

PRELIMINARY GEOLOGICAL INVESTIGATION OF THE
BI 'R HAYZAN DIATOMITE DEPOSIT,
KINGDOM OF SAUDI ARABIA

by

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with a section on

SELECTED PHYSICAL PROPERTIES AND IMPLICATIONS
FOR FUTURE GEOPHYSICAL EXPLORATION

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CONTENTS

	<u>Page</u>
ABSTRACT.....	1
INTRODUCTION AND A GENERAL DESCRIPTION OF DIATOMITE AND ITS USES.....	2
LOCATION AND ACCESSIBILITY.....	6
GEOLOGIC SETTING, OUTCROP DESCRIPTION, AND GEOLOGIC HISTORY.....	6
COMPOSITION OF THE DIATOMITE.....	13
SELECTED PHYSICAL PROPERTIES AND IMPLICATIONS FOR FUTURE GEOPHYSICAL EXPLORATION, by Mark E. Gettings.....	19
RECOMMENDATIONS FOR FURTHER STUDIES.....	22
REFERENCES CITED.....	24

ILLUSTRATIONS

Figure 1. Map showing location of Bi'r Hayzan diatomite deposit.....	3
2. Photomicrographs of the Bi'r Hayzan diatomite.....	4
3. Photograph of the exposed diatomite lakebed in the Nafud sand sea.....	8
4. Photograph of the upper half of exposed diatomite.....	9

TABLES

Table 1. Chemical analysis of four units of the Bi'r Hayzan diatomite.....	15
2. Comparison of the chemical composition of Bi'r Hayzan diatomite with that of diatomites from other localities.....	16
3. Elemental analysis of four units of the Bi'r Hayzan diatomite.....	18
4. Density and direct-current resistivity measurements of diatomite samples.....	20

ABSTRACT

A 2.2-m-thick lake bed composed entirely of diatomite was found in the southwestern arm of the Nafud sand sea, about 67 km east of Tayma in northwestern Saudi Arabia. Its stratigraphic position above eolian sand and below a large bar-chanoid dune indicates deposition during an exceptional period of pluvial climate in an otherwise arid sand desert. Radiocarbon-dated carbonate lake beds found in similar stratigraphic settings in other parts of the Nafud suggest that the diatomite was deposited in the late Pleistocene epoch sometime between 32,000 and 20,000 years ago. Diatomite of the same pluvial episode has also been found in the Afar region of Ethiopia.

Four samples of the diatomite were analyzed for major chemical components and 32 minor and trace elements. Two of the samples appeared to be representative of the lake bed. These samples contained about 85 percent SiO_2 , 2.34 percent Fe_2O_3 , 1.4 percent Al_2O_3 , and 8.27 percent ignition loss, with only traces of CaO , P_2O_5 , MgO , Na_2O , and TiO_2 . The high content of silica and low contents of alumina, iron oxide, lime, and other constituents indicate low contamination. Analyses of samples from the two atypical units indicate a small amount of contamination, probably clay or mica, in the basal unit and addition of iron oxide and carbonate by ground water in an isolated green-colored unit. Chemically the Bi'r Hayzan diatomite compares favorably with commercial deposits from other parts of the world. Low bulk densities of 0.64 g/cm³ (30-40 lbs/ft³) and an average porosity of 63 percent for five samples also suggest the deposit is of industrial grade.

Further studies are recommended to determine: (1) the size and extent of the deposit and (2) the suitability of the diatomite for commercial applications. As means to these ends, electrical-resistivity surveys following winter rains are suggested to determine both the extent and thickness of the lake bed beneath the overlying sand dunes. A complete species identification of the diatom association and further laboratory testing of physical properties of the diatomite also should be made. Further exploration in the Nafud is recommended to locate other possible diatomite deposits.

INTRODUCTION

AND A

GENERAL DESCRIPTION OF DIATOMITE AND ITS USES

A nearly pure diatomite deposit was discovered in January 1981, by John Whitney, D. J. Faulkender, and John Murdock while examining and collecting samples of surficial deposits in northwestern Saudi Arabia (fig. 1). The apparent low bulk density and bright white color of the deposit in outcrop suggested that it was unusually free of contaminants and thus warranted a preliminary investigation to determine whether it is a potential economic prospect. Two visits were made to the outcrop to study the geologic setting and stratigraphy of the deposit and to collect samples for analysis. The diatomite is provisionally named the Bi'r Hayzan diatomite deposit after a water well located about 12 km to the southwest.

Diatomite, or "diatomaceous" earth, is a light-colored, lightweight, friable sedimentary rock composed of siliceous shells of microscopic aquatic plants called diatoms (Bates, 1969). Most diatoms are floating organisms and belong to one of the divisions of algae. They are single-celled and develop shells, or frustules, of amorphous silica ($\text{SiO}_2 \cdot n\text{H}_2\text{O}$), a form of opal. The shells are commonly complexly perforated and bear ribs, spines, and bristles (fig. 2). The combined area of holes in the frustules generally ranges from 10 to 30 percent of the total surface area (Durham, 1973). Many valuable properties of the rock depend upon the aggregate effect of the microscopically complex and chemically inert frustules. Porosity, for example, can range from 20 to 75 percent.

The frustule consists of two halves, an epivalve and a hypovalve, which fit together without a hinge. One half fits into the other in a telescoped fashion. Diatoms differ from other algae in that they concentrate silica from surrounding waters during photosynthesis. Different species thrive in marine, fresh, and brackish waters. Several thousands of species have been identified. The variations in shape and detail are of both economic and biologic significance. These variations are instrumental in determining two of the rock's most valuable properties: an extremely large surface area and the loose packing that results in high porosity.

Shells accumulate at the bottom of a lake, bog, or the sea when the organisms die. The rate of accumulation is variable and depends on how favorable environmental conditions are to growth. Because of the microscopic size of the shells, the rate of accumulation is thought to be very slow. A cubic inch of diatomite contains upwards of 40 million

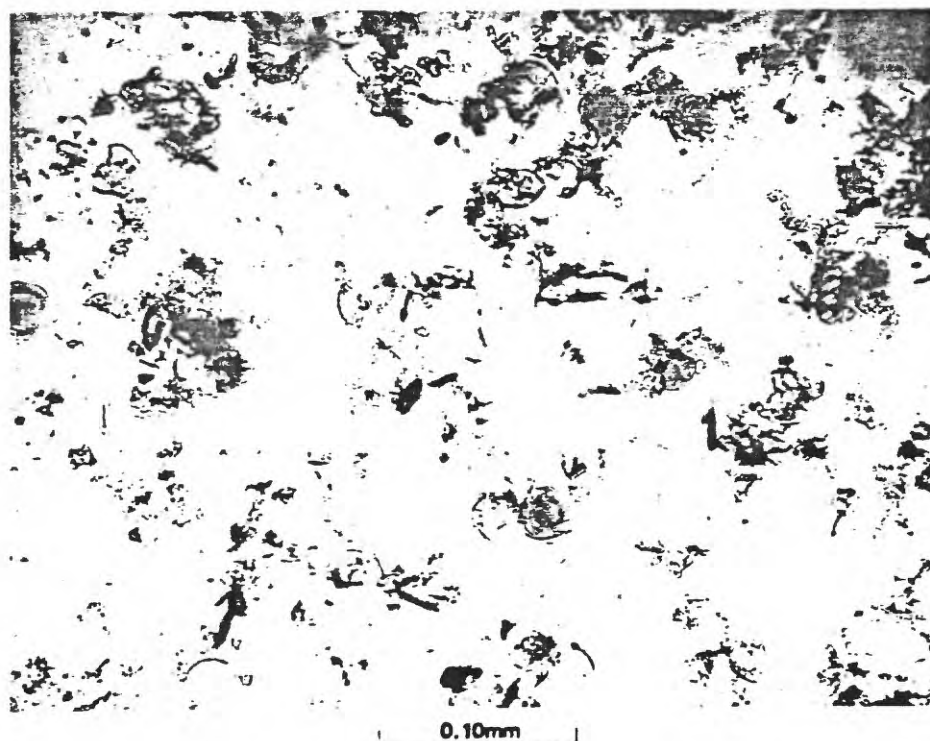
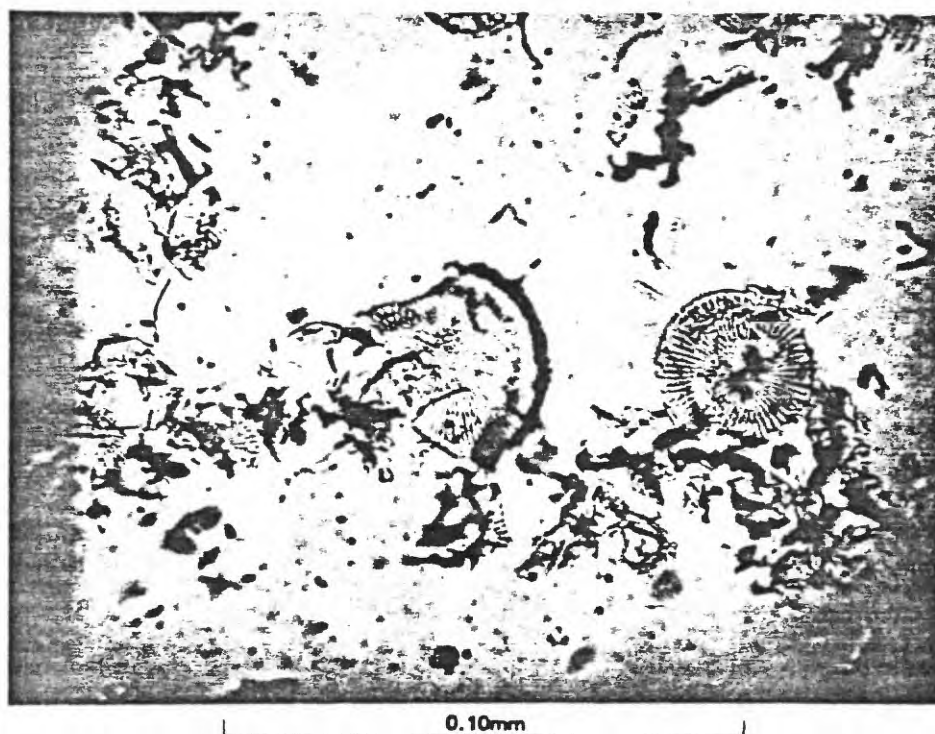


Figure 2.—Photomicrographs of the Bi'r Hayzan diatomite; samples collected 30 to 40 cm above the base of the deposit. The diatom assemblage is dominated by *Stephanodiscus astraes*, a species that is still found in modern environments.

frustules (Bates, 1969). Individual diatomite beds range from a few inches to several hundred feet in thickness. However, thick deposits without impurities are rare because of the length of time required for deposition. Common contaminants are organic matter, clay, silt, carbonates, and volcanic ash. All gradations from pure diatomite to diatomaceous shale or clay can occur in nature. The thickest deposits in the world are of marine origin, although known marine deposits are fewer in number than those of lacustrine origin.

In outcrop, a fresh face of diatomite is predominantly white to whitish-tan and contains minor units of yellowish tan to brownish and sea-foam green. The color is determined by the kind and amount of contaminant or moisture present and, generally, the lighter the color, the fewer the contaminants. Diatomite is finely granular and feels soft and chalky. The beds can be massive or finely laminated.

Diatoms became abundant during Cretaceous time and are still abundant in oceans and lakes. Most commercial deposits of diatomite are of Tertiary age, although many smaller deposits of Quaternary age, such as the Lüneburger Heide deposits in Germany, have been mined (Cummins and Mulryan, 1949).

The major commercial use of diatomite is as a filter aid for the separation of suspended solids from liquids. In 1979, this use accounted for 65 percent of all processed diatomite produced (Meisinger, 1980). Other common uses are fillers for paints, plastics, papers, fertilizers, and insecticides; mild abrasives, especially in polishes; absorbents; catalyst carriers; and structural products. These last two uses may be of special interest in Saudi Arabia. As a catalyst carrier, diatomite is used in petroleum refining. It can also be used as an additive, or pozzolan, for making highly resistant concretes that are noncorrodible by seawater.

All work on the Bi'r Hayzan diatomite was performed under a cooperative agreement between the U.S. Geological Survey (USGS) and the Saudi Arabian Ministry of Petroleum and Mineral Resources. All analytical work except X-ray mineral identifications was done at X-Ray Assay Laboratories, Ltd., Ontario, Canada. Mineral identifications were made by Mohammed Naqvi and Mohammed Bashir of the USGS petrologic services laboratory, Jiddah, Saudi Arabia. Photomicrographs of the diatoms were made by Mustafa Mawad.

D. J. Faulkender helped to determine the exact location of the deposit. Meyer Rubin (USGS, Reston, Virginia) isotopically dated lake bed materials from the Nafud. George

Andrews (USGS, Washington) identified the dominant diatoms from two sample locations within the deposit.

LOCATION AND ACCESSIBILITY

The Bi'r Hayzan diatomite is located in the southwestern arm of the Nafud sand sea at lat 27°35'40" N. and long 39°10'23" E. (fig. 1). The village of Tayma is approximately 67 km west of the deposit. Because the deposit is about 18 km north of the southern edge of the sand sea, accessibility by vehicle is difficult but not impossible. With the aid of aerial photography or Landsat imagery, one can enter the dune field without having to cross a major ridge of transverse sand dunes. Most dunes in this region are stable, and mobile sands are usually confined to the crests of larger dunes. The sand is packed firmly enough for light-vehicle and truck traffic, as attested to by the large number of vehicle tracks seen from the air. Bedouin tend their flocks of sheep, goats, and camels in the area during the winter and after substantial rainstorms. The most hazardous aspect of driving in the sand sea is presented by steep dune slip faces that can have local relief of as much as 150 m.

Between the edge of the dune field and Tayma, a mostly bare and flat sandstone surface has many small, sharp features of local relief that make travel by truck or four-wheel drive necessary. Many tracks cross this surface, and some have been upgraded by bulldozers. Driving off the tracks is possible but slow due to the nature of sandstone erosion in the region. From Tayma, an all-weather highway connects the village to Khaybar and points south and to Tabuk in the northwest.

GEOLOGIC SETTING, OUTCROP DESCRIPTION, AND GEOLOGIC HISTORY

The Bi'r Hayzan diatomite deposit is exposed on the windward side of a large transverse dune in the southwestern arm of the Nafud sand sea. From the air the deposit appears as a thin, bright-white linear outcrop in contrast to the sparsely vegetated sand dunes around it. As measured from a 1:100,000-scale aerial photograph, the exposed section of the deposit is about 450 m long. Similar white outcrops in other dunes were seen during two helicopter traverses across the southwestern arm of the Nafud. Some of these outcrops were visited; however, the deposits were found to be carbonaceous or gypsiferous lake beds or a white sand exposed in the lee of some large barchanoid dunes. Other diatomite lake beds were not found. It should be emphasized, however, that only a small number of these outcrops were visited because the

study of surficial deposits in the region was combined with a project for obtaining topographic control in order to make efficient use of available helicopter time.

The Nafud sand sea occupies more than 70,000 km in the north-central part of Saudi Arabia. The western part of the sand sea is composed of large transverse ridges of sand dunes that reflect the dominant westerly winds responsible for their existence. The transverse ridges appear to be composed of a series of connected barchanoid dunes. Individual slip faces on these barchanoid dunes are commonly as much as 100 m high, and exceptionally large dunes were found to have local relief of as much as 160 m. From the air, this part of the Nafud looks as though it is composed of individual waves of sand, each wave in some stage of encroachment upon the next. Because of this configuration, true interdunal areas are only rarely exposed. This dense packing of dunes is probably the main reason why so few former interdunal deposits, such as the diatomite are exposed. The last major episode of dune movement undoubtedly buried and perhaps partially eroded most of these deposits.

The diatomite is situated just downwind of a barchanoid dune that is 149 m high (fig. 3). A small deposit of gypsiferous sand occupies the topographic low in the lee of the dune. The diatomite is exposed 34 m above this interdunal lake bed, or pan, on the windward side of the adjacent downwind dune. Eolian sand lies stratigraphically above and below the deposit. In sunlight, the outcrop appears bright white; however, the color actually varies from pure white to whitish tan throughout most of the vertical section, with darker yellowish units at the base and top of the deposit.

The outcrop ranges from 1.6 to 2.2 m in thickness, and parallel laminae are visible throughout the section. This variation in thickness is due to local erosion of the outcrop, including undercutting of the beds by wind erosion. The average thickness is about 1.85 m. Visible with the laminae on the surface of the outcrop are iron oxide stains less than 1 cm in diameter that first appear to be small concretions (fig. 4). These stains, however, are mostly concentrated on the surface of the outcrop and near the top of the deposit. Moisture infiltrates the lake bed after infrequent storms, and evaporation draws the moisture to the surface of the lake bed and leaves the iron picked up in solution on the face of the outcrop.

Except for the base and top of the lake bed, the internal characteristics are remarkably uniform. The entire bed is laminated diatomite with slight variations in color and in density of iron oxide stains. Interbeds of sand, silt, clay, or ash are not present, suggesting that deposition of diatoms was uninterrupted in the area of the exposed section. The

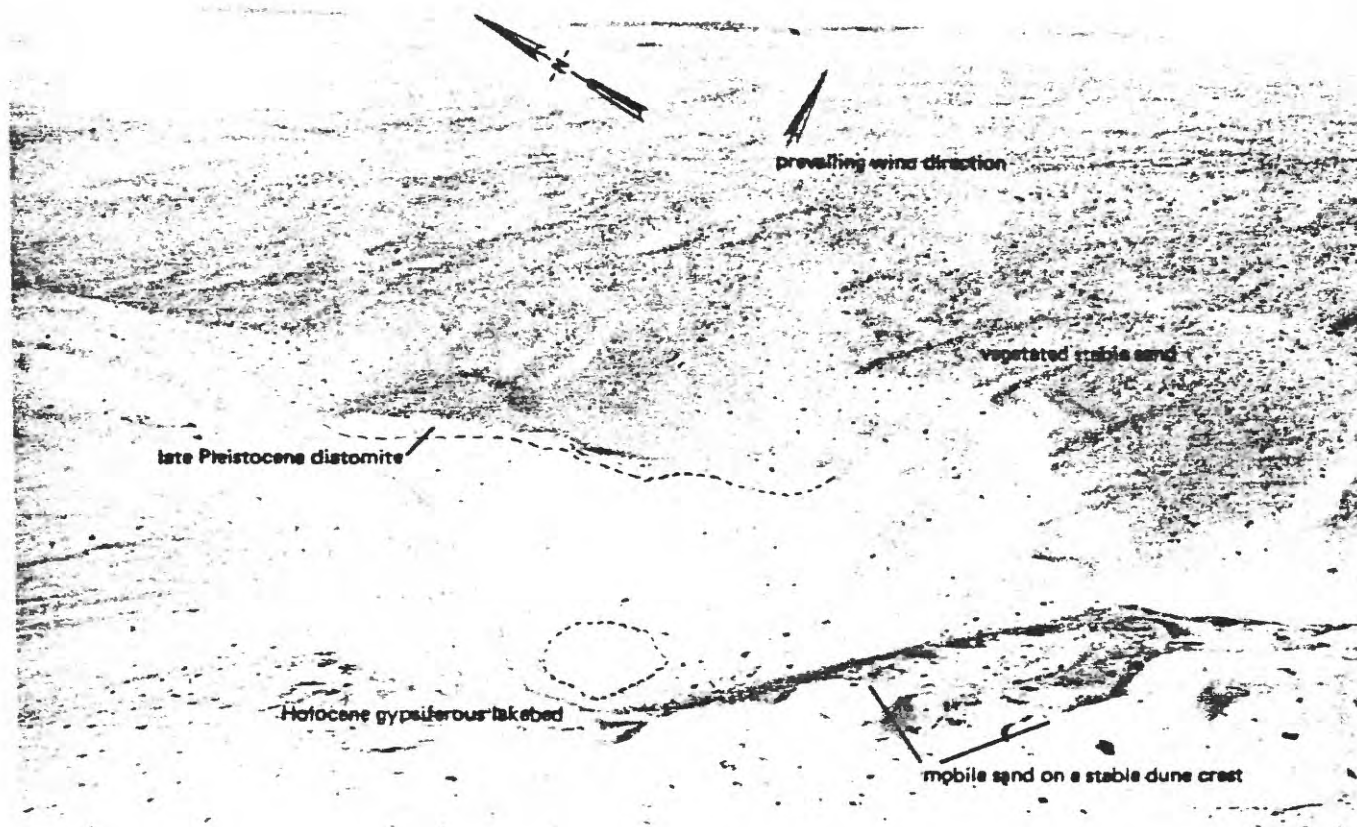


Figure 3.—Photograph of the exposed diatomite lakebed in the Nafud sand sea. Photograph taken from a helicopter above the slip face of a barchanoid dune. Vertical distance between the dune crest and the Holocene lakebed at the base of the dune is almost 150 m.

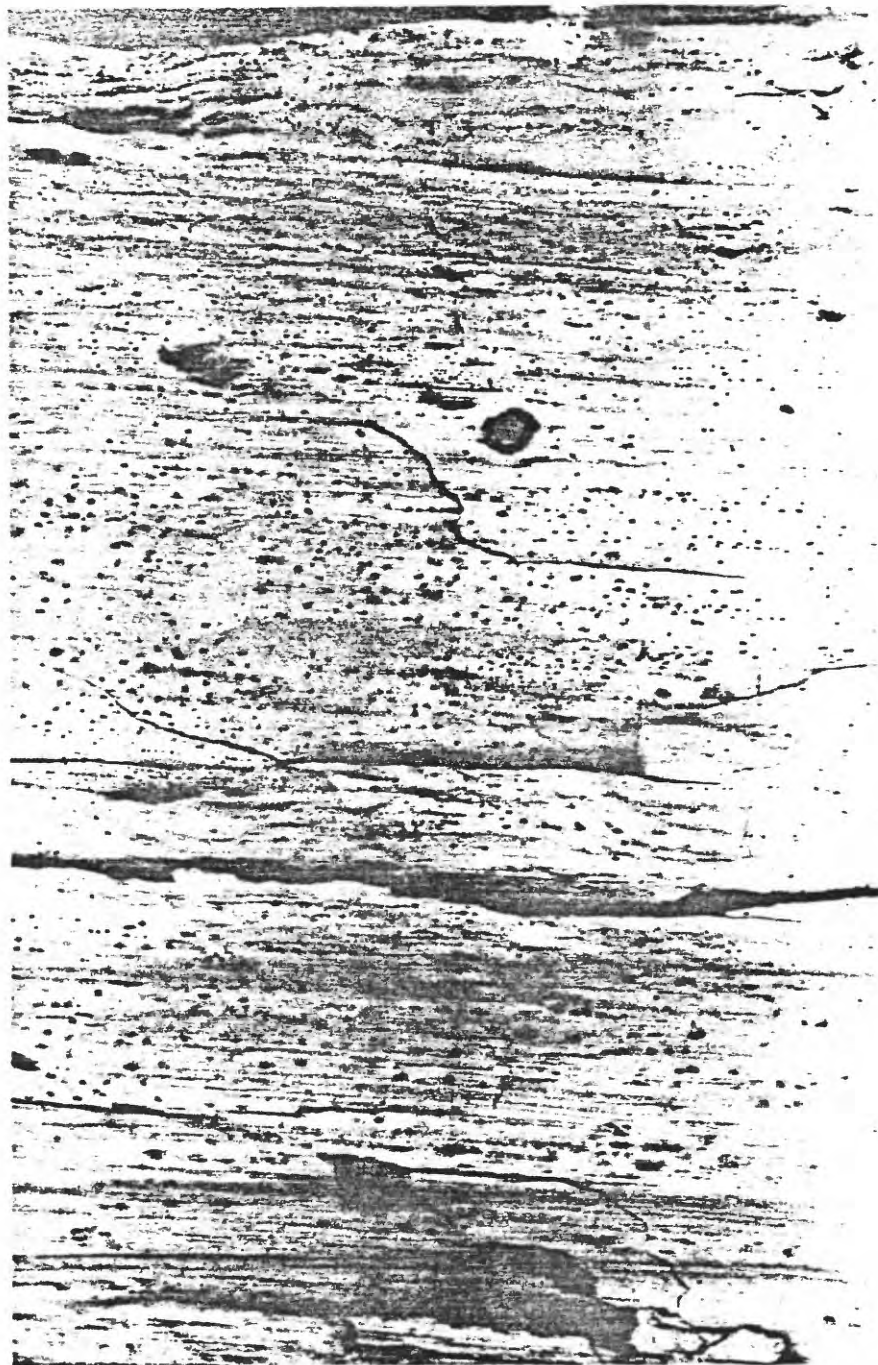


Figure 4.—Photograph of the upper half of exposed diatomite. Note laminations and small limonite stains. Hand lens is 2 cm in diameter.

basal 15 to 20 cm (sample WA-66) has a slightly shaly texture and breaks up in thin slabs parallel to the laminae. Judged from the hand specimen, this unit appears to have a higher specific gravity and is more yellow than the others. The top unit (sample WA-70, collected 210 to 220 cm above the base of the lake bed) is whitish tan and differs from the rest of the deposit in that it has a higher density of visible iron oxide stains. In localized areas the top unit contains patches of greenish-brown opaline chert, 10 to 15 cm thick, with laminae still visible. A sea-foam green unit 85 to 92 cm above the base (sample WA-65) pinches out laterally in both directions within the outcrop. The fact that the green color unconformably crosses laminae boundaries implies that it is a postdepositional feature. The balance of the outcrop varies from brilliant white (sample WA-64, collected 35 to 40 cm above base) to tannish white (WA-122, collected 120 to 125 cm above base). In hand specimen, these samples have a chalky texture and feel very light, similar to balsa wood, for example. The samples, in fact, float until they absorb enough water to sink.

The laminations suggest a rhythmic cycle of sedimentation in the former lake, probably seasonal or annual. Under the assumption that each pair of laminae, one thicker and coarser grained and the adjacent thinner and finer grained, represents annual deposition, an estimate can be made of the length of time represented by the 2.2-m-thick bed. The number of pairs of laminae ranged from 38 to 43 per 10 cm in one vertical section and averaged 4 per centimeter. These calculations suggest that diatomite sedimentation lasted at least 880 years. Considering probable postdepositional erosion of the lake bed by the wind and the probable thickening of deposit beneath the overlying dune sand, this figure should be regarded as a minimum.

The lake beds dip 5° to 9° NE. (azimuth 040°). Local dips on disturbed laminations are higher. This orientation indicates that the center of deposition, and presumably the deepest part of lake, lies to the northeast. Unfortunately, the eolian sand above the lake bed does not form a well-defined barchanoid or transverse dune. Without a nearby dune slipface downwind, it is difficult to assess how much diatomite is preserved under the sands.

Eolian sand lies stratigraphically below as well as above the lake bed. The deposition of the lake bed represents a change in climate between two episodes of active eolian deposition. No isotopically datable materials were found in association with the diatomite lake bed or the dunes. However, the age of the deposit can be reasonably ascertained because carbonate lake beds have been found in the same

stratigraphic setting in other parts of the Nafud. Two lake beds have been dated by radiocarbon methods and are 29,000±600 and 24,340±300 years old. These are the first isotopically dated deposits to be reported from the Nafud desert, and the ages correlate well with those of dated lake beds in the Rub al Khali desert (McClure, 1976) and in East Africa (Gasse and others, 1980).

The ages of these carbonate lake beds strongly suggest that the diatomite was deposited during the last interglacial climate of the Pleistocene. This interstadial lasted from approximately 32,000 to 20,000 years ago and includes a time of transition between interglacial and glacial climates worldwide. At this time the world's subtropical deserts experienced a relatively mild climate with much more effective precipitation than immediately before or after this period. This precipitation increase was reflected in high lake levels over both East and North Africa (summarized in Rognon and Williams, 1977, and Gasse and others, 1980).

During the glacial climates of the Pleistocene, the subtropical deserts were more arid than they are today. Sand deserts grew to their largest areal extents during these periods of "glacial aridity," and their borders retreated when the glaciers of the more poleward latitudes began to melt (Sarnhein, 1978). The eolian sand both above and below the diatomite represents the last two glacial stades (ice advances in the temperate zones) of the Würm, or Wisconsinan, glaciation, the last glacial stage of the Pleistocene Epoch. The dunes overlying the lake bed today were formed during the last glacial stage of the Würm, which reached its maximum extent about 17,000 years ago, and probably remained active until sometime early in the Holocene. It is not known exactly when the Nafud became a sand desert; however, previous investigators believe that its formation probably coincided with the beginning of the Quaternary period (Brown, 1960; Holm, 1960). In light of the relationship between the onset of worldwide colder climates and expanded aridity in the subtropics, it is likely that sand dunes began to accumulate in the Nafud at that time.

Between the exposed diatomite and the large barchanoid dune to the west, another lake bed, much smaller in size, lies in the lee of the dune. This lake bed is composed of sandy gypsum and most likely began to form when the climate became more pluvial in the early Holocene. Located in a topographic low, this lake bed, or pan, still receives moisture that percolates through the surrounding dunes after unusually heavy or persistent rains. Holocene lake beds in similar topographic settings have been reported from the Rub al Khali (McClure, 1976). This pluvial interval does not appear to have been so intense or so effective in producing as many or as large lakes in comparison with deposits of the

last interstadial of the Pleistocene. The general climatic effect, however, was far reaching. Holocene lake beds are in North and East Africa (see, for example, Haynes and others, 1979, and Gasse and others, 1980).

Diatomaceous marl of middle Holocene age has been reported by McClure (1976) from the Mundafan lake basin along the western edge of the Tuwaiq escarpment in southwestern Saudi Arabia. Beds of diatomite have not been discovered in the Rub al Khali, where lake bed remnants are common interdunal deposits (McClure, 1978), or in any other areas in the Kingdom.

Thick deposits of diatomite have been found, however, in the Afar basin of Ethiopia (Gasse, 1975). During the same pluvial episode in which diatomite was deposited in the Nafud, the water level of Lake Abhe in the central Afar was 180 m higher than it is today. As in the Bi'r Hayzan deposit, deposition was almost exclusively biogenic. The diatom flora in this late Pleistocene lake, dominated by Synedra acus var. neogena and Stephanodiscus hantzschii, indicate a fairly tropical environment of deposition. When the diatom association from the Nafud is more completely known, it will be of interest to compare paleoenvironments.

The uniqueness of the Bi'r Hayzan deposit raises important questions concerning its origin and preservation. All other lake beds found in the Kingdom by other researchers and the author are composed primarily of either gypsum or carbonate. Of course, it is possible that many more lake beds of pure, or nearly pure, diatomite in the Kingdom have yet to be discovered. This possibility is certainly plausible because little to no detailed mapping or exploration has taken place in sand deserts. It is also possible that the soft diatomite is much less resistant to wind erosion, especially abrasion, than are lake beds of marl and sandy gypsum. Preservation of diatomite may require quick burial by dune sand. Another possibility is that deposition near Bi'r Hayzan was affected by volcanic activity taking place on one of the nearby basalt plateaus that lie to the west and south of the Nafud sand sea. An abundant supply of free silica from a volcano upwind of the lake may have accelerated diatom productivity in a localized area of the region. This association between volcanism and high diatom production has been confirmed for marine deposits where layers of volcanic ash are found as contaminants (see discussion in Kadey, 1975). No ash, however, was detected in a petrographic study of two samples (WA-64 and WA-65) of the Bi'r Hayzan deposit.

Another possible explanation of the singular occurrence of the diatomite is that it was deposited during an older pluvial episode than were the carbonate lake beds in other

parts of the Nafud. The deposit may have survived at least two cycles of wind erosion by chance burial. This explanation is considered highly unlikely because burial by stable eolian sand during times of highly active dunes is nearly impossible.

In summary, the diatomite was most likely deposited within a brief pluvial episode of 10,000 to 12,000 years in the late Pleistocene that similarly affected the Rub al Khali and large regions of North Africa. Before and after this lake-forming period, the Nafud sand sea was extremely arid and eolian deposition predominated. The accumulation of more than 2 m of pure and nearly pure diatomite implies the existence of a shallow lake at least several square kilometers in area. Although no strand lines remain, the shallow dip of the lake bed to the northeast indicates that the center of basin deposition most likely lies in that direction. Possibly the lake bed thickens in that direction as well. The low visible contamination in the diatomite implies that the sand dunes in the area must have been stabilized by vegetation and that strong, persistent wind storms were rare during the time of lake sedimentation. Ecological information reflecting the climate at that time will be better known when the diatom association has been studied in detail. It is possible that the purity of the diatomite may be related to volcanic activity on one of the nearby harrats.

After the climate of the Nafud returned to its more normal aridity at the end of the Pleistocene, all lake-forming activity ceased and eolian processes prevailed. Another episode of pluvial activity took place in the first half of the Holocene and resulted in small interdunal deposits, commonly gypsiferous, in the lee of major dunes. Because these interdunal lakes, or pans, have been only infrequently wetted since the middle Holocene, a general trend toward drier conditions is indicated. The major dune forms, however, have not been reactivated (Whitney, 1981).

COMPOSITION OF THE DIATOMITE

The Bi'r Hayzan deposit is composed almost entirely of freshwater diatoms. Sample WA-65 (USGS diatom loc. 6826) contains an assemblage of nearly 100 percent Aulacosira granulata var. angustissima, and sample WA-64 contains an assemblage of nearly 100 percent of a small variety of Stephanodiscus astrea (fig. 2). Both of these species are found in modern environments and are known to have existed during the Pleistocene.

These single-species diatom assemblages may have significance in the paleoecology of the deposit. More detailed

examinations of these samples and the other samples collected from the deposit are being carried out.

So that mineralogy of the diatomite could be determined, three samples (WA-64, WA-65, and WA-70) were analyzed by X-ray diffraction. All three exhibited a broad peak in the region of the cristobalite peak. The main quartz peak was present on all samples, as well as a low, broad, ill-defined peak in the region of the clay and mica minerals. The quartz peak indicates the presence of grains of quartz silt, which can also be seen in thin sections. The other peak indicates that minor amounts of clay are probably present throughout the lake bed.

Chemically, diatomite is essentially silica with some combined water (2-8 percent). Alumina and iron oxide contents are generally at least 1.5 and 0.2 percent, respectively. The purity of a diatomite deposit is commonly reflected in the amount of silica present. Diatomites analyzed from around the world show a range of 70 to 90 percent SiO_2 , 2 to 10 percent Al_2O_3 , and variable but small percentages of Fe_2O_3 , TiO_2 , P_2O_5 , CaO , MgO , Na_2O , and K_2O (Durham, 1973).

The Bi'r Hayzan diatomite was sampled at five different levels in the exposed lake bed. The samples were chosen because they represent the range of slightly different colors seen on the outcrop and might reflect the range of contamination within the deposit. The two white samples (WA-64 and WA-70) are considered to be representative of the total outcrop, and their values were averaged for comparison with diatomites from other localities (table 2).

Four samples were analyzed for major chemical components and 32 minor and trace elements (tables 1,3). Major-element chemistry was done by X-ray fluorescence spectroscopy. Rubidium, strontium, and zirconium were analyzed by X-ray fluorescence spectroscopy; all other minor and trace elements were analyzed by emission spectroscopy.

The two white samples (WA-64 and WA-70) contained 85.5 percent and 84.2 percent SiO_2 . The fact that the samples were not oven-dried before analysis is probably reflected in the relatively high ignition losses of 8.08 percent and 8.47 percent. Under the assumption that most of this loss is water, the actual silica content of these units when dried was in excess of 89 percent. The iron oxide visible in sample WA-70 was reflected in the sample's composition. It contained 3.5 percent Fe_2O_3 , whereas the pure white sample (WA-64) contained only 1.19 percent. The alumina content in both samples was low, 2.11 and 0.69 percent, when compared with published figures for other diatomites (table 2). Low

Table 1.--*Chemical analysis of four units of the Bi'r Hayzan diatomite*

[All constituents analyzed by X-ray fluorescence, X-ray Assay Laboratories, Ltd., Ontario, Canada]

Constituent (percent)	WA-66	WA-64	WA-65	WA-70
Silica (SiO ₂)	75.3	85.5	74.5	84.2
Alumina (Al ₂ O ₃)	7.66	2.11	1.23	0.69
Lime (CaO)	0.59	0.36	3.16	.49
Magnesia (MgO)	.65	.21	0.37	.20
Sodium (Na ₂ O)	.30	.21	.25	.14
Potassium (K ₂ O)	.93	.28	.17	.11
Iron oxide (Fe ₂ O ₃)	3.66	1.19	7.67	3.50
Manganese (MnO)	.01	.01	.01	.01
Titanium oxide (TiO ₂)	.45	.14	.09	.06
Phosphate (P ₂ O ₅)	.04	.02	3.66	.12
Ignition loss (LOI)	<u>8.47</u>	<u>8.08</u>	<u>8.85</u>	<u>8.47</u>
TOTAL	98.1	98.1	100.0	98.0
Sample locations	WA-70: 210-220 m above base of lakebed, whitish-tan color WA-65: 85-92 cm above base of lakebed, sea-foam green color WA-64: 30-40 cm above base of lakebed, white color WA-66: 0-10 cm basal unit of lakebed, whitish-yellow color			

Table 2.--Comparison of the chemical composition of Bi'r Hayzan diatomite with that of diatomites from other localities

[Leader, data not available. Source: Kadey, 1975. Note that all samples except from the Bi'r Hayzan deposit were oven-dried before analysis. Chemical composition of Bi'r Hayzan deposit an average of data for WA-64 and WA-70, table 1]

Constituent (percent)	Bi'r Hayzan Lompoc, CA	Maryland	Russian Urals	Kenya	Algeria
Silica (SiO ₂)	85.0	89.70	79.55	79.92	84.50
Alumina (Al ₂ O ₃)	1.40	3.72	8.18	6.58	3.06
Lime (CaO)	0.43	0.30	0.25	3.00	1.80
Magnesia (MgO)	.21	.55	1.30	0.81	0.39
Sodium (Na ₂ O)	.18	.31	1.31	.50	1.19
Potassium (K ₂ O)	.20	.41		.39	.91
Iron oxide (Fe ₂ O ₃)	2.34	1.09	2.62	3.56	1.86
Titanium oxide (TiO ₂)	.10	.10	.70	.48	.17
Phosphate (P ₂ O ₅)	.07	.20	--	--	.04
Ignition loss (LOI)	8.27	3.70	5.80	5.20	6.08
TOTAL	98.2	99.98	99.71	99.37	100.0
					99.22

alumina content presumably reflects low clay contamination. When the compositions of WA-64 and WA-70 are averaged together and compared with a selection of mined diatomites from around the world, the Bi'r Hayzan deposit appears impressively pure and compares chemically to the deposits at Lompoc, California, the largest and most important commercial deposit in the world (table 2).

The two atypical units sampled (WA-65 and WA-66) contained more contaminant than did the two white samples. The yellowish basal unit (WA-66) had the highest alumina content (7.66 percent) of all samples, most likely caused by a higher content of clay or possibly by the presence of detrital grains of feldspar or mica. The greenish sample (WA-65) revealed higher iron oxide and lime (mostly carbonate) contents than the rest of the samples. Both of these constituents were probably deposited in the diatomite from moisture that first infiltrated through the overlying dune sands. Perhaps this process was intensified during the minor pluvial episode of the middle Holocene.

Elemental analysis of the four Bi'r Hayzan diatomite samples also reflects the relative purity of the deposit (table 3). The semiquantitative analyses detected a significant amount of iron in each sample, and the iron content is corroborated by the major chemistry. The basal unit (WA-66) also contained higher amounts of chromium, titanium, and zirconium than did the other Bi'r Hayzan samples. These elements most likely reflect the clay content of that sample; perhaps a small grain of zircon was present. A more detailed knowledge of the elemental composition of the deposit will be required in order to classify the deposit as to its suitability and grade for various commercial applications.

Table 3.--*Elemental analysis of four units of the Bi'r Hayzan diatomite*

[Results in percent unless other indicated. T, trace; leader, not detected in sample. All elements were analyzed by emission spectroscopy except for Rb, Sr, and Zr, which were analyzed by X-ray fluroescence. Analysis by X-ray Assay Laboratories, Ltd., Ontario, Canada]

Element	WA-66	WA-64	WA-65	WA-70
Beryllium	T	T	--	--
Chromium	0.01-0.10	0.01-0.10	T	--
Copper	T	T	T	T
Iron	.5-5.0	.5-5.0	1.0-10	0.1-1.0
Lead	T	T	T	T
Nickel	T	T	T	--
Titanium	.05-5.0	T	T	--
Vanadium	T	T	T	T
Yttrium	T	T	T	T
Rubidium	30 ppm	20 ppm	--	20 ppm
Strontium	130 ppm	50 ppm	130 ppm	10 ppm
Zirconium	210 ppm	60 ppm	30 ppm	20 ppm

Elements undetected in all samples

antimony	cobalt	mercury	tin
arsenic	gallium	molybdenum	tungsten
bismuth	germanium	niobium	uranium
cadmium	lithium	silver	zinc
cerium	manganese	thorium	tantalum

SELECTED PHYSICAL PROPERTIES AND IMPLICATIONS FOR FUTURE GEOPHYSICAL EXPLORATION

by Mark E. Gettings

Bulk density, grain density, porosity, and electrical-conductivity determinations were carried out on five samples, both as an aid to the comparison of the Bi'r Hayzan diatomite with other deposits and as part of an evaluation to select geophysical prospecting methods that might be profitably employed to map the areal extent, thickness, and depth of burial of the diatomite (table 4). Density and porosity determinations were completed on specimens WA-64, WA-65, WA-66, WA-70, and WA-122. Dry weight, water-saturated weight, and weight of the saturated sample in water were measured on a Mettler Pl-1200 electronic balance and used to determine bulk density, grain density, and apparent porosity according to the formulae of G. R. Johnson and G. R. Olhoeft (unpub. data).

Direct-current apparent resistivity was determined for a core from specimen WA-122, which was collected 120 to 125 cm above the base of the diatomite, by means of a Scintrex CTU-2 core-testing unit and Scintrex IPR-8 induced-polarization receiver. Apparent resistivities for bulk specimens WA-64 and WA-70 were estimated by means of an ohmmeter and comparison with the measured core WA-122 because of difficulties in obtaining a coherent core in this friable material. Apparent resistivity was measured both perpendicular to and parallel with the bedding and appears to be isotropic within experimental error. Apparent resistivity was also measured with the same apparatus on the flat surface of the specimen WA-70 by use of an equally spaced, linear-electrode configuration ("Wenner array"; see Telford and others, 1976, p. 655). Electrode spacing was 1.88 cm, which, with the specimen thickness of about 10 cm, yielded a good measure of the apparent resistivity. This measure was in good agreement with the ohmmeter estimates. All determinations were made on damp specimens that had dried for 3 days in laboratory conditions after a saturation. Results of the physical-properties measurements are summarized in table 4.

As noted above, the samples were not oven-dried before measurement, so that the measured bulk density is a maximum estimate and the porosity is a minimum. The mean apparent porosity of 62 percent is in the upper part of the range of industrial-quality diatomite. The low mean apparent resistivity of 26 Ω -m is notable and must mean that the contained salts are sufficient (tables 1, 2) to make the material a good conductor when saturated.

Table 4.--Density and direct-current resistivity measurements of diatomite samples

[n.d., not determined. Experimental uncertainty in density values is about ± 0.002 g/cm³; uncertainty in apparent resistivity is about ± 20 percent. Densities determined at 25°C except for sample WA-122, which was determined at 21°C]

Sample	Dry weight (g)	Saturated weight (g)	Weight in water (g)	Bulk density (g/cm ³)	Grain density (g/cm ³)	Apparent porosity (percent)	Apparent direct-current resistivity (Ω -m)
WA-66	173.66	301.65	90.59	0.821	2.085	60.6	n.d.
WA-64	294.54	647.32	92.66	.529	1.455	63.6	151/
WA-65	133.63	268.45	54.49	.623	1.684	63.0	n.d.
WA-122	10.83	21.66	2.93	.577	1.368	57.8	162/
WA-70	198.42	395.19	86.54	.641	1.769	63.8	301/, 433/
Mean							26
Standard Deviation							13

- 1/ Value estimated by ohmmeter comparison with sample WA-122.
2/ Direct-current apparent resistivity measured by means of a Scintrex CTU-2 core-testing unit and IPR-8 induced-polarization receiver.
3/ Measured on flat surface with Wenner electrode configuration.

The low mean bulk density (0.64 g/cm^3) immediately suggests high-precision gravity surveys as a mapping tool for buried deposits (Durham, 1973) because the expected bulk density of the dune sand ranges from 1.4 to 1.7 g/cm^3 (Heiland, 1968, p. 83) yielding a large negative density contrast for the target. In this case, however, the relief on the dune surface is about 100 m and a simple calculation shows that, unless the topographic mapping is high precision, the uncertainty due to terrain corrections to the gravity data will mask the gravity effect of a diatomite layer 2 m thick. Therefore, unless the diatomite thickens considerably beneath the sand cover, gravity surveys are not recommended as a mapping tool for this deposit.

The low apparent resistivity of the damp diatomite suggests that the most successful mapping tool will be electrical-resistivity surveying, especially if the mise-a-masse electrode configuration is used (Telford, 1976, p. 662). In this arrangement, one current electrode is placed in the outcrop of the target and the other a long distance, for example 3 km , away. The potential electrodes are then moved about at a fixed spacing chosen to optimize the response for the anticipated depth of burial to map the applied field. The low-resistivity anomalies of the map should then define the areal extent of the deposit. Electrical soundings using other electrode configurations can then be carried out to determine the depth and thickness of the target. Electrical resistivities of sand containing a few percent moisture generally range from $1,000$ to $10,000 \text{ } \Omega\text{-m}$ (Heiland, 1968, p. 664). However, if significant salts are present and moisture contents are high enough, much lower values can be obtained. Good results can probably be obtained if the survey is made in the wet season long enough after a rainfall for the sand cover to be reasonably dry and the diatomite still moist. Resistivity surveys will probably be the most cost-effective tool for mapping the buried parts of the diatomite and are certainly the first method to attempt.

Finally it should be noted that, although seismic velocity measurements for diatomite were not found in the literature, the diatomite is lithologically similar to chalks and might therefore be expected to have similar seismic velocity properties. Typical compressional-wave velocities for chalks range from 2 to 4 km/sec , as compared to 0.5 km/sec for dune sand (Heiland, 1968, p. 469-471), and thus a marked velocity contrast may exist between the sand cover and the diatomite. This possible contrast suggests that selected, shallow seismic-refraction profiles might be used to help map the deposit. The seismic-refraction method, however, is costly, both in terms of manpower and time, and is recommended only as a complement to resistivity surveys or as an alternative method if for some unforeseen reason the resistivity surveys do not provide clear results.

RECOMMENDATIONS FOR FURTHER STUDIES

The first chemical and elemental analyses performed on a lake bed found in the Nafud sand sea indicate the deposit is a diatomite of low contamination. Bulk densities of 0.64 g/cm^3 (30-40 lbs/ft³) and a porosity of 63 percent indicate that the Bi'r Hayzan deposit is comparable to industrial-grade diatomite. The next stage of exploration is to delineate the reserves of the Bi'r Hayzan deposit and to locate deposits of similar quality in the same region. The diatomite now should be tested further for quality and for specialized physical properties.

It is highly recommended that the area surrounding the deposit be investigated by helicopter to see if the lake bed crops out through nearby sand dunes. This quick survey will give some indication as to the size of the deposit if it is not completely buried by sand. To map larger areas in the Nafud, it would be very useful to have color aerial photography at a large-enough scale, such as 1:25,000, to distinguish small exposures of lake beds in the dune field. Color photography is recommended over black and white because reflectance and glare make it very difficult to distinguish light-colored sand from lake beds on black and white photography. It should be noted that, except for petroleum, the sand deserts have not been explored in any detail for mineral potential. As part of the 1:500,000-scale geologic mapping of the Kingdom, only large lake bed deposits were mapped, and the Bi'r Hayzan diatomite, for example, was not noted. Larger scale mapping in both the Nafud and Rub al Khali may locate other lake beds having economic potential.

To determine the extent and thickness of the Bi'r Hayzan deposit, several geophysical methods can be employed. The most feasible and cost-effective method recommended is electrical-resistivity surveying. This survey should be conducted during the late winter or early spring when moisture from the seasonal rains has had time to infiltrate the porous diatomite and to create a conductivity anomaly in contrast to the overlying eolian sands. A mise-al-a-masse survey is recommended to delineate the areal extent of the buried diatomite. A logical followup to this work would be electrical-resistivity soundings to determine the depth and thickness of the diatomite beds in several places. If required, selected seismic-refraction profiles could be employed to help define the extent of the deposit. Taken together, these studies would allow calculation of the reserves.

More laboratory testing and evaluation of the diatomite is needed. A more complete study of the diatoms in the

deposit is needed because the physical properties and therefore the economic potential of the diatomite are determined by the types, sizes, shapes, and species of the diatoms themselves. Species identification will also be useful in reconstructing the environment of deposition of the diatomite.

Whereas the chemical analysis of a diatomite is useful in a general way to determine the relative purity of the deposit, it is not an effective criterion for predicting the performance of the material for most applications (Kadey, 1975). A high silica content is a good indication that a deposit is pure but does not mean that the deposit is of commercial grade. Properties that can be used to detect the performance of the material for different uses must be determined in a testing laboratory. Properties that must be determined are weight, wet density, screen size, brightness, abrasion, water absorption, filtration flow rate, clarity, porosity, pH, and resistivity. Other specialized tests are needed when a sample is being considered for a specific use. Most of these tests are well known; however, some are proprietary. If the Bi'r Hayzan diatomite is to be analyzed further, it should be sent to a testing laboratory familiar with such tests, or, if tests are done in the Kingdom, specifications and test procedures specified by the American Society for Testing Materials or those published by U.S. military organizations should be followed (Kadey, 1975).

In summary, the discovery of a lake bed in the southern Nafud composed almost exclusively of siliceous diatoms calls for a second stage of exploration and laboratory testing. The extent and volume of the deposit should be determined by mapping, by electrical-resistivity surveys, and possibly by shallow seismic-refraction surveys. Laboratory work should concentrate on species identification and determination of the physical properties of the diatomite. Only when the extent of the deposit and the internal characteristics of the rock material are better known can the economic potential of the deposit be evaluated. Exploration for other diatomite deposits in the Nafud and in the Rub al Khali is also encouraged.

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