in the northern Great Basin. Bimodal volcanic activity waned after about 14 Ma but has continued weakly to the present. The Yellowstone hotspot, a thermal and magmatic plume, penetrated the crust near McDermitt, Oreg. (fig. 2), inducing much of the bimodal volcanism in the northern Great Basin and surrounding areas. As the North American craton moved southwestward over the hotspot, a northeast-trending track of hotspot-related volcanism and faulting formed along what is now the Snake River Plain; currently, the hotspot is beneath Yellowstone National Park (fig. 2; Pierce and Morgan, 1992). Bimodal volcanism in the southern Great Basin produced widespread middle Miocene rhyolites and less extensive related mafic flows (fig. 2; Best and others, 1989; Ludington and others, 1996), as well as Quaternary basalt flows and cones.

A third volcanic event, which formed the interior andesite-rhyolite assemblage, swept southwestward through the Great Basin region between about 43 and 22 Ma. Although this event is older than the Late Cenozoic sedimentation and diatomite formation, the related volcanic rocks that are present near several of the sedimentary basins may have contributed sedimentary materials, silica, and nutrients to the lakes.

Possible topics of study:

- What volcanic systems were active during lacustrine sedimentation, both regionally and locally?
- How did the volcanic systems affect the formation and modification of the basins and lakes?
- Were specific volcanic forms or compositions more influential on lake environments and diatomite formation than others?

Climate

Global, regional, and local conditions affected the Late Cenozoic climate in the Great Basin and Western United States. About 17–14 Ma, west-central North America was warm and had moderate rainfall (Axelrod, 1956; Zachos and others, 2001). The climate then began to cool, and precipitation in the region gradually decreased into the Pliocene. The middle Miocene flora in the Great Basin region was similar to that along the modern western Sierra Nevada of California (Axelrod, 1956): conifers, pines, and mixed oak-birch woodlands were common, with marshes in lowlands (Schorn and Erwin, 2002). With cooling and drying, woodlands diminished, and grasslands and sagebrush expanded, eventually evolving into a more typical desert-scrub and grassland flora during the Pliocene (Davis and Moutoux, 1998; Retallack, 2001). Limited leaf-morphologic evidence suggests that the central core of the Great Basin region may have been 1 to 1.5 km higher than at present and that the elevation of the western margin was the same as today (Wolfe and others, 1997). Other researchers, however, have questioned the validity of this leaf-morphologic methodology (see Hamilton, 2002).

Regional and local events—primarily volcanism and tectonism—also influenced the climate of west-central North America during the Late Cenozoic. Eruption of the Steens and Columbia River basalt flows may have contributed significant CO_2 to the atmosphere and been a factor in the global mid-Miocene climatic optimum (Zachos and others, 2001). Tectonism in various parts of the region created uplifts that interfered with the eastward-flowing weather patterns, much as the Sierra Nevada has blocked eastward-flowing weather patterns since the Pliocene (Henry and Perkins, 2001). Uplift-related elevation changes likely influenced precipitation, erosion and sediment transport, and vegetation changes.

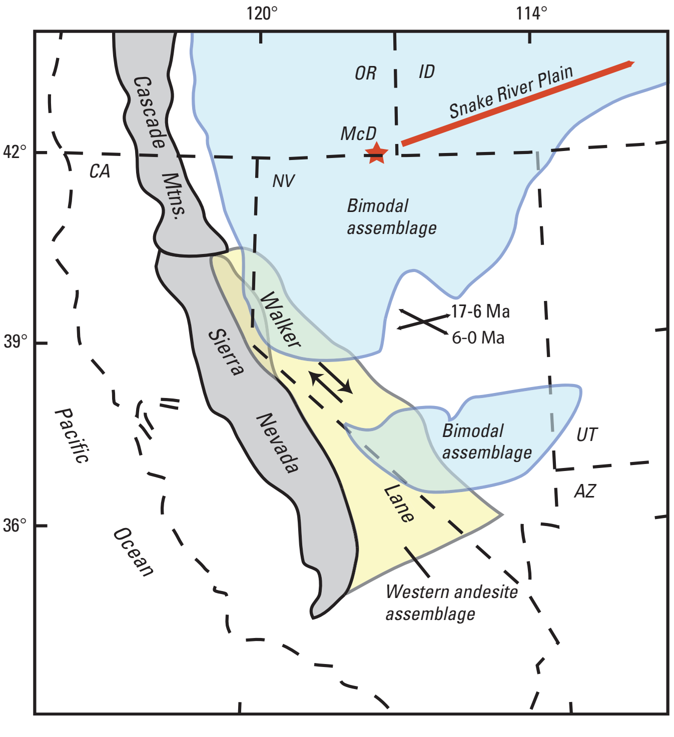

Figure 2. Regional Late Cenozoic geologic setting of the Great Basin region. Two Late Cenozoic volcanic assemblages include early to late Miocene western andesite assemblage (light yellow) and middle Miocene to Holocene bimodal assemblage (light blue). Northeast-trending red arrow denotes the trace of Yellowstone hotspot from its ~16.5-Ma inception near McDermitt (McD). Double-headed arrows in central Nevada denote different extension directions and their timing in the central Great Basin; opposite-pointing arrows along the Walker Lane show dextral strike-slip movement during the past 12 m.y. Modified from John and others (2000).

Possible topics of study:

- How is the progressive cooling and drying reflected in Great Basin flora and fauna?
- What isotopic data (oxygen, deuterium) indicate climate change, and what materials are most suitable for study?
- How did local and regional climatic variations affect runoff and nutrient inputs into lakes?

Late Cenozoic Lacustrine Basins

Overview

Remnants of Late Cenozoic sedimentary basins are scattered throughout the Great Basin region. The preserved sedimentary deposits demonstrate that lake-filled basins were common and, at times, widespread in the region throughout the Late Cenozoic. Some basins episodically have contained a lake from at least 15 Ma to the present (Davis and Moutoux, 1998), whereas the lakes in most other basins had lifespans of less than 1 m.y. to several million years. In other basins, voluminous influxes of clastic materials prevented sizable, long-lived lakes from forming. Some, but certainly not all, lacustrine basins contain diatomite deposits of various sizes.

Ages and Distributions

Basins and lakes in the Great Basin region formed during several episodes in the Late Cenozoic (fig. 3). The

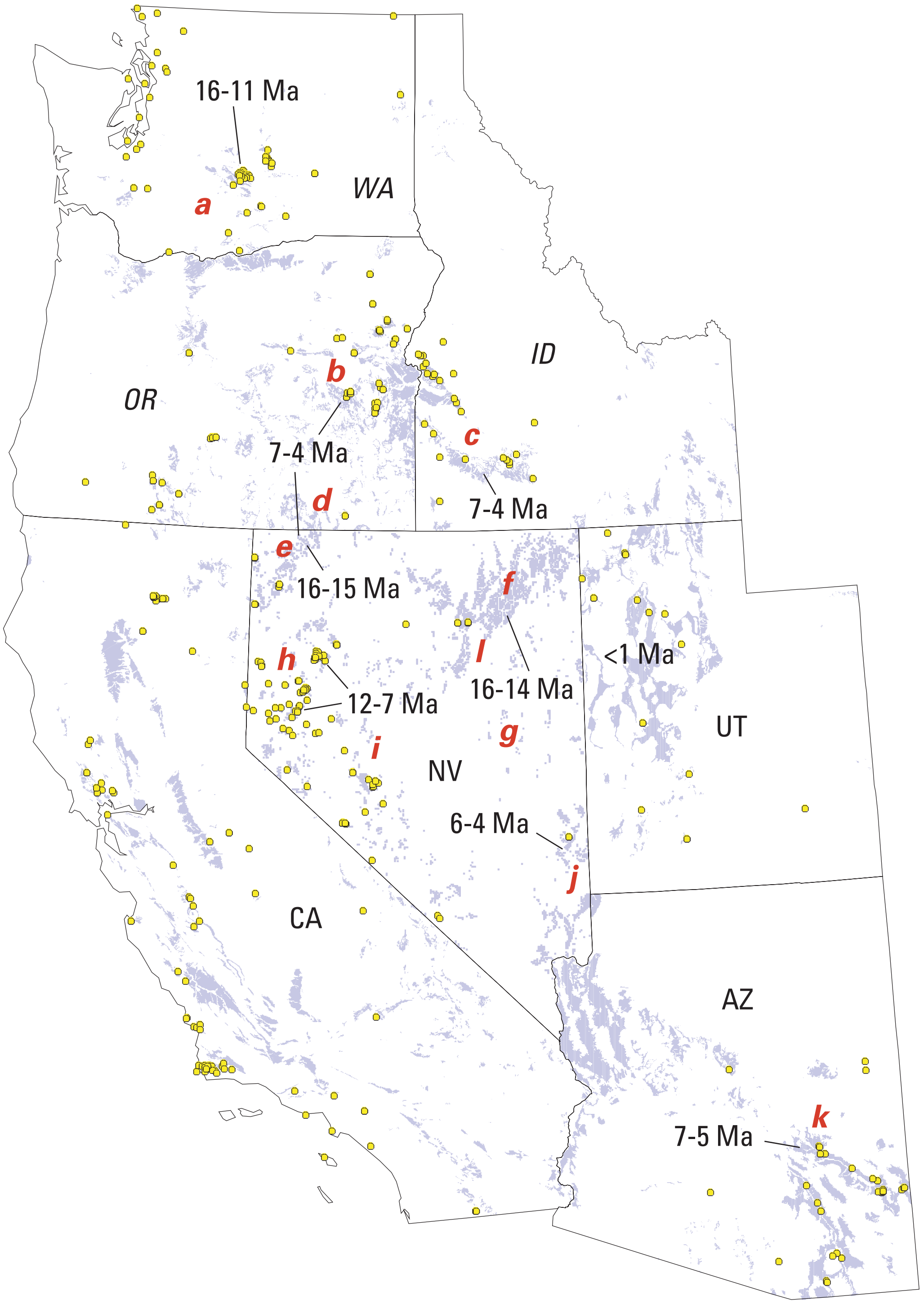

Figure 3. Western United States, showing distribution of Late Cenozoic sedimentary rocks (blue areas). Quaternary sedimentary deposits are omitted except for playa deposits in Utah. Sedimentary deposits near the Pacific coast are largely marine (such as the Monterey Formation in California). Yellow circles mapped in figure 1. General ages of selected basins are based on studies cited in text. Major formations and terrestrial basins: a, Ellensburg Formation; b, Baker basin; c, Glenns Ferry/Chalk Hills Formations; d, Trout Creek Formation; e, Virgin Valley (Miocene) and Thousand Springs (Miocene and Pliocene) Formations; f, Humboldt and Carlin Formations; g, Horse Camp Formation; h, Truckee/Verdi/Chalk Bluff Formations; I, Stewart Valley/Middlegate basins; j, Panaca Formation; k, Quiburis Formation; l, Pine Valley (Hay Ranch Formation of Gordon and Heller, 1993).

earliest lakes began to form about 16.5 Ma and were more widespread by about 15 Ma (Perkins and others, 1998). This period corresponds to the inception of early west-southwestward-directed crustal extension in the region and the early formation of shallow, broad basins. These lakes formed throughout much of the region. In eastern Washington and Oregon and northern Idaho, small to large lakes formed behind basalt-flow dams of the middle Miocene Columbia River Basalt Group and younger basalt flows (Smith and others, 1989). More localized lakes filled basins that were formed by coeval volcanic units, such as in the Trout Creek area of southern Oregon (Barrow, 1983).

A second period of lake formation took place about 13–7 Ma, largely in western Nevada along the Walker Lane and in the Mojave region of southeastern California (fig. 3; Perkins and others, 1998). Lacustrine sedimentary materials contain some of the larger freshwater diatomite deposits in the region.

The youngest lakes formed during the late Miocene and Pliocene (fig. 3), and related lacustrine deposits are exposed in southeastern and northern Nevada and southwestern Idaho. Some of these lakes likely were precursors to the Pliocene and Pleistocene lakes that were extensive throughout the Great Basin (Reheis, 1999) and western North America.

Possible topics of study:

- What are the ages of the lacustrine sedimentary materials and diatomite deposits in the Great Basin?
- What was the duration of sedimentation in each basin?

Basin Characteristics

Evidence from basin-filling material reveals considerable regional variation in basin configuration, processes, and evolution. At one extreme are orogenic basins, such as the Horse Camp basin in eastern Nevada (g, fig. 3), which formed during detachment faulting in the middle Miocene. Coarse clastic debris derived from the adjacent, rapidly rising highland was shed into the developing basin, and lacustrine deposits accumulated only in the upper and distal parts of the section (Horton and Schmitt, 1998); diatomite was not formed. Similar middle Miocene orogenic basins are present at Sacramento Pass in eastern Nevada (Martinez, 2001) and in the eastern part of the Humboldt Formation northeast of Wells (Mueller and others, 1999).

At the other extreme are non-orogenic or early-orogenic basins, such as the western part of the middle Miocene Humboldt (Carlin) Formation basin in northeastern Nevada (f, fig. 3). This part of the basin contained a relatively long lived, but at times ephemeral, lake between about 16 and 10 Ma (Sharp, 1939; Smith and Ketner, 1976; Perkins and others, 1998; Wallace, 2003). Coarse clastic materials are far less common than near Wells, and airfall ash is a significant component of the basin-filling material, ranging in abundance from 5 to 10 volume percent near Elko (Sharp, 1939) to nearly 100 percent at Ivanhoe (Wallace, 2003). Diatomite deposits are minor in this part of the basin, with only a small deposit near Carlin. The overall Humboldt (Carlin) basin represents a broad spectrum of depositional environments and processes. Other middle Miocene, early-extensional basins formed in the Stewart Valley and Middlegate areas of west-central and southwestern Nevada (i, fig. 3) and the in Virgin Valley Formation near McDermitt (e, fig. 3). Sedimentary deposits in those areas contain modest to significant amounts of diatomite (Axelrod, 1956; Barrow, 1983; Greene, 1984; Starratt, 1987; Stewart and others, 1999).

In eastern Oregon and Washington, extensive middle Miocene basalt flows of the Columbia River Basalt Group dammed drainages and formed lakes (Rember, 2002), such as the Ellensburg Formation in central Washington (a, fig. 3). With successive basaltic eruptions, existing lakes were covered, and new ones created (Smith and others, 1989; Retallack, 2002). In eastern Oregon, middle Miocene rhyolite eruptions disrupted the drainage systems and formed locally extensive, diatom-bearing lakes (Barlock and Vander Meulen, 1991).

In western Nevada along the Walker Lane, thick, extensive remnants of middle to late Miocene basins are exposed from near Lovelock southward to Hazen and Yerington and westward to the Reno area (h, fig. 3). Sedimentation began in the basins at somewhat different times, ranging from about 13 Ma near Brady Hot Springs (southwestern Trinity Range) to about 6 Ma in the Wellington Hills Basin west of Yerington (Stewart and Perkins, 1999; Trexler and others, 2000). Tephrochronologic studies indicate that several of these basins were active simultaneously (Stewart and Perkins, 1999), but whether they were connected is unknown. In all areas, the lakes eventually were succeeded by coarse alluvial systems related to incipient uplift of nearby horsts, or by volcanic flows. The diatomite deposits, several tens of meters to more than a hundred meters thick, that formed in these basins are the main focal point of the diatomite industry in Nevada and are mined in the Lovelock, Brady, Hazen, and Fernley areas.

Latest Miocene and Pliocene basins formed as the modern basin-and-range physiography began to develop about 6 Ma. The Pliocene Panaca Formation (j, fig. 3) is composed primarily of fine-grained fluvial, marsh, and pedogenic deposits, with smaller amounts of lacustrine deposits and diatomite near the center of the basin (Pederson and others, 2000). Volcanic rocks dammed the drainage to form the depocenter (Ekren and others, 1977); breaching of the dam during the Pliocene initiated a through-flowing drainage system. The late Miocene Glenns Ferry and Pliocene Chalk Hills Formations (c, fig. 3) formed in successive lakes, each of which were created by tectonic extension and damming by volcanic flows (Kimmel, 1982); both formations contain economic diatomite deposits. Other late Miocene and Pliocene basin sedimentary deposits are exposed in the late Miocene Thousand Springs Formation of northwestern Nevada (d, fig. 3; Greene, 1984) and the Pliocene Hay Ranch Formation of northeastern Nevada (l, fig. 3; Regnier, 1960; Gordon and Heller, 1993), as well as isolated to more widespread basins in eastern Oregon and western Idaho. In addition, the basal fill beneath Quaternary alluvial fans in many major basins consists of late Miocene and Pliocene sedimentary materials, some of which contain lacustrine deposits (Madden-McGuire and others, 1991; McCarthy and Ehni, 2000).

Possible topics of study:

- How do the morphologies of Late Cenozoic sedimentary basins differ, and which morphologies were most conducive to the formation of a quiet lacustrine environment?
- How did local tectonic and volcanic events affect basin morphology, history, and contained materials?
- What was the space-time sedimentologic, hydrologic, and geohydrologic context of each basin with regard to the surrounding area?
- Were the basins connected or isolated?

Diatomite Deposits and Diatoms

Overview

On the basis of the brief summaries given above, diatomite deposits in the Great Basin region formed in some Neogene basins in response to different regional and local processes over the past 16 to 17 m.y. Although the general geologic setting of several of the deposits is known, detailed published descriptions of most of the deposits are sparse, and studies on Great Basin diatomite taxonomy and formation are limited.

Diatomite mines and prospects in the Western United States are mapped in figures 1 and 3. Most of the deposits shown are small, and development on those has been minor. Currently (2003) operating diatomite mines are concentrated in western Nevada, eastern Oregon, and central Washington, with mines in other States. All of these mines are near existing highways or railroads. Several diatomite deposits in western Nevada reportedly would be economically viable if they were closer to transportation infrastructure. Dolley and Moyle (2003) present additional information on diatomite production in the Western United States.

Diatom Taxonomy

Relatively few studies have been done on Late Cenozoic diatom taxonomy in the Western United States. The most common diatom genera in the diatomite deposits being mined in western Nevada are Melosira, Fragilera, and Cymbella (Krebs and Bradbury, 1984; Papke, 1992; Lenz and Morris, 1993), and various other diatom genera are present as well. Melosira and Fragilera are the dominant genera in the Trout Creek basin in southeastern Oregon (d, fig. 3; Barrow, 1983). Navicula, Melosira, and Epithemia are the main diatom genera in the late Miocene to Pliocene deposits of southwestern Idaho (Moyle, 1985). Research by W.N. Krebs and J.P. Bradbury (Krebs and others, 1987; Bradbury and Krebs, 1995; Krebs and Bradbury, 1995) focused on the taxonomy and regional distribution of the middle Miocene genus Actinocyclus. Although this genus is widespread in the region, it generally is not the major diatom genus in the deposits.

Possible topics of study:

- What diatom genera are present in Great Basin diatomite deposits, and in what relative abundances?
- Where in the deposits do these diatom genera occur, and what is their relation to other sedimentologic features and events?
- Economically, what diatom genera and species are most important, and what conditions favored their growth?

Deposit Characteristics

The few published reports on diatomite deposits in the Great Basin region indicate that the deposits vary considerably in form, size, and stratigraphy. All of these deposits contain diatomite beds or zones of varying thickness, and all contain varying amounts of clastic sedimentary material and air-fall ash. Higher-quality diatomite deposits, including those currently being mined, are thick (tens of meters to more than 100 m) and relatively free of contaminants.

The amount of interbedded material varies vertically and laterally through the diatomite deposits. Several deposits contain relatively pure diatomite near the center of the deposit but laterally contain increasing amounts of clastic material, indicating proximity to shorelines. Other variables that may influence diatomite quality include the position of inflowing streams relative to centers of diatomite formation or the amount of rainfall and transport of clastic sedimentary materials to the depocenter. Thin to thick clastic beds and (or) volcanic flows separate diatomite zones at the Quincy deposit in western Washington (a, fig. 3) and at the Hazen deposits in western Nevada (h, fig. 3). The interdiatomite beds indicate interruptions of, and then a return to, low-energy lacustrine conditions. Diatom genera commonly vary with depositional environment, indicating formation in different parts of the lake ecosystem. The presence or absence of ash could be due to the positions and sizes of eruptions that took place during diatomite formation, coupled with the wind direction, or to the recurrence rate and size of eruptions relative to the timespan of diatomite formation.

At several deposits, including the Trinity, Brady's, and Hazen deposits in western Nevada (h, fig. 3), the diatomite-rich beds apparently occur near the base of the Miocene section and are covered by either clastic sedimentary materials or volcanic rocks, suggesting that lacustrine sedimentation took place during early-extensional-basin development. Other deposits, such as Trout Creek (d, fig. 3; Barrow, 1983) and Chalk Hills (h, fig. 3; Schwartz, 2001), formed in basins between volcanic eruptions, although at least 1 m.y. may have separated volcanism and diatomite formation. The Miocene and Pliocene Clover Creek Formation in southwestern Idaho (c, fig. 3; Moyle, 1985) formed on two suites of Miocene basalt shortly after each suite was erupted.

Most of the diatomite deposits in the Great Basin region are small and represent relatively short periods of lacustrine sedimentation in restricted areas. Some of these deposits have been prospected, but most are undeveloped and so are not shown in figure 1. Diagenetic alteration is common in many of the deposits, possibly because the enclosing clastic sedimentary materials allowed ample interaction with ground and pore water.

Possible topics of study:

- Where and when did diatomite form within the space-time context of sedimentary and lacustrine basins?
- How do diatomite deposits fit into the sedimentologic and hydrologic histories of the host basins?
- Is there a correlation between basin morphology and the size of the contained diatomite deposit?
- What processes influenced the vertical and lateral variations in the amount of clastic sedimentary materials in diatomite deposits?
- What short- and long-term effects did ashfalls and clastic deposition have on diatom activity?
- How did continued tectonic activity modify basin dynamics and depositional environments during diatomite formation?

Paleoecology and Formation

Modern diatom studies use the ratio of pennate diatoms (such as *Fragilera*) to centric diatoms (such as *Melosira*) to show relative degrees of eutrophication (productivity) (Wetzel, 2001), which can be a function of changes over time (seasonal to longer) or position within a lake. Geologic relations in the Great Basin indicate that many lakes were shallow and eutrophic (as locally indicated by *Fragilera* species), but the abundance of *Melosira* species may indicate locally deeper and (or) less productive environments (Krebs and Bradbury, 1984). At the Hazen deposits, *Melosira* and *Fragilera* diatoms occur in different parts of the deposits, indicating temporal and spatial variations in water depth and eutrophy (Krebs and Bradbury, 1984). At Trout Creek (d, fig. 3), Barrow (1983) used alternating *Melosira*- and *Fragilera*-rich beds to infer seasonal changes in eutrophy. Plant, mammal, and diatom fossils indicate that marshes and wetlands rimmed many of the lakes in the region, although the abundance and types of these various organisms varied as the climate gradually became relatively drier through the Neogene (Davis and Moutoux, 1998; Retallack, 2001). Many of the lakes also supported abundant fish (Smith and others, 1982; Brown, 1986; Smith, 1987), as well as algal buildups that formed thin to thick carbonate beds (Willden and Speed, 1974; Smith and Ketner, 1976).

Water temperature, pH, chemistry, and nutrients influence diatom activity, and all of these parameters are influenced by a wide variety of processes. Limited studies on Great Basin diatomite deposits indicate that the lake waters were warm and had neutral to slightly alkaline pHs (7–8 and possibly greater), carbonate buffering, and low salinities and Na/K:Ca/Mg ratios, all of which favor diatom activity (Barrow, 1983; Sheppard and Gude, 1983; Lenz and Morris, 1993). Barrow (1983) noted that the diatom species in the Trout Creek deposits indicate low salinities and a continual balance between lake inflow and outflow.

Since diatom frustules (the preserved amorphous cell walls of diatoms) are composed entirely of silica, the diatoms need dissolved silica in the water to flourish. Abundant silica was needed to form the large diatomite deposits in western Nevada. High diatom productivity can consume all available silica and eventually limit diatom activity (Wetzel, 2001). However, if viewed from a typical twice-a-year diatom bloom cycle, sufficient silica was needed only on a semiannual basis for the thousands of years it took to form the deposits. Silica sources likely included the volcanic highlands that surrounded the lakes and ashfalls on the lakes. As shown in the ash-rich Humboldt (Carlin) Formation, too much direct volcanic input may limit diatom activity by basically smothering the lake.

Phosphorus is the most important nutrient for diatom activity (Hall and Smol, 1999; Wetzel, 2001), and the cycle and bioavailability of phosphorus within lakes are complex. This element can be derived from many sources. In the Great Basin and much of the Western United States, runoff from nearby highlands is the most common source (Wetzel, 2001). Andesitic to basaltic volcanic rocks were common in the highlands near many of the large diatomite deposits in the Great Basin region, as well as at the basalt-related deposits in Idaho, Washington, and Oregon. Basalts and andesites contain, on average, far more phosphorus (1,400–1,600 ppm) than do other igneous (170–700 ppm) and sedimentary (170–750 ppm) rocks (Krauskopf, 1979). Speculatively, phosphorus in seasonal runoff from intermediate-composition to mafic volcanic rocks may have favored diatom activity at many diatomite deposits in the region. However, rhyolitic volcanic rocks apparently dominated the highlands at a few large diatomite deposits, such as those in the Trinity Range near Lovelock (h, fig. 3; Nash, 1995), and volcanic-rock composition may not be the only factor in phosphorus source and availability.

The long- and short-term hydrologic balances between precipitation and evaporation, and among inflow, throughflow, and outflow, strongly affect the compositions and eutrophy of lakes. For example, drought decreases precipitation and runoff; in combination with continued evaporation, lakes can decrease in size and lose connections to outflow. As a result, eutrophy (Webster and others, 1996), elemental concentrations, and possibly, pH increase. Conversely, higher rainfall creates more input into the lake (including clastic materials and nutrient-rich runoff). The lake expands, connects with other basins, and may have a greater throughflow. All of these factors contribute to diatom activity and the formation of diatomite.

Possible topics of study:

- What were the short-term (seasonal to multiannual) versus long-term hydrologic and chemical changes during diatom blooms and diatomite formation, and how can they be determined and differentiated?
- What other flora and fauna provide evidence for the paleoecology of diatom-rich lakes?
- What were the important sources of phosphorus, silica, and other essential elements in diatomite deposits?
- Were any elements or environments toxic to diatoms?
- What are the essential processes that contribute to the formation of a diatomite deposit, and what are their relative importance?
- Similarly, what are the essential combinations of processes that form a diatomite deposit?

Duration of Diatomite Formation

The general ages of most diatomite deposits in the Great Basin region are known from the ages of enclosing volcanic rocks. In the few places where tephras within the deposits have been dated, a specific age is known; however, how long it took to form the deposits is largely unknown. The duration of diatomite formation is constrained somewhat at the Brady's deposits in western Nevada (h, fig. 3), where the base of the diatomite section was not dated but tephrochronology data suggest a duration of at least 600 k.y. (Stewart and Perkins, 1999). Additional $^{40}Ar/^{39}Ar$ ages and tephrochronology on interbedded ash layers and $^{40}Ar/^{39}Ar$ ages on bounding or interbedded volcanic flows could further constrain the duration of diatomite formation. The ages of bounding units, however, provide only maximum durations in the absence of other evidence of relation to lacustrine sedimentation. For example, many diatomite deposits overlie dated volcanic rocks, but the time between eruption and the start of sedimentation is unknown. The same holds true for overlying volcanic units and the end of sedimentation. Units bounding a large lacustrine basin in northernmost Nevada illustrate these points. The basal sedimentary deposits overlie Paleozoic, Eocene, and middle Miocene (15.8–16.1 Ma) rocks (Wallace, 1993; A.R. Wallace, unpub. data, 2000), giving an imprecise date for earliest sedimentation; this date would be even more imprecise were the Tertiary units not dated. In contrast, the capping 15.1-Ma welded tuff contains conspicuous phreatic-eruption textures at its base, clearly indicating that the tuff was erupted into a shallow lake or wet sedimentary deposits and likely eliminated the lake environment (Wallace, 1993; A.R. Wallace, unpub. data, 2002). Thus, the sedimentary deposits were deposited between 15.8 and 15.1 Ma, but this estimate of duration is a maximum because of the imprecise date for the onset of sedimentation.

Many studies, both in marine and nonmarine environments, have demonstrated accumulation rates for diatoms in bottom sediment. These rates vary widely, depending on the paleoecology, productivity of the lake, climate, and many other factors. Depending on water chemistry, significant amounts of diatom frustules (max 90 percent) can dissolve during settling. Therefore, a direct comparison between diatomite thickness and the time needed for the deposit to form may be impossible in such fossil lakes as those in the Western United States.

Possible topics of study:

- How long did it take to form diatomite deposits in the various basins?
- What processes controlled accumulation rates?
- How long were the diatomite-forming sedimentary and lacustrine basins active, and during what stage(s) of basin formation did the diatomite deposits form?

Postdepositional Events

Overview

Presuming that various processes led to the formation of a diatomite deposit in a lake-filled basin, preserving that deposit requires an optimum combination of other processes. Two major processes—alteration and erosion, either alone or in combination—can destroy a diatomite deposit. In addition, within a purely economic context, cover rocks must be minimally thick for the deposit to be discovered or economically viable.

Cover Units

Consolidated and unconsolidated materials cover most of the diatomite deposits in the Great Basin region, and the cover units include clastic sedimentary deposits and volcanic flows and tuffs. The cover units vary widely in thickness, from thin alluvial deposits to 1 km of volcanic flows. Some of the cover units were emplaced during or shortly after lacustrine sedimentation, whereas other cover units were deposited well after the lake environment ceased. Some younger lacustrine basins, such as the Panaca Formation and parts of the Pliocene deposits along the Snake River Plain, did not have significant cover units. In places, evidence suggests that younger units covered a diatomite deposit but that erosion has partly or largely removed them.

Cover units also provide information on the processes that ended lake sedimentation and that may have led to later alteration and erosion. The cover units that were emplaced during or immediately after diatomite formation effectively terminated the lake environment – for examples, in the Brady area, where coarse clastic sedimentary materials related to nearby incipient uplift buried the diatom-rich section (Stewart and Perkins, 1999), and the previously mentioned lake in northern Nevada, where a 15.1-Ma ash-flow tuff was erupted across the shallow lake (Wallace, 1993). At Ivanhoe in northern Nevada, the lakebeds (though without diatomite) were covered episodically by volcanic flows and air-fall ash and replaced by volcanic-related hydrothermal silicification (Wallace, 2003). Interdiatomite clastic sedimentary deposits and basaltic andesite flows near the Hazen deposits likely disrupted the lacustrine environment, followed by renewed lacustrine and diatom sedimentation. The capping basaltic andesite flows at the Hazen deposits are undated; if approximately contemporaneous with the upper diatomite beds, they may have ended the lacustrine sedimentation.

Possible topics of study:

- What types and thicknesses of cover units overlie diatomite deposits, and when did they form relatively to the end of lacustrine sedimentation?
- What effect did these cover units have on preservation of the deposits?

Diagenesis and Alteration

Diagenesis of lacustrine sedimentary material can begin almost immediately after deposition. Diagenetic and postdiagenetic products can include various cements, chert phases, zeolites, and clay minerals, many of which form at the expense of the original sediment and diatoms. Many of the recorded zeolite prospects in the central Great Basin are within Late Cenozoic sedimentary deposits. The amount and type of diagenetic alteration depend on several factors, including pore- and ground-water composition and the level of the ground-water table during lithification. In basins where diagenetic alteration was extensive, such as in one middle Miocene basin east of Paradise Valley in northern Nevada (Sheppard and Gude, 1983; Wallace, 1993), determination of the original presence or absence of diatomite may be difficult. Diatoms themselves undergo a structural transformation almost immediately after deposition, with a subsequent change to more stable silica phases.

Miocene and younger hydrothermal activity was localized around the many volcanic centers, and high heat flow in the northern Great Basin, especially in northern Nevada, over the past 6 m.y. has produced additional epithermal deposits and geothermal centers. Many of the volcanic and hydrothermal systems were emplaced in or adjacent to coeval lakes or, for young geothermal systems, in the sedimentary deposits of long-extinct basins. Although alteration related to these hydrothermal systems generally was not widespread, hydrothermal silicification and other alteration partly to completely replaced lacustrine sedimentary deposits in some basins (Ebert and Rye, 1997; Wallace, 2003). In coeval lakes and hydrothermal systems, subaqueous fluid venting may have contributed silica and, possibly, such elements as As, Hg, and Au into the lakes themselves.

Possible topics of study:

- What processes prevented or enhanced the formation of diagenetic minerals in lacustrine sedimentary materials and diatomite deposits?
- What are the effects of subaerial exposure on diatomite deposits?
- What effect did hydrothermal alteration have on lacustrine sedimentary materials and diatomite deposits, and what is the sphere of influence of an epithermal- or geothermal-alteration halo?

Tectonic activity and erosion

Uplift related to Late Cenozoic northwestward-directed crustal extension affected various parts of the Great Basin region, and the amount of uplift and related erosion varied widely throughout the region. As a result, basins and lacustrine deposits in some areas retain much of their original dimensions, whereas a relict patchwork is all that remains in other areas. Such areas as the Snake River Plain and the Columbia River Plateau have undergone some crustal extension but relatively little uplift, and the original extents of the basins and lacustrine deposits remain fairly intact, though possibly concealed by volcanic and sedimentary units. In marked contrast, significant Late Cenozoic basin-and-range uplift and erosion in northwestern Nevada has disrupted the original basins considerably, and synchronous sedimentation into intermontane basins has concealed many earlier lacustrine sedimentary deposits that lie beneath the basins. Basin and lake reconstruction in this subregion likely would be extremely difficult. Indeed, Bradbury (1999) pointed out that the scattered remnants of the original lakebeds limit studies of basin morphologies and, thus, of the context of the diatomite deposits in a basinwide scenario. Tephrochronologic studies, such as those by Perkins and others (1998) and Perkins and Nash (2002), suggest a temporal continuity between some of these isolated basin remnants.

The amount, style, and timing of uplift and erosion profoundly influenced diatomite deposits. As shown in the Brady area (Stewart and Perkins, 1999), uplift began during lacustrine sedimentation, sedimentary materials stripped from the highlands inundated the lake, and normal faulting began to modify and segment the basin. Uplift that immediately follows sedimentation also influences diagenetic and postdiagenetic alteration by eliminating the lake and modifying the ground-water table. In most places, this influence is beneficial economically because it limits alteration of the diatoms, retains the original diatom textures and purity, and permits oxidation and removal of organic materials. However, poorly cemented lacustrine sedimentary materials are more susceptible to erosion than more resistant rocks, such as volcanic flows. These materials generally accumulate in topographic lows that are closer to the water table or more likely to be covered by later volcanic units or alluvium. Again, this influence may not be entirely detrimental; Nash (1995) noted that modest fault-related downdropping of diatomite and concealment by relatively thin alluvial deposits combined to preserve the diatomite deposits in the Trinity Pass area west of Lovelock, Nev. At the full extreme, extensive high-angle faulting and related erosion can completely eliminate a diatomite deposit or conceal it beneath extensive, thick alluvium. Given the high heat flow in the Great Basin region over the past 6 m.y. (Lachenbruch and Sass, 1978), burial to 100–500 m could cause thermal recrystallization of the diatom frustules (Knauth, 1994; Nash, 1995).

Possible topics of study:

- In what tectonic environments and local structural settings were diatomite deposits most likely to be either preserved or destroyed by uplift and erosion?
- What effect does burial have on diatomite, including destruction of frustules and increased availability to ground water?

Conclusions and Future Plans

This chapter introduces many, but not all, of the factors that led to the formation and subsequent preservation or destruction of diatomite deposits in Late Cenozoic lakes of the Great Basin region. Some of these factors are global to regional, such as climate and tectonics, whereas others are more local, such as volcanic flows and controlling structures. A favorable combination of these processes led to the presently exposed diatomite deposits in various parts of the region, and less than optimum combinations elsewhere prevented the formation of diatomite deposits or destroyed or buried them after formation.

The goal of the Industrial Minerals in Lacustrine Environments Task of WIMP is to study these processes in more detail. Several critical regional and local factors have received little or no research attention, and more information on some or all of these factors would provide a better understanding of diatomite deposits in the region. Regional factors include original distribution and extents of lakes, elevation variations, subregional climate variations, volcanic activity, and tectonic environment. Basin- and deposit-specific factors include duration and age of diatomite formation; paleoecology, paleogeography, and chemistry of the lakes; sources and amounts of silica and nutrients; diatom speciation and related flora and fauna; structural environment during and after diatomite formation; sedimentologic controls, including types and sources of clastic materials; causes of lake formation and termination; and postdepositional alteration. Using a combination of past and ongoing research in related fields and new work for this project, we expect to gain a better understanding of the processes that formed and preserved diatomite deposits. From this understanding, development of better regional exploration and assessment models for undiscovered economic diatomite deposits will be feasible, especially for those deposits that may be only slightly concealed.

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