Sedimentation in the Lake of Tunis: A Lagoon Strongly Influenced by Man

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ABSTRACT / The Lake of Tunis in northern Tunisia is a eutrophic marine lagoon covering 45 km² to an average depth of 1 m. Exchange of water with the Mediterranean Sea is restricted to a few canals. Bottom sediment is mainly calcareous sandy mud with much organic material. Sand-size grains commonly include quartz, dolomite, gypsum, and pyrite, as well as calcareous skeletal material dominated by molluscan fragments. Pyrite is the only important authigenic mineral presently forming. Principal sources of sediment are sewage sludge and fill, calcareous marine organisms, including abundant worm reefs, and local intermittent streams. The concentrations of Hg, Pb, Cd, Cr, Zn, Cu, and Fe are significantly higher in Lake of Tunis sediments than in sediments from Bahiret el Bibane, an unpolluted lagoon in the south of Tunisia.

Man has affected the Lake of Tunis in four important ways. (1) Cultivation by early settlers, particularly the Romans, caused increased regional erosion and probably provided the sediment that encloses the lagoon. (2) In the mid-1800's the French constructed a ship canal which reduced intralagoonal circulation as well as exchange with the Mediterranean. (3) Nutrient pollution from sewage has encouraged the growth of circulation-restricting worm reefs, caused eutrophication and fish kills, and produced H_2S odor which permeates the city of Tunis during the summer. (4) Finally, man has significantly reduced the size of the lagoon by filling the lagoon and operating salt pans.

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Introduction

The Lake of Tunis is a shallow eutrophic lagoon in northern Tunisia (Fig. 1). Although locally referred to as a lake, it is actually a marine lagoon. One of four major lagoons in Tunisia, it is unquestionably the most polluted. The Lake of Tunis may well have been subjected to longer continuous man-made pollution than any other lagoon in the world.

The Lake of Tunis covers 45² km (Fig. 2). The Gulf of Tunis, an extension of the Mediterranean Sea, lies to the east, separated from the lagoon by a narrow strip of land on which are the small towns of Khereddine and La Goulette. The city of Tunis, with a population of 800,000, borders the lagoon on the west.

Cutting across the lagoon and connecting the Mediterranean with the port of Tunis, a navigation canal divides the lagoon into two basins. Levees on each side of the canal separate the 10 m deep waters of the canal from the lagoon which averages one m in depth. Chekli Island, presumably of artificial origin, lies in the western half of the northern basin.

Direct exchange of lagoon waters with the Mediterranean Sea is limited to a channel that connects the northern basin to the Mediterranean at Khereddine, and another channel connecting the southern basin to the Mediterranean. Smaller channels cut across the levees of the navigation canal and allow exchange with ship canal waters. These channels are approximately 15 m wide and 1.5 deep (Fig. 2).

No perennial natural streams empty into any part of the Lake of Tunis. However, there is considerable drainage into the northern basin from three types of sources (Fig. 2):

1. numerous ditches and one small intermittent stream drain farmlands and urban-suburban development to the north,
2. forty to fifty thousand m³ of waste water per day enter the northern

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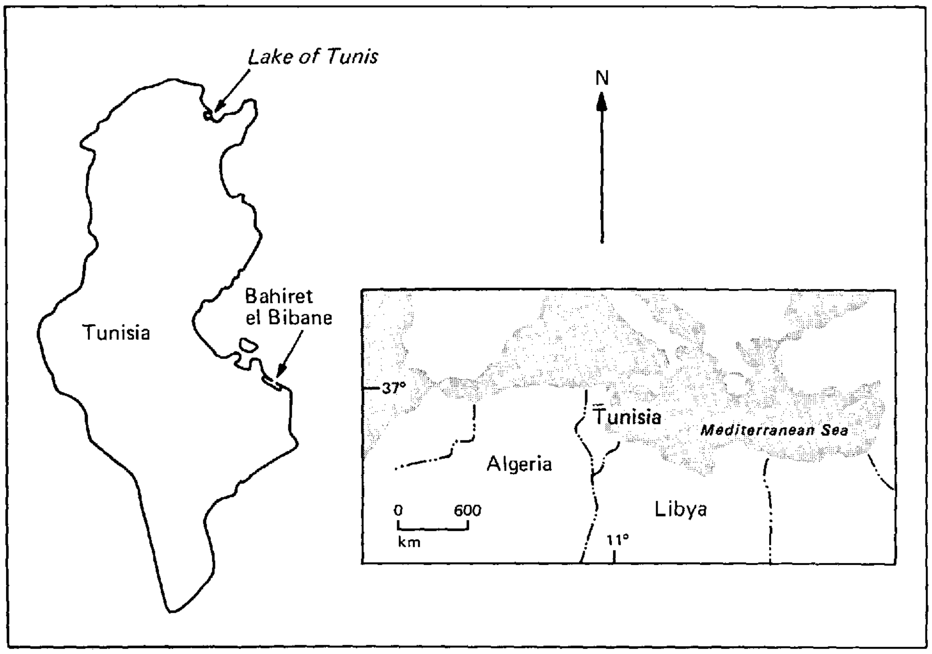


Figure 1. Index map showing the location of the study area.

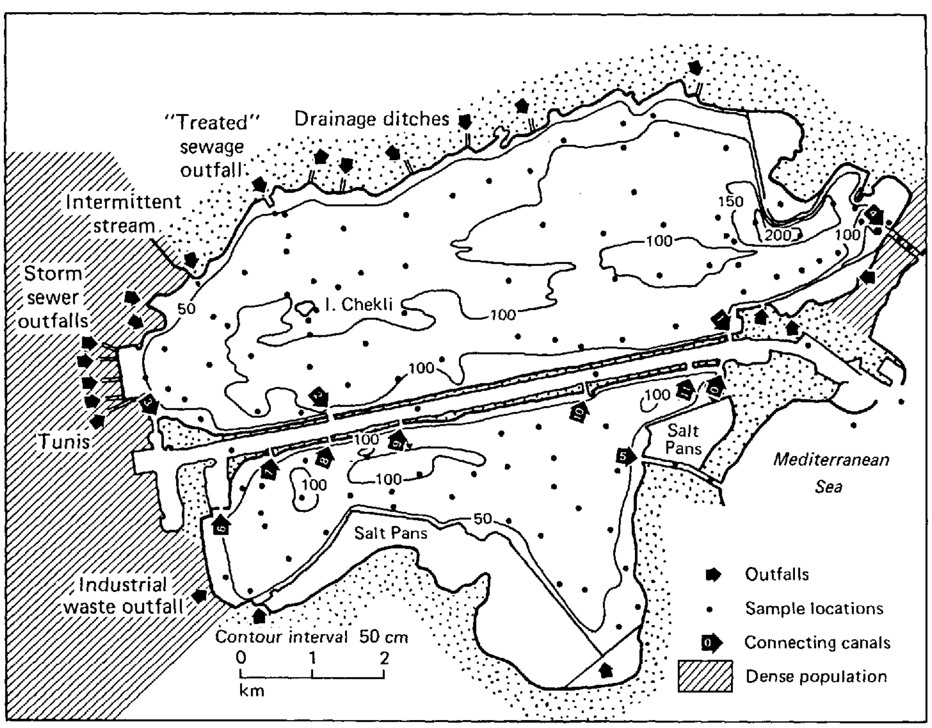


Figure 2. Map of the Lake of Tunis Showing bathymetry and sample locations.

basin from the sewage treatment plant at the sewage outfalls,

3. At least five storm sewer outfalls from the city of Tunis empty into the north lake at the western end.

The southern basin receives industrial effluent from the factories south of the city of Tunis. One small intermittent stream empties into the southern basin.

The climate in this region is arid. Potential evaporation rate exceeds average precipitation. Records of the Tunis-Carthage meteorological station for 1971 indicate precipitation of 438 mm compared to potential evaporation of 1,659 mm. The imbalance was greatest in August and least in February. Strong winds are common. In winter, westerly winds are most frequent, reaching velocities of 28 mps (meters per second) (Zaouali 1971). In summer dominant winds are from the northeast and northwest, with velocities usually much lower than in the winter.

Pimienta (1959) described the sediments in the Lake of Tunis. More recently research has been focused on the eutrophication of the lake (Stirn 1968a, 1968b, 1971). Ecological studies include those of Stirn (1971) and Zaouali (1971).

Pliocene marine sediments consisting of unconsolidated, poorly sorted sand, surround most of the lagoon (Pimienta, 1959). The sand is composed of limestone rock fragments, quartz, feldspar, clay minerals, and minor amounts of mollusc shell fragments and forams. Massive limestone, possibly of Eocene age, is quarried 2 km southwest of the lagoon.

The purpose of this investigation is to determine the parameters of sedimentation and the nature of the sediment in this complex lagoon system.

Origin of the lagoon

This discussion of the evolution of the Lake of Tunis is based on data from Pimienta (1959), Warmington (1967), Brogan (1967), Craig (1967), and Coque (1967), plus sixteenth-century sketch maps of uncertain origin found in the Museum Nationale le Bardo, Tunis.

In the early seventh century B.C., a peninsula extended eastward into the Mediterranean Sea just north of the present Lake of Tunis. This peninsula, on which Punic Carthage was built, was 3 or 4 km wide at its narrowest point and was surrounded by sandy beaches. The area south of Carthage (present-day La Goulette and Khereddine) was part of the Gulf of Tunis and was open to the Mediterranean Sea.

During the second century A. D. a spit began to grow south-westward from the end of the peninsula. Longshore drift supplied sediment from the Medjerda River, 30 km to the north. Erosion in the Medjerda River basin, which supplied the river with 500 km^3 of sediment each year, was accelerated by man's removal of forests. The accumulation of sediment finally obscured the peninsular character of the land around Carthage.

From the fifth to the thirteenth century the spit continued to grow. Although flow past the spit still occurred, isolation of the Lake of Tunis from the Mediterranean Sea had begun. By the sixteenth century the enclosure was complete and the lagoon began to take its present shape. Prior to the sixteenth century, the "salt lake," Sebkha Sedjoumi, was isolated from the Lake of Tunis.

Numerous attempts were made to maintain channels between the lake and the Mediterranean, for they provided the only access to the sea from the city of Tunis. One documented attempt to dredge a canal across the Lake to the city of Tunis was made by Charles V of France in the sixteenth century. The canal, which passed close to Chekli Island where guns controlled access to the city was deep enough for sailing ships. It is not known how long this canal was in use, but in 1855 a much larger canal was built by the French. This navigation canal is still in use today.

Land-fill operations have significantly changed the physiography of the lagoon. At one time a marsh extended to the gate of the Medina, or old city of Tunis approximately one km farther westward than the present lagoon shoreline. This area west of the lagoon has been filled within the last two centuries to allow expansion of the city.

The pollution problem

Although the pollution problem is one of long standing (the Romans complained of an odor from the lake) the constuction of the ship canal in the mid-1800's increased the problem. The ship canal divides the lagoon into two separate basins and greatly restricts the circulation. The combination of poor circulation, shallow depth (average of one meter), and very high nutrient pollution causes eutrophication which results in an obnoxious, permeating odor during summer.

The excess nutrient is contributed mainly by the sewage reaching the lagoon along the northwest shore (Fig. 2) (Stirn, 1968a; 1971). The sewage usually is secondarily treated, but often the sewage plant is overloaded and/or non-functioning and only primary treatment is afforded. Industry is the principal source of pollution in the south lake, but the nature of the industrial effluent is not known. Small amounts of sewage are probably also piped to the southern basin.

Both the north and south basins of the Lake of Tunis are biologically highly productive. Therefore, the lagoon supports an important fishing industry. Fish traps are stationed at all of the channels connecting the lagoon with the ship canal or the Mediterranean Sea. As water temperatures rise during the summer, biologic productivity increases. Salinity also increases owing to increased evaporation and limited exchange with the Mediterranean Sea. The condition triggers a rapid increase in the reproductive spores from algal growth and the biochemical oxygen demand rises until the water becomes anaerobic. Oxygen transfer between the surface waters and the atmosphere stops after a few windless days, and rapid eutrophication occurs (W. Davis, personal communication). This eutrophic state creates favorable conditions for explosive growths of chromic sulfide bacteria. Their high H_2S production, coupled with the high biochemical oxygen demand, creates a toxic condition that affects both vertebrates and invertebrates. The result is a sudden increase in the mortality rates of these organisms and a large contribution of organic and skeletal material to the sediment.

Several solutions have been proposed for reducing eutrophication of the lake, including:

1. Increase the capacity of the sewage treatment plant to eliminate the frequent discharge of raw sewage into the lagoon,
2. Build a pumping station and canal to carry effluent to the ship canal, to a nearby Sebkha, or to the open Mediterranean Sea;
3. Improve water circulation by widening channels, deepening the lagoon, and pumping sea water into the lagoon, or by building one-way tide gates;
4. Build stabilization ponds in which sludge is digested and oxidized by bacteria.
5. Harvest algae before peak die-off periods, to decrease the accumulation of organic matter in the lagoon.

Methods

Field. More than 100 grab samples were taken from the bottom of the Lake of Tunis (Fig. 2). Grab samples were taken by pushing a 5 cm diameter tube 6 to 10 cm into the sediment and retrieving the sample by sealing the top of the tube before removing it. Ordinary sampling devices failed owing to the extremely heavy growth of green algae on the bottom. Surface temperature and salinity in the lagoon were measured during summer and winter. Salinity was measured to the nearest part per thousand with a Goldberg optical refractometer.

Laboratory. Per cent $CaCO_3$ was determined in total samples and in the mud fraction by a standard HCl acid dissolution technique. The percent of mud

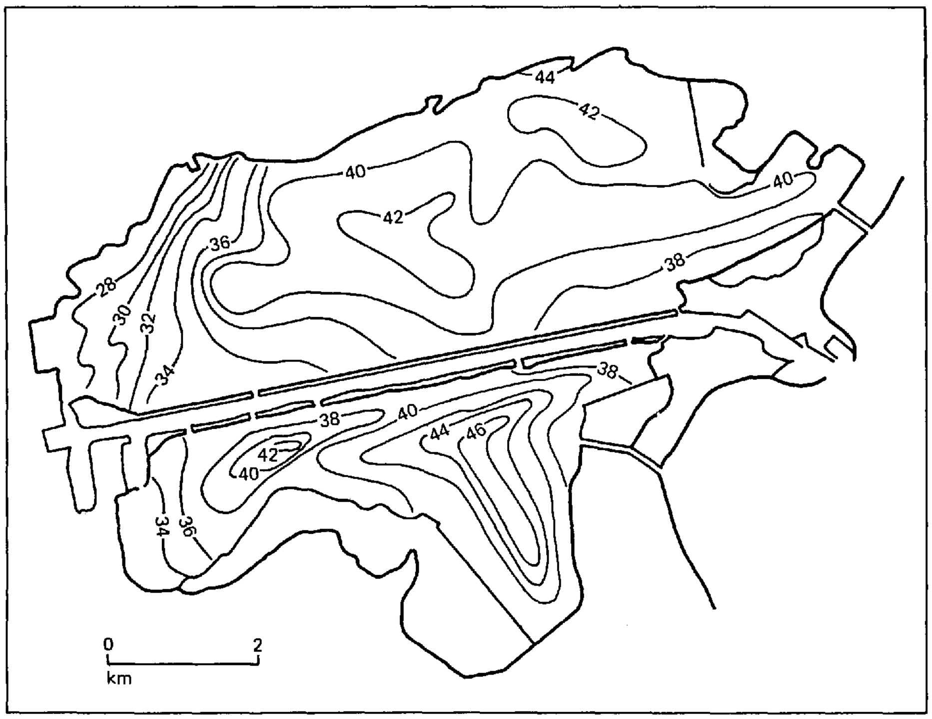


Figure 3. Isohaline map showing salinity distribution in surface waters during June and July, 1973. The contours are based on 90 measurements with an optical refractometer; contour interval 2 ppt.

was determined using the moisture-replicate method (Folk 1968). Carbonate mineralogy was determined by X-ray diffraction. Peak-area ratios of high- and low-Mg calcite, aragonite, and dolomite were compared with similar ratios of known mixtures. Clay mineralogy of 45 samples was determined using standard techniques. The constituents in 20 samples of the sand fraction were identified by studying the sand mounted in glass slides. Organic matter in lagoon surface samples was analyzed by the percent-loss-on-ignition technique (Ball 1964).

Sediments to be analyzed for mercury were dried to remove excess water, ground, and dried again at 45° C prior to weighing.

Three one-half gram fractions of each sample were weighed and digested with 5 ml of concentrated nitric acid and 8 ml of concentrated sulfuric acid in a water bath at 70° C for at least 17 hours. Samples were then oxidized with potassium permanganate and potassium persulfate for 24 hours. Reduction of excess permanganate was accomplished by hydroxhyamine hydrochloride, followed immediately by vaporization with stannous chloride. The concentration of mercury was determined with a Coleman MAS-50 cold vapor spectrophotometer.

The following procedure was used to determine Pb, Cd, Cr, Cu, Fe, Za, and Mn. A 5 g fraction of the sample was burned at 500 ° C for 48 hours. The sediment was then oxidized with 5 ml of concentrated nitric acid and dried on a hot plate. Next, the material was filtered through a 0.45 μ millipore filter. The concentration of metal was determined by a flame spectrophotometer (Varian AA6).

Water Characteristics

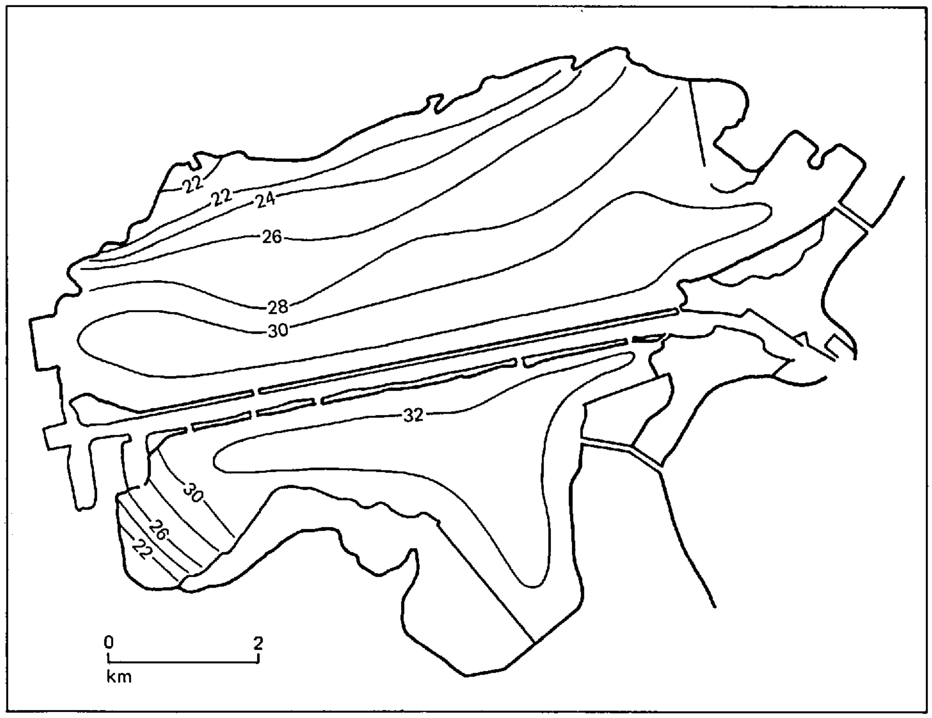
The isohalines for the months of June and July, 1973, are based on 90 data points widely distributed throughout the lagoon (Fig. 3). During this time of year the winds, the major driving force of water circulation, push water to the southwest. This restricts the influx of low-salinity water from Tunis to the western margins of the lagoon, from where it is forced into the ship canal and ultimately into the Mediterranean Sea. The crowded isohalines near the city clearly show this effect. Salinities range from 28 ppt near Tunis to 47 ppt in the center of the south basin. Water temperature during this time of year ranges between 25° and 30° C.

During the winter, because of the reversal of dominant wind direction, lateral salinity gradients tend to be more constant throughout the entire lagoon. The pattern indicates that low-salinity water from Tunis is pushed to the east (Fig. 4). The salinities average 10 ppt lower during the winter because of higher rainfall. In the north basin salinity ranges from 20 to 30 ppt and in the south basin, from 22 to 32 ppt. The south Lake of Tunis has a higher winter salinity than the north lake because a relatively small area of land drains into this part of the basin. Fig. 4 is based on 50 data points obtained during February, 1973. During the same period water temperatures ranged from 8° C to 12° C.

Circulation in the lagoon is dominated by wind. Tides play a secondary role. Maximum spring tides are about one m. (Habib Ben Alaya, personal communication). Circulation in the basins is very sluggish, which adds to the eutrophication problem. The circulation of water in the northern basin is greatly restricted by the presence of polychaete worm reefs, which grow to within a few cm of the low tide water surface (Fig. 5).

Water clarity varies greatly in the lagoon. At the east end of both the north and south lagoons the water is sufficiently clear that features on the bottom can

Figure 4. Isohaline map showing salinity distribution in surface waters during February, 1973. Contours are based on 50 measurements; contour intervel 2 ppt.



be seen during all seasons. Clarity gradually decreases westward. From Chekli Island westward, the water usually is opaque.

During all seasons algae accumulate on the surface, particularly toward the west end of the lagoon. The algae, dominantly *Ulva,* are in varying states of decomposition. These accumulations are particularly extensive during the summer.

Worm Reefs

Three species of polychaete worms are present in the lagoon: *Mercierella enigmatica, Hydroides norvegica,* and *Hydroides unicata* (Zaouali 1971).

The tubes of all three species of worms are composed almost entirely of high Mg calcite, but trace amounts of aragonite occur in some samples.

Mercierella enigmatica, the most abundant of the three species, is found mainly in the northern basin where it grows in massive colonies to within cm of the water surface. These reefs serve as substrate for other organisms, such as barnacles and bryozoans, and as traps for detrital sediment. Zaouali (personal communication) has found that many of the reefs in the western portion of the northern basin are being killed off by an encrusting bryozoan, *Conopeum seurati,* though none was observed by the authors, Zaouali (personal communication) has found *Hydroides norvegica* forming small reefs in the eastern portion of the southern basin, near the Mediterranean channel. The prolific growth of worms in the northern basin is assumed to be due

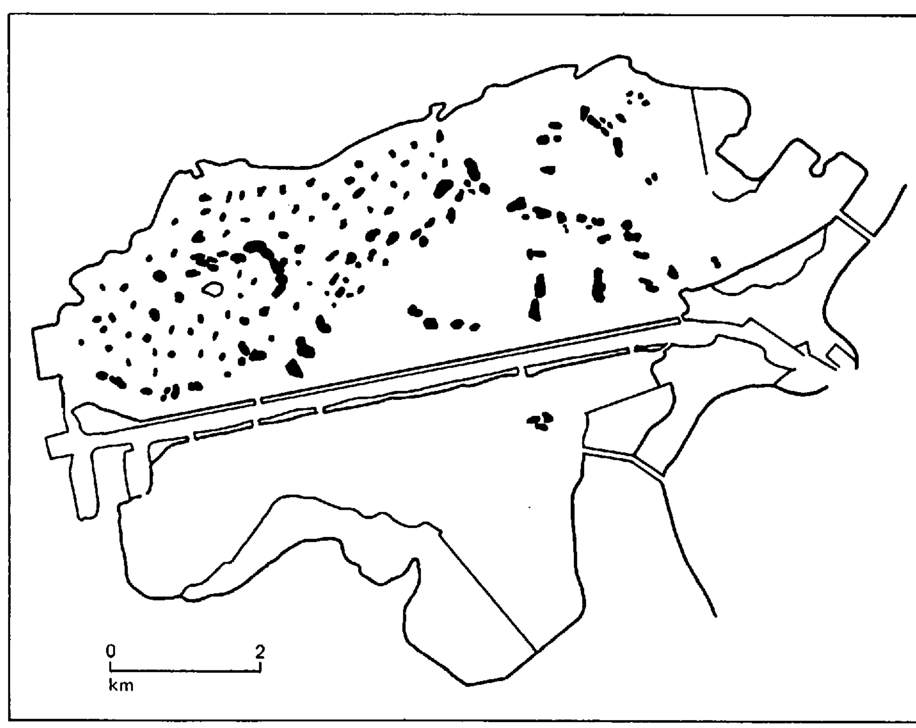


Figure 5. Partially diagrammatic illustration of the areal distribution of serpulid worm reefs in the Lake of Tunis.

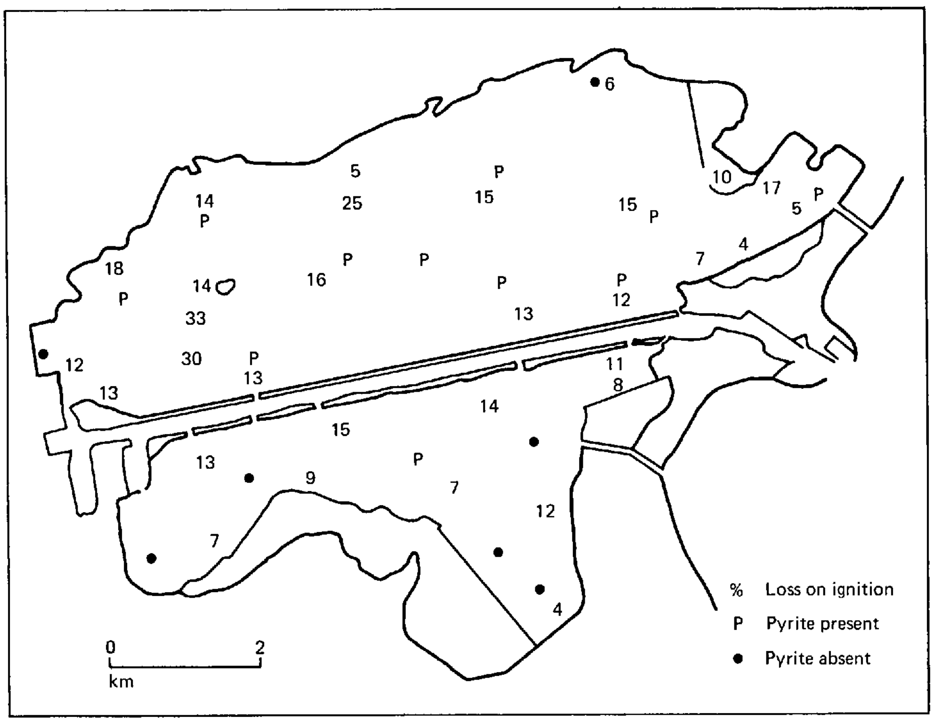


Figure 6. Percent organic matter in Lake of Tunis sediments expressed as weight loss on ignition. Also shown on the figure are locations where pyrite was observed in the mud size fraction.

to the high nutrient content of the waters there. Worm reefs occasionally are exposed briefly to subaerial conditions when strong winds combine with spring tides. In such instances, worm reefs on the upwind side of the lagoon may be exposed.

Study of cores (Scott Thornton, personal communication) indicate that the serpulid worm reefs began growing after the French ship canal was constructed in 1856. However, Peres (1967) suggested that this species of worms may have been introduced into the Mediterranean via the Suez Canal. Lucas (1959) argued that reef formation began in Lake of Tunis about 1931. His observations recorded in 1956 indicate that the reefs at that time were much smaller and less extensive than they are now (1974).

The reefs play an important role in restricting lagoon circulation, which enhances eutrophication. The reefs range from circular patch reefs less than 1 m in diameter to ridges 100 m or more long. All the reefs rise abruptly and vertically from the lagoon floor. They are a hazard for small boats and reduce access to the lagoon. The reefs are rather fragile but are sufficiently strong to withstand the weight of a person, at least in the center of a patch. An individual patch can be broken up or fragmented with a boat paddle.

Lagoon Sediments

Mud

Fig. 7 shows the distribution of sediment less than 63 microns in size in 14 selected samples. The percentage of mud ranges from 15 percent to 96 percent. The average values in the northern basin are higher than in the southern basin. The mud is composed of quartz, feldspar, clay minerals, low Mg calcite, high Mg calcite, aragonite, and dolomite. Pyrite is locally present in certain areas as are large amounts of organic matter.

There are several possible sources of sediment finer than 63 microns in the Lake of Tunis: (1) local streams, (2) dust storms, (3) Mediterranean Sea, (4) shoreline erosion, (5) authigenesis (pyrite), (6) calcareous marine organisms, (7) organic matter (algae), and (8) man-made sludge and land fill.

Man's activities generate most of the present-day lagoon sediment. Sludge is the most abundant sediment, and land fill material is next most abundant. Local streams contribute the third largest volume of sediment, although in the past streams must have been the most important source. Sludge, land fill sediment, and fluvial material are all much less important in the south basin. Since the construction of the ship canal, the rate of sedimentation in the south Lake of Tunis probably has been very small relative to the rate in the northern basin.

Carbonate sediment: Carbonate minerals comprise 7 to 51 percent of the mud. More than 50 percent of the mud carbonate fraction is low-Mg calcite. Most of the carbonate sediment is probably detrital, deposited by winds or derived from the fine fraction of the soil within the drainage basin, which is covered mainly by limestones.

Aragonite and high-Mg calcite presumably are of biogenic origin. Dolomite, comprising as much as 14 percent of the carbonate material, occurs throughout the lagoon and in the navigation canal. The dolomite occurs only in the silt-size fraction of the mud. Pimienta (1959) suggested that dolomite is precipitating directly from the lagoon waters. However, he presented little evidence to substantiate this hypothesis. The ubiquitous distribution and the grain size of the dolomite in the Lake of Tunis suggests it has a detrital source, perhaps both aeolian and fluvial.

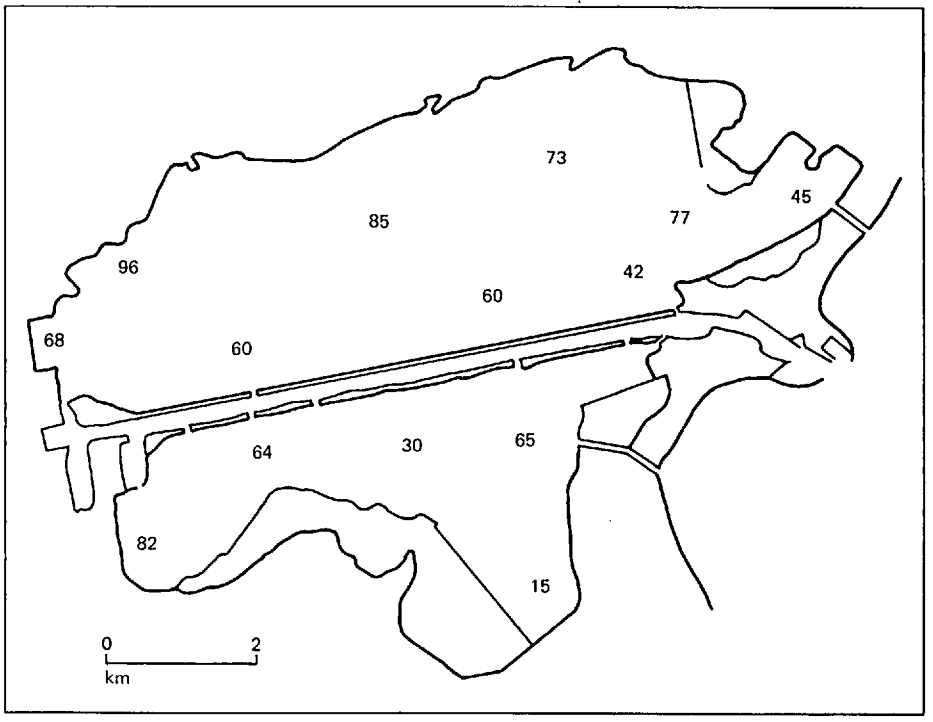


Figure 7. Percent mud in selected Lake of Tunis samples.

Clay minerals. Kaolinite, montmorillonite, and clay mica are the most abundant clay minerals in the less than 2 micron size-fraction. Vermiculite, chlorite, and mixed layer clays, as well as quartz and feldspar are present in minor amounts.

Organic matter and pyrite: The highest values for percent loss-on-ignition, some as high as 30 percent, occur for samples from the northern basin where eutrophication is most extensive (Fig. 7). Similarly pyrite, which occurs in the less than 63 micron size fraction, is more abundant in the northern basin than in the southern basin. This abundance is probably due to the high concentration of organic compounds which can be used by sulfate-reducing bacteria to produce hydrogen sulfide (Berner 1971). The organic compounds can be derived from dead organisms which accumulate in the lagoon as a result of eutrophication. Dissolved sulfate, a second limiting factor in the formation of pyrite, is readily availabe from the lagoon waters (Zaouali 1971). Iron compounds, a third limiting factor, can be obtained from detrital sediment, especially the clay minerals which often have absorbed ferric oxide coatings (Carrol 1958).

Sand-size sediment

Inasmuch as gravel is not common in the sediments, the distributions of sand-sized material can be inferred from Fig. 6, by subtracting the silt plus clay fraction from 100 percent. The south basin contains more sand than the north basin because dilution by sludge in the western part of the northern lagoon reduces the sand percentage.

Sources of sand in the Lake of Tunis include (1) local streams, (2) Mediterranean Sea, (3) shoreline erosion, (4) land fill, (5) calcareous marine organisms, and (6) wind.

Calcareous material are always greater than 92 percent of the sand fraction of the north Lake of Tunis sediments. In the south lagoon, non-calcareous particles, mostly quartz, make up 15 to 30 percent of the sand fraction. In both basins the quartz content of sands increases in the immediate vicinity of the channels leading to the Mediterranean. The following is a brief summary of the principal sand size components.

Quartz. Clear, non-pitted, sub-angular to rounded grains of quartz occur throughout the lagoon, principally as fine sand.

Gypsum. Medium sand-size crystals of gypsum are present in all lagoon sediment samples, but usually comprise less than 1 percent of the sand. The stubby blade form crystals are clear or cloudy owing to inclusions, and are occasionally twinned. Many crystals are pitted and rounded. Other crystals have perfect crystal form, and some have shell fragments as inclusions.

Kinsman (1969) concluded that gypsum crystals formed within a Sebkha environment are stubby and cloudy, whereas elongate, clear crystals are characteristic of direct precipitation from seawater. The form of Lake of Tunis gypsum crystals, their size distribution and their ubiquitous nature suggest that most of the gypsum is detrital. The most likely source is Sebkha Sedjoumi, one mile to the west. Wedman (1964) noted that wind deflation is an important process for the removal of evaporite grains from Sebkha Sedjoumi. The source of the unabraded gypsum crystals may be the salt pans adjacent to the lagoon.

Rock fragments. Angular to rounded rock fragments composed of quartz and fine-grained limestone comprise 1 to 15 percent of the sand in the lagoon. Similar rock fragments are abundant in the sand fraction of the soil adjacent to the la-

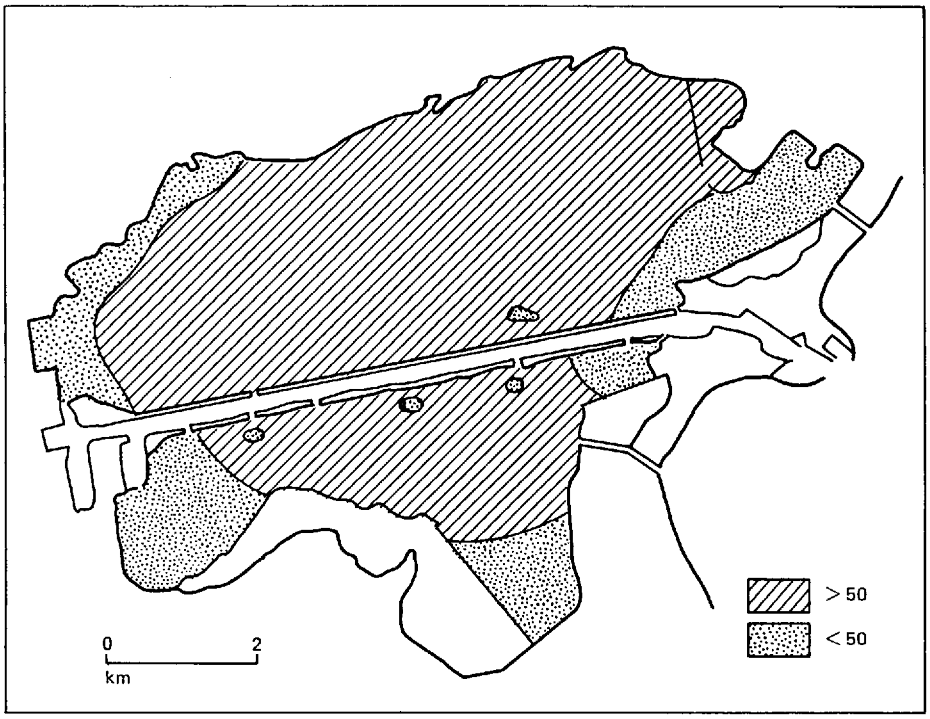
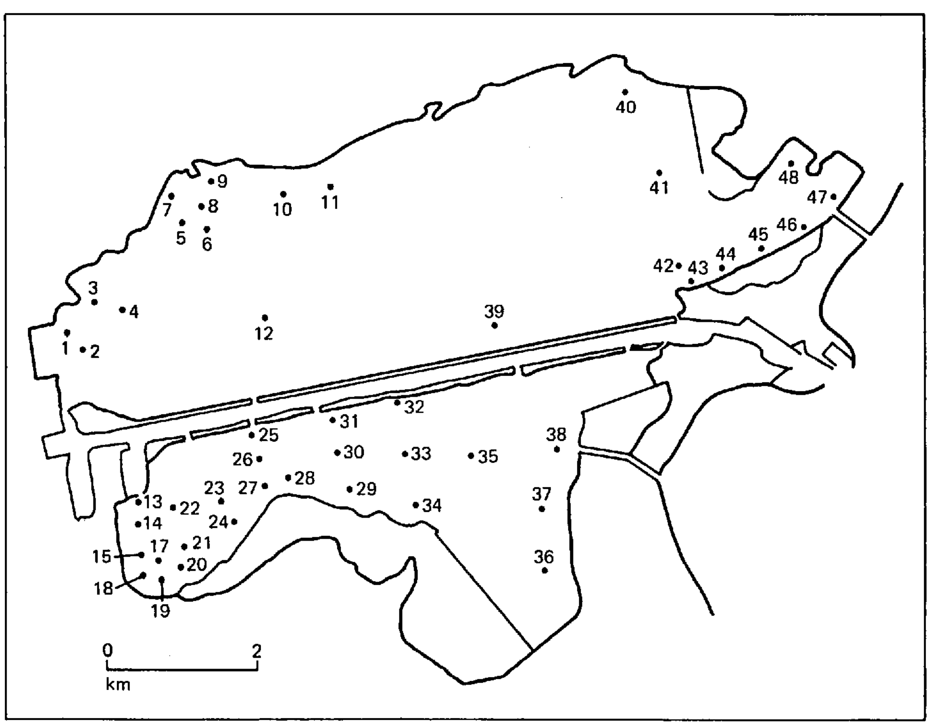


Figure 8. Percent $CaCO_3$ in the Lake of Tunis sediments based on analyses of over 100 samples.

Figure 9. Location map of samples used for heavy metal analyses.



goon, which is the most likely source of the lagoonal rock fragments.

Heavy minerals. Heavy minerals are very minor constituents, usually comprising less than 1 percent of the sand fraction. The mineral suite is a stable one, reflecting a sedimentary provenance. The suite is identical to the one reported from adjacent beach sands by Watkins and Pilkey (1973).

Biogenic constituents. As much as 95 percent of the sand in certain areas of the lagoon is composed of biogenic fragments. The biogenic constituents are largely the tests of benthic fauna, of which there are relatively few species, but large numbers of individuals (Zaouali 1973). *Hydrobia ventrosa* is the most common of the gastropods. As many as 36,500 and 36,300 individuals per square meter were counted at the center of the northern and southern basins, respectively (Zaouali 1973). *Pirenella conica,* a gastropod characteristic of reducing environments with high organic content, is also present in the lagoon. There are ostracodes in both the northern and southern basins, comprising as much as 5 percent of the sand. Barnacles, *Balanus amphitrite,* live within the worm reefs of the northern basin, but their contribution to the sediment is minor.

Worm-tube fragments usually make up a surprisingly low percentage, less than 5 percent of the sand-size bottom sediment in the northern basin. However, occasional patches of sediment are composed almost entirely of worm tubes. The tubes are more abundant in the greater than sand size fraction of the sediment, which also includes pelecypod shells, and usually represents less than 15 weight percent, of the total sample.

Semi-consolidated fecal pellets are whitish gray to dark gray and are either rod-like or ovoid. Their mineral composition is similar to the muds found in the lagoon, which would be expected if they are formed from the sediment ingested by burrowing organisms (Moore 1953). Fecal pellets are about twice as abundant in the southern basin (12 percent average) as in the northern (6 percent average). Sponge spicules and echinoid fragments are minor skeletal constituents which are largely restricted to the north Lake of Tunis near the channel to the Mediterranean.

Total $CaCO_3$ content

The areal distribution of total $CaCO_3$ content of lagoon sediments is shown in Fig. 8. The values do not include samples composed entirely of worm reef material. The average content calculated for the northern basin is 64 percent and for the southern basin, 48 percent. If the abundant worm reefs are included the $CaCO_3$ productivity of the north Lake of Tunis far exceeds the productivity of the south basin.

Most of the total $CaCO_3$ content of lagoon sediments is produced by molluscs, ostracodes, and forams. Sludge dilutes the sediment in the western portions of the lagoon and probably is responsible for a lower $CaCO_3$ content there. In other parts of the basin there are small protected areas of sediment with low $CaCO_3$ content where fine muds accumulate.

Heavy metals

If the Lake of Tunis can be considered to be one of the world's most continuously polluted lagoons, Bhairet el Bibane, a lagoon in the south of Tunisia (Fig. 1) may be one of the world's least polluted. This lagoon may be a good analog of the pre-French ship-canal Lake of Tunis. The only important effect of man on Bahiret el Bibane probably would be related to extensive local overgrazing by goats and camels, which increases the dust and flash flood contribution to the lagoon. Other than a few Bedouin encampments, the only human habitation near the lagoon is a small fishing village. Bahiret el Bibane is larger than the Lake of Tunis, covering 300 square km in a trough-shaped basin with a maximum depth of 6 meters. Salinites reach values as high as 49 ppt. A channel about 200 meters wide averaging less than 2 m in depth, allows exchange be-

Table 1 Heavy Metals in Lake of Tunis Sediments

ppm dry weight of total samples

Station number	Loss on ignition(%)	Hg	Cd	Cr	Cu	Fe (×100)	Pb	Mn	Zn
1		3.55 ± 1.7							
2	31	.96 ± .12	2.2		>200		90	48	594
3	35	5.54 ± .19			>350		>350	98	
4	27	3.39 ± .32	2.5		>300		159	34	>667
5		.53 ± .05	>10.0	>200	>250		>350	107	>800
6	16	.52 ± .07	1.6		54		64	58	250
7	33	.95 ± .09	3.1		194		168	42	>827
8		1.78 ± .58	1.4		13		42	60	99
9	34	2.27 ± .33	2.2		>300		139	43	>774
10	33	1.00 ± .01							
11		.54 ± .15	1	10	27			45	103
12	18	.38 ± .03	6	5	8		57	20	48
13	22	1.23 ± .14	13.3	325	>150				
14		.56 ± .20		12	357				
15	36	1.23 ± .04	30	>125	>300		164	12	>749
16		1.06 ± .17							
17	17	1.43 ± .23	3.5	55					
18		.86 ± .20	12.3	357	>150			55	
19		.97 ± .39							
20	24	.94 ± .11	.4	347	1	.03	1		
21		1.43 ± .17	3.7	347	43			93	
22		.83 ± .08							
23		1.36 ± .06							
24		.95 ± .12							
25		.63 ± .02							
26	22	1.35 ± .17	.1	12	2	.14	2	1	3
27	10	.59 ± .32	4.0	49	14		100		
28		.30 ± .01							
29	29	.63 ± .19	1.5	16	10			39	
30		1.17 ± .13							
31	13	1.24 ± .30	1.6	12	3		38	2	29
32	19	.68 ± .12	3.6	12	16		233	18	98
33		.63 ± .05							
34		.40 ± .01							
35		.62 ± .09							
36		.35 ± .05							
37		.58 ± .03							
38		.44 ± .14			1		1		
39		.25 ± .11							
40		.61 ± .14	.2	14	12		40	65	
41		.29 ± .06	.3	5	6		27	8	34
42		.30 ±							
43	18	.25 ± .01			17		22	53	60
44	18	.21 ± .10			34		42	96	130
45	12	.20 ± .03			14		27	24	40
46		.19 ± .11							
47		.21 ± .13							
48	5	.09 ± .01	.1	4	1	.8	1	5	1

Table 2 Heavy Metals in Lake Bibane Sediments

ppm dry weight of total samples

Sta	Loss on ignition(%)	Hg	Cd	Cr	Cu	Fe (×100)	Pb	Mn	Zn
1	5	.01 ± <.005	.8	1.0	2.0	.4	7.0	37	4.7
2	6	.03 ± .02	.5	1.0	2.0		2.0	21	6.9
3	10	.01 ± <.005	.4	2.2	1.2	.3	2.3	15	6.2
4	9	.02 ± <.005	.3	6.7	3.0	4.2	2.0	99	12.1
5	4	.01 ± .01	.7	3.5	4.0	.9	.4	24	5.7
6	14	.02 ± .01	.3	4.2	1.3	1.2	2.2	37	7.9
7	6	.01 ± .01	.3	1.0	1.9	.7	1.9	18	4.4
8	17	<005 ± .01	.2	3.2	1.7	.8	1.7	21	6.6
9	7	<.003 ± .01	.3	5.2	.7	1.1	3.2	18	3.8
10		.01 ± .05	.1						
11		.02 ± .02	.1						
12		.02 ± .01							
13	20	.10 ± .03				1.6		>100	
14	22	.22 ± .14					3.7	102	

tween the lagoon and Mediterranean waters. Lagoon sediment is derived from the surrounding desert by wind and sheet wash; from the Mediterranean by tidal exchange; and from calcareous marine organisms.

Tables 1 and 2 compare heavy metal concentrations in Lake of Tunis and Bahiret el Bibane. The values represent analyses of total samples. There is remarkable uniformity of heavy metal concentrations in sediments from Bahiret el Bibane, so no sample location map of that area is presented.

Mercury in Lake of Tunis sediment ranges from 0.19 ppm to 3.5 ppm. Mercury in Bibane sediments is less than 0.005 ppm to 0.22 ppm. There is a clear-cut trend in the areal distribution of Hg in the Lake of Tunis. Mercury is most abundant in sediments near the city of Tunis. Lead ranges from 0.5 to 223 ppm in the Lake of Tunis compared to a range of 0.3 to 7.0 ppm in Bibane. However, unlike Hg, there is no obvious trend in the areal distribution of this metal. Lake of Tunis sediments contain between 0.10 to 13.3 ppm Cd compared to an 0.10 to 0.75 ppm in Bibane. There is a clear trend of higher Cd values near the city. Chromium exhibits the best developed areal trend in distribution in Lake of Tunis sediments. Near Tunis, Chromium concentrations are 110 to 400 ppm, whereas in the entire lagoon, Chromium ranges from 4 to 400 ppm. This compares with a range in Bibane of 1 to 6.7 ppm. Zinc, copper and iron are more abundant in the Lake of Tunis than in Bahiret el Bibane. The high iron content of Tunis Lake sediments must reflect the pyrite content of the sediment (Fig. 7). Iron and Zinc seem to be distributed randomly through out the Lake of Tunis, but Cd is most abundant in sediments near the city. Manganese occurs in similar concentratious in both lagoons. Interpretation of the results is difficult because the heavy metal analyses are of total sediment samples, rather than of the various size fractions of the samples. Bibane sediments are sandier than Lake of Tunis sediments, but clay mineralogy of the two lagoons is similar (Keer, 1975), and percent mud is similar in sediments from the two lagoons. Thus these preliminary data are somewhat indicative of the extent of pollution in the Lake of Tunis. The concentrations of heavy metals are high relative to other sedimentary environments (Mathis and Commings 1971, Aston and others 1974, Klein 1975, Kronfeld and Naurot 1975, Nelson and others 1975). The data further suggest that a detailed comparison of heavy metal chemistry in the two lagoons may afford an unusual opportunity to study methods of heavy metal disperal and concentration.

Summary

The lake of Tunis lagoon is divided into two basins by a ship canal which greatly restricts circulation. Winds are the most important cause of circulation, whereas tides are of secondary importance. The north basin differs from the south basin in several respects. North Lake of Tunis sediments have a higher mud content, higher organic carbon content, and larger amounts of $CaCO_3$ than south Lake of Tunis. Pyrite is present only in the north part. The south Lake of Tunis has a slower rate of sedimentation because few ephemeral streams empty into it. The south lake has no source of sludge, and biological productivity is lower than in the north lake. Polychaete worm reefs are widespread in the north lake and are a major cause of reduced circulation which enhances eutrophication.

Sources of bottom sediment in the Lake of Tunis include: adjacent streams, wind blown material, sludge and industrial effluent, authigenesis, calcareous marine organisms, shoreline erosion, land fill, and the Mediterranean Sea. Sewage sludge, calcareous marine organisms and local streams currently furnish most of the sediment.

All the heavy metal elements analyzed except Mn, occur in significantly higher concentrations in the Lake of Tunis than in the unpolluted Bahiret el Bibane. Pb, Fe and Zn appear to be randomly distributed throughout the lagoon. Hg, Cd, Cr, and Cu exhibit highest concentrations in sediment samples nearest the city of Tunis. There are no consistent differences between north and south Lake of Tunis sediments.

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REFERENCES

Aston, S. R., 1974, Stream sediment composition, an aid to water quality assessment: Water, Air and Soil Pollution, v. 3, 29 p.

Ball, D. F., 1964, Loss on ignition as an estimate of organic matter and organic carbon in non-calcareous soil: Jour. Soil Sci., v. 15, p. 84–95.

Berner, R. A., 1971, Principles of chemical sedimentology: New York, McGraw Hill Book Co., 240 p.

Brogan, O., 1967, Roman Tunisia, *in* Guidebook to the geology and history of Tunisia: Libya Petroleum Exploration Soc. of Libya, 9th Ann. Fld. Conf. Guidebook p. 17–35.

Carroll, D., 1958, Role of clay minerals in transporting iron: Geochim. et Cosmochim. Acta, v. 14, p. 1–29.

Craig, L., 1967, Arab Tunisia, *in* Guidebook to the geology and history of Tunisia: Libya Petroleum Exploration Soc., 9th Ann. Fld. Conf. Guidebook p. 37–48.

Coque, J., and A. Jauzein, 1967, The geomorphology and Quaternary geology of Tunisia, *in* Guidebook to the geology and history of Tunisia: Libya Petroleum Exploration Soc., 9th Ann. Fld. Conf., Guidebook, p. 227–258.

Folk, R. L., 1968, Petrology of sedimentary rocks: Austin, Texas, Hemphills, 170 p.

Glennie, K. W., 1970, Desert sedimentary environments: New York, Elsevier Co; Developments in Sedimentation 14, 198 p.

Grim, R. E., 1965, Clay mineralogy: New York, McGraw Hill Book Co., 582 p.

Keer, F., 1975, Sediments of Bahiret el Bibane: Duke Univ., unpub. M.S. Thesis 85 p.

Kinsman, D. J. J., 1969, Modes of formation, sedimentary associations and diagnostic features of shallow-water and supratidal evaporites: Am. Assoc. Petroleum Geologists Bull., v. 53, p. 830–840.

Klein, D. H., 1075, Fluxes, residence times and sources of some elements to Lake Michigan: Water, Air and Soil Pollution, v. 4, p. 3–8.

Kronfeld, J., and J. Naurot, 1975, Aspects of trace metal contamination in the coastal rivers of Israel: Water, Air and Soil Pollution, v. 4, p. 127–134.

Levy, Y., 1974, Sedimentary reflections of deposition environment in the Bardawil Lagoon, Northern Sinai: Jour. Sed. Petrology, v. 44, p. 219–227.

Lucas, G., 1959, Deux exemples actuels de biolithosores construits par des Annelides: Bull. Soc. Géol. de France, v. 1, p. 385–389.

Mithis, B. J., and N. R. Kevern, 1973, Distribution of mercury, cadmium, lead, and thallium in a eutrophic lake: Michigan State Univ. Inst. Water Res., Tech. Rept. 34, 23 p.

Moore, H. B., 1955, Faecal pellets in relation to marine deposits, *in* Trask ed., (Marine Sediments) Soc. Econ. Paleon. and Min., Spec. Paper 4., p. 516–524.

Nelson, C. H., D. E. Pierce, K. W. Leong, and Frank F. Wang, 1975, Mercury distribution in ancient and modern sediment of Northeastern Bering Sea: Marine Geology, v. 18, p. 91–104.

Peres, J. M., 1967, The Mediterranean benthos: Oceanography and Marine Biology Annual Review, v. 5, p. 449–533.

Pimenta, J., 1959, Le cycle Pliocène-Actuel dans les bassins paraliques de Tunis: Société Géologique de France, Mem. no. 85, 27 p.

Shepard, F. P., 1973, Submarine geology: New York, Harper and Row, 3rd ed., 517 p.

Stirn, J., 1968a, The pollution of the Tunis Lake: Revue Internationale d'Océanographie Médicale, Tome IX, p. 99–106.

——— 1968b, The consequences of the increased sea bioproduction caused by organic pollution and possibilities for the protection: Rev. Intern. Oceanogr. Med., Tome X, p. 123–129.

——— 1971, Ecological Consequences of Marine Pollution: Rev. Intern. Oceanogr. Med., Tome XXIV, p. 13–46.

Warmington, B. H., 1967, Phoenician Carthage, *in* Guidebook to the geology and history of Tunisia: Libya Petroleum Exploration Soc., 9th Ann. Fld. Conf., Guidebook p. 5–16.

Watkins, J., and O. H. Pilkey, 1973, Le Sable des plages tunisiennes: Notes du Serv. Geol., no. 39, 41 p.

Wedman, E. J., 1964, Geohydrology of Sebkha Sedjoumi's (Tunisia): Internat. Assoc. Scientific Hydrology, pub. 64, 67 p.

Zaouali, J., 1971, Etude de l'écologie du Lac de Tunis et de la Mer de Bougrave (Tunisie), leurs peuplements malecologiques: L'Université de Caen, France, unpub. dissert., 254 p.