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The influence of peripheral sabkhas on the geochemistry and sedimentology of a Tunisian lagoon: Bahiret el Biban

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ABSTRACT

Bahiret el Biban is a restricted lagoon in an arid climate. The general geological setting is briefly analysed, especially with respect to the relations between the water body and its evaporitic bordering areas, i.e. supratidal sabkhas.

The geochemical behaviour of the lagoon waters has been studied over a 2-year period following floodings. In spite of some exchange with the open sea, there is a general tendency towards increasing salinity, calcium sulphate impoverishment and a consequent increase of the Mg/Ca ratio. Thus, unless large floodings occur, the basin waters undergo an evaporitic evolution.

Sedimentation and early diagenesis are controlled largely by this geochemical pattern, but also by exchange with the open sea and by the water depth. Organic matter derived from the sea is deposited on entering this highly saline basin and locally produces sediments which could eventually become source rocks.

Bahiret el Biban is a possible model which may be of considerable interest in the reconstruction of the early stages of the evolution of evaporitic basins.

INTRODUCTION

Bahiret el Biban is a coastal lagoon in SE Tunisia (Fig. 1). It merits studying for at least two reasons: first, under the conditions of aridity affecting this region, evaporation largely exceeds precipitation plus run-off during long periods. Secondly, the restricted communications between the lagoon and the open sea (Gulf of Gabes) lead to the confinement of this basin. Also, the most important fishery of Tunisia is located near the main communication at El Biban. It is hoped that progress in the knowledge of the geochemistry of the lagoon may help to improve its fish production.

The present study is an attempt to analyse the mechanisms which control both the geochemistry of the lagoonal waters and modern sedimentation.

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GEOGRAPHICAL AND GEOLOGICAL SETTING

Morphology

Bahiret el Biban (sometimes called El Biban lake or laguna) covers approximately 230 km^2. It has an ovoid shape being 32 km long and 8·5 km wide. The maximum depth of 6·5 m occurs along the main axis of the basin (Fig. 2). At low tide, the water body occupies an approximate volume of 0·81 km^3 (Medhioub & Perthuisot, 1977).

Climatic conditions

The wide coastal plain of southern Tunisia, the so-called 'Jeffara maritime' has a desert climate slightly attenuated by the proximity of the sea. During the hot season (May to September) the mean temperature is about 28 °C while the winter mean temperature is 15 °C (Perthuisot, 1975a).

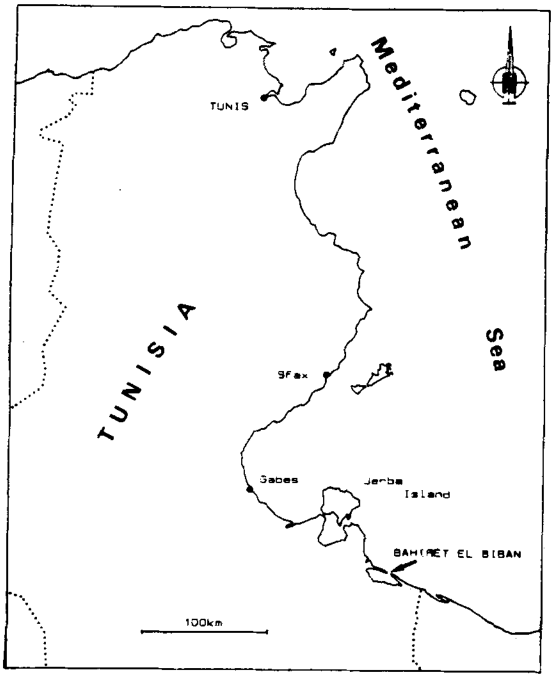

Fig. 1. Geographical setting of Bahiret el Biban.

Breezes and winds induce drift along the shores of the lagoon and slow rotation of peripheral water masses.

The mean annual rainfall is about 200 mm in Ben Guirden but precipitation is very irregular with episodic catastrophic floodings followed by long periods of drought which may extend over several years (Fig. 3).

The humidity, due to the proximity of the sea explains the rather low potential evaporation rate which is near 2500 mm y^{-1}. Experimental data from Sabkha el Melah near Bahiret el Biban give values of 2 or 3 mm day^{-1} for evaporation of highly concentrated brines (350 g l^{-1}) (Floridia, 1971).

The continental margins of Bahiret el Biban

The southern shore of the basin shows three types of morphology:

(1) Low plateaus whose constituent rocks are, from top to bottom: Villafranchian, continental, reddish calcrete with *Helix* shells, known by the geologists of Tunisia as 'calcaire saumon à hélicidés'; it is generally covered by a layer of Würmian silt

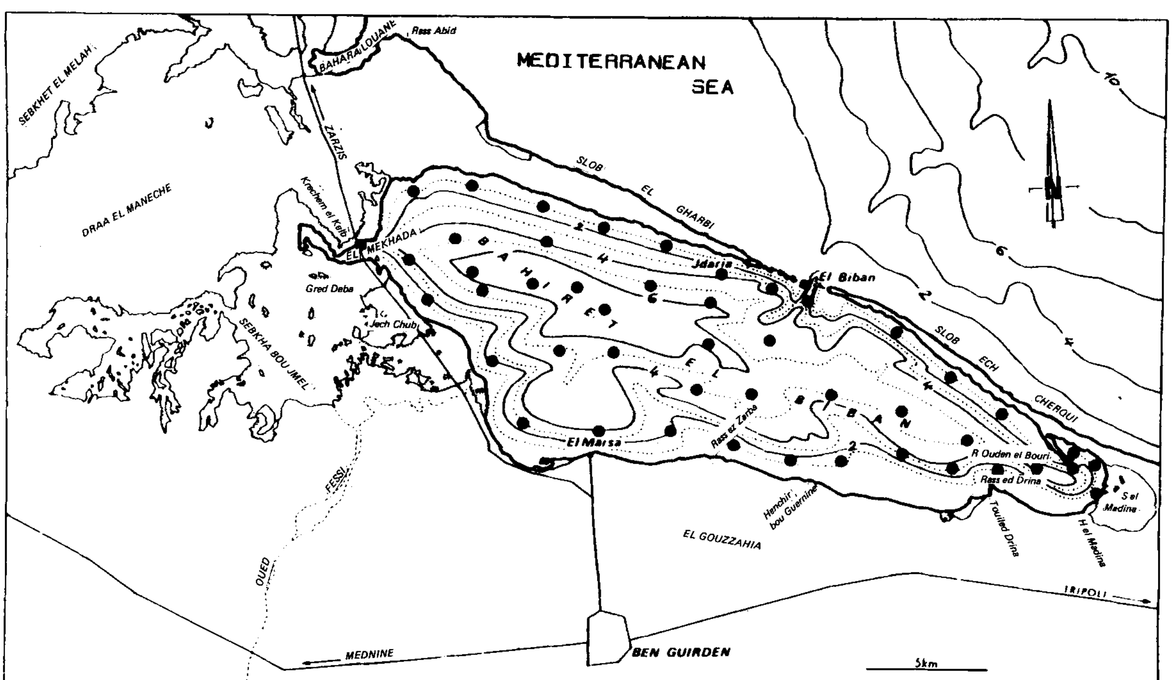

Fig. 2. Geographical setting of Bahiret el Biban. Water depth in metres. Black dots: water and sediment sampling points.

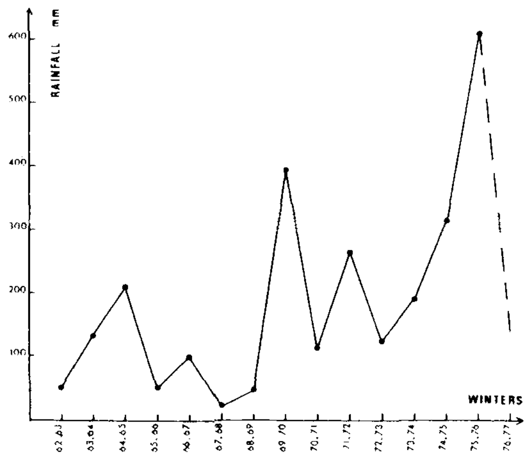

Fig. 3. Variations of rainfall from 1962 to 1977 in the Ben Guirden–Zarzis region.

which is favourable for olive plantation; Pliocene conglomerates, locally absent; Mio-pliocene red and yellow clays and sands, with gypsum, dolomite and calcite: these are partly the lateral equivalents of Messinian evaporites in the Mediterranean sea.

(2) Wide valleys eroded during Quaternary climatic cycles. The Ben Guirden plain is probably Rissian (Medhioub, 1979). The Oued Fessi valley which is Würmian has a Flandrian delta.

(3) Supratidal sabkhas. These are wide flats constructed by the Flandrian marine and fluvio-marine sedimentation (Fig. 2). Today, they are situated slightly above sea-level (0–2 m) because of a Recent regression (Perthuisot, 1975a, b). The Flandrian sediments are covered locally by a thin sheet of aeolian sand or recent alluvium.

The widest of these sabkhas, Sabkha bou Jmel, comprises the Flandrian to modern Oued Fessi delta. An earlier river channel is still visible and forms a small shallow sound called El Mekhada (the churn). Locally, poorly developed thin algal mats grow on the banks of this sound. The tidal movements allow continuous water exchanges between El Mekhada and the lagoon through several pipes under the road which crosses the sound (Fig. 2).

The sabkha sediments are essentially carbonates, siliciclastic sands and clays containing marine shells. These sediments generally contain lens-shaped gypsum crystals especially in the upper capillary zone. On the surface, a thin halite crust forms in summer but disappears following flooding.

Sabkha bou Jmel contains highly saline interstitial brines whose compositions are expressed on Table 1. These strongly suggest a marine origin with loss of calcium carbonate and (principally) calcium sulphate by crystallization and sulphate reduction by bacterial processes similar to those which occur in neighbouring Sabkha el Melah (Perthuisot 1975a). Boreholes made in order to sample interstitial waters emmited a smell of hydrogen sulphide.

Hence, it would seem that the most important input of water and salt to the sabkhas comes from the lagoon whose waters travel through the sabkha sediments and gradually concentrate under the effect of capillary evaporation. Such a phenomenon has been already suggested by studies in the Persian Gulf (Butler, 1969; Kendall & Skipwith, 1969; Shearman, 1980). The interstitial waters of sabkhas thus attain concentrations which allow gypsum and even halite to precipitate. While the high Mg content of these brines causes a slight dolomitization, subsequent gypsum precipitation maintains a much higher Mg/Ca ratio than in sea-water.

The seaward limits of the lagoon

The lagoon is separated from the open sea by two narrow tongues which locally are called 'slob'. They end near El Biban as a succession of small islands

Table 1. Chemical analyses of interstitial brines of Sabkha bou Jmel

Sample no	B 53		B 33		B 54	
Date of sampling	28-7-71		6-11-72		28-7-71	
	g l^{-1}	% meq	g l^{-1}	% meq	g l^{-1}	% meq
Na^+	35·60	77·5	69·74	80·00	85·60	82·0
K^+	1·19	1·5	2·09	1·4	2·49	1·4
Mg^{2+}	4·34	17·9	7·87	17·1	8·70	15·9
Ca^{2+}	1·27	3·2	1·15	1·5	0·63	0·7
Cl^-	64·26	90·8	126·47	94·6	165·20	95·0
SO_4^-	8·84	9·2	9·79	5·4	11·27	5·0
Total	115·5		217·02		263·89	

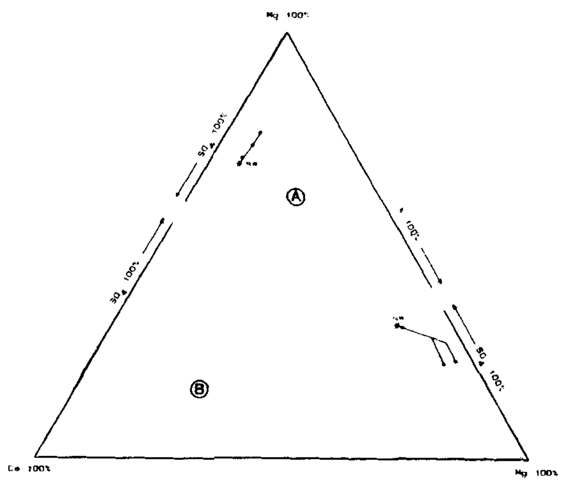

Fig. 4. Chemical compositions of Sabkha bou Jmel interstitial brines plotted on a Jaenecke's diagram (Mg, SO_4, K) (A) and on a Ca, SO_4, Mg diagram (B). Black star (sw): seawater. (A) On a Jaenecke diagram, the coordinates are calculated after $CaSO_4$ and $CaCO_3$ have been subtracted from the initial analysis so that the point which represents an evaporating seawater theoretically does not move from point sw until the brine becomes saturated with astrakhanite. As Sabkha bou Jmel brines are obviously undersaturated with halite, the positions of their representative points suggest that these brines are of marine origin but have lost SO_4^{2-} by another way than gypsum precipitation: this may be due to bacterian reduction. (B) In this diagram, the positions of the representative points of the sabkha brines suggest gypsum precipitation plus sulphate reduction.

with a series of passes between them (El Biban means 'the doors'). The main pass is immediately east of El Biban island where the fishery is located. These earth barriers are not Recent sand bars or spits as the geographical map could suggest, but are parts of an old Tyrrhenian coastal dune belt. The main channel at El Biban must be considered as a prolongation of the Würmian valley of Oued Fessi, presently flooded by the Flandrian transgression (Medhioub, 1979).

The El Biban channel reaches a depth of 9 m in its narrowest part. The very strong tidal currents slow down rapidly both seaward and lagoonward. Thus, the particles carried by the inflow current are rapidly deposited near the pass forming a tidal delta on the lagoonal side (Fig. 2). Seaward, the channel is partly barred by a red algae reef which helps to restrict the water exchanges between the bahira and the sea.

Another small and narrow reef extends along the northern shore of the lagoon. It has been constructed essentially by annelids and red algae (Thornton Pilkey & Lynts, 1978).

Water exchanges and currents

The tidal amplitude in the Gulf of Gabes reaches 1 m. Thus strong alternating tidal currents flow through the El Biban passes favouring continuous exchanges between the lagoon and the sea.

Studies of sedimentary features along the shore of the lagoon show that the wind system generates a slow rotation of the water body. It also deviates the tidal currents so that water movements at El Biban do not exchange exactly the same stock of water at each tide. Hence, the waters of Bahiret el Biban are probably entirely renewed after a certain, but still unknown, period of time. Nevertheless there is evidence that the water of the central area is more rapidly renewed, as may be inferred from the water concentration map (Fig. 5).

THE GEOCHEMICAL BEHAVIOUR OF THE WATERS OF BAHIRET EL BIBAN

The chemical behaviour of the waters of the lagoon has been studied over a 2-year period with four successive sampling campaigns (March 1976, August 1976, January 1977, August 1977). Forty-four samping points were located on a map as accurately as possible. Apart from March 1976, both surface and bottom samples were collected but unfortunately, for financial reasons, only half of the water samples were analysed. These data nevertheless permit the preparation of various chemical maps some of which are included (Figs 5, 6).

Total concentration

For each period of study, the total concentration varies over the whole basin. The general pattern is an increase of salinity with increasing distance from the El Biban passes and the waters at both extremities are more concentrated: these areas are obviously more confined and their waters have been more evaporated than in the central part of the basin where exchanges with the open sea moderate the salinities.

The distribution in March 1976 is slightly different, this being due to important freshwater flooding during the winter of 1975–76 and by a strong northwest wind which probably displaced the tidal inflow to the north coast of the basin.

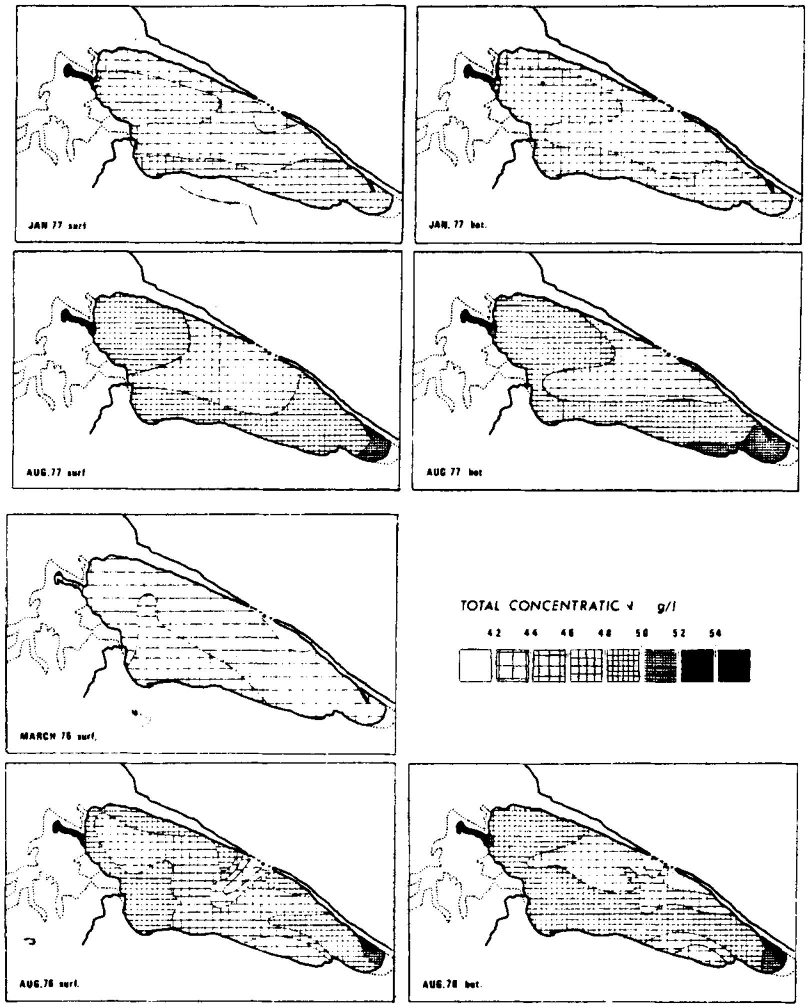

Fig. 5. Water concentration (g l^{-1}) maps of Bahiret el Biban. Left, surface water; right, bottom waters.

Apart from these periods of flooding, El Mekhada waters are always the most concentrated: in summer the total content reaches 120 g l^{-1}. Naturally, tidal exchanges between El Mekhada and the lagoon tend to increase the salinity of the latter in its western part.

As far as the 'mean' concentration of the lagoonal waters is concerned (Table 2), there is clear evidence for seasonal variation related to the higher evaporation rate in summer plus input of continental waters which dilute the lagoon waters in winter. This is the case for March 1976.

In spite of these seasonal variations, the general tendency of the water body is towards increasing concentration when no important flooding occurs. The mean concentration in August 1977 is 2 g l^{-1}, higher than that of August 1976. Hence, in spite of the continuous tidal exchanges with the open sea and the rotation of the water body within the lagoon, it is probable that a long period of drought would considerably increase the salinity of the lagoon. This would be disastrous for fish production (Medhioub & Perthuisot, 1977).

Because there is a bidirectional flow between the lagoon and the open sea, an equilibrium should exist. However, the basin is so small and the climatic conditions change so rapidly from year to year that this theoretical equilibrium probably is never reached.

There seems to be a significant difference between the surface and the bottom waters. The latter are

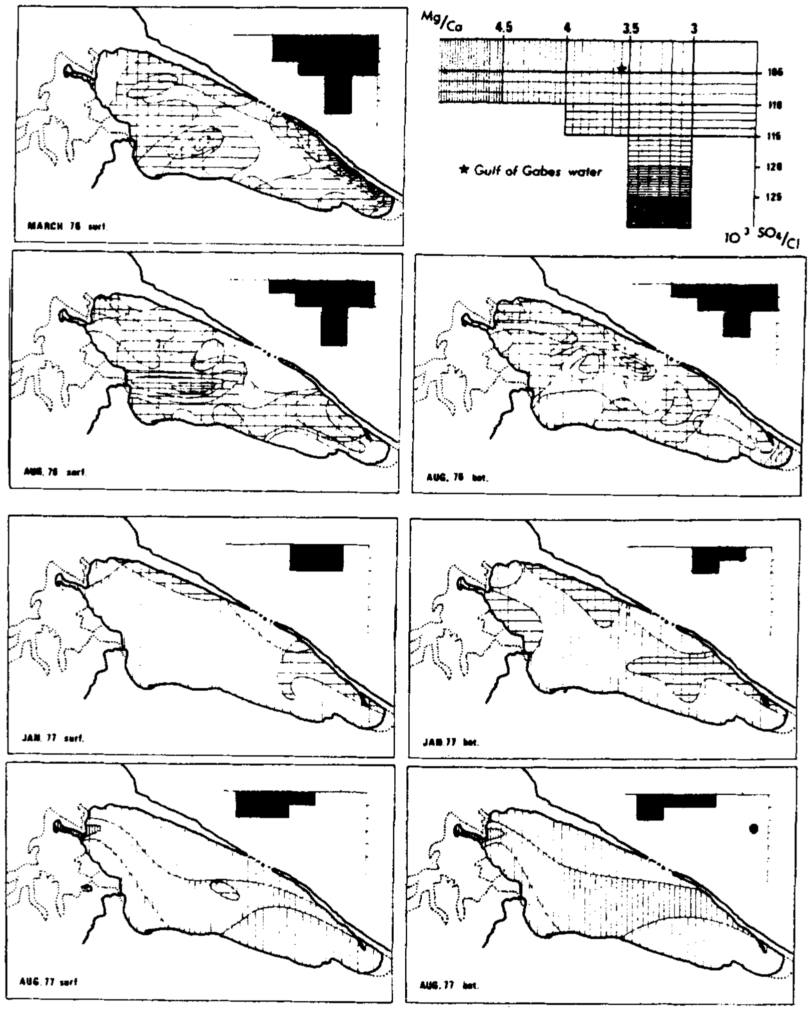

Fig. 6. Mg^{2+}/Ca^{2+} versus SO_4^{2-}/Cl^- maps of Bahiret el Biban Left: surface waters. Right: bottom waters.

generally slightly more concentrated, especially in the western part of the lagoon. The highly concentrated waters coming from El Mekhada probably flow on the bottom and increase salinities. It is interesting to note that such a shallow water body as Bahiret el Biban displays stratification.

Chemical composition of waters

The major ionic components of the waters of the lagoon have been analysed. Data were compared with Rass ez Zira water collected at some 20 km offshore in August 1977 and which is assumed to represent typical Gulf of Gabes seawater (Table 2). The behaviour of most ions has been dealt with by Medhioub (1979) and only general tendencies will be reviewed (Fig. 6).

The mean concentration of HCO_3^- displays seasonal variations which can reasonably be attributed to photosynthetic activity, water temperature and salinity variations. These also account for carbonate precipitation, especially in summer, in the whole basin. Over the entire period of studies there is a general tendency towards impoverishment in HCO_3^- which is in accordance with the salinity increase. In summer the HCO_3^- content of the bottom waters is slightly higher than that of the surface waters; the reverse situation occurs in winter. This phenomenon could be explained by a higher photo-

Table 2. Mean ionic composition of Bahiret el Biban waters from March 1976 to August 1977. The unit is the percentage of milliequivalents for each ion (total of anions: 100 %; total of cations: 100 %). The numbers are the means of all analyses effected for each campaign: even if these numbers have no real significance by themselves, we think their variations depict the general tendencies of the lagoonal water body

meq	March 1976	August 1976	January 1977	August 1977	R. Zira (Gulf of Gabes)
% Cl^-	89·805	90·05 90·06	90·25 90·24	90·36 90·32	90·13 90·20
% SO_4^{2-}	9·836	9·622 9·612	9·369 9·451	9·264 9·267	9·42 9·35
% HCO_3^-	0·357	0·316 0·329	0·347 0·340	0·318 0·326	0·39 0·39
% Na^+	77·74	77·70 77·24	77·11 77·09	76·71 76·67	77·71 77·71
% K^+	1·60	1·60 1·60	1·56 1·56	1·57 1·58	1·53 1·53
% Ca^{2+}	3·361	3·283 3·259	3·051 3·043	2·864 2·909	2·92 2·92
% Mg^{2+}	17·373	17·544 17·823	18·263 18·363	18·812 18·860	17·82 17·82
Mg/Ca	3·143	3·263 3·339	3·631 3·663	3·988 3·931	3·64 3·64
Total salt content	43·45	48·33 49·08	45·00 46·25	50·54 51·18	40·00 40·00

synthetic activity in winter on the floor of the lagoon where abundant sea-grasses grow and in summer by a high bacterial activity in the organic rich sediments favoured by temperature elevation.

The decrease of HCO_3^- content from March 1976 to August 1977 does not account for the diminution of Ca^{2+} which is much more important. Thus, carbonate precipitation is not the only reason for the calcium decrease of the lagoon. Furthermore, in March 1976 the 'mean' relative contents of the waters in Ca^{2+} and SO_4^{2-} were higher in the lagoon than in the Gulf, but lower in August 1977. Two important points are implied:

(1) In the winter of 1975–76, the important floods brought into the basin large amounts of calcium sulphate, leached from Quaternary and Tertiary rocks.

(2) The waters of the lagoonal system of Bahiret el Biban progressively lose calcium sulphate. This cannot be easily effected other than by gypsum precipitation and/or sulphate reduction. Although neither of these processes occur in the lagoon itself, they do occur within the peripheral sabkha sediments where waters, coming from the lagoon, undergo an evaporitic evolution and sulphate reduction. Hence, the geochemical properties of the waters of Bahiret el Biban are best explained by reflux seepage of the sabkha brines into the lagoon. The effects of such a phenomenon must be less important in winter but are more important after a long period of drought such as spring 1976 to summer 1977.

The geochemical consequences of this mechanism appear clear from the chemical data:

(a) *The 'mean' relative Na^+ content decreases* from March 1976 to August 1977 probably by trapping of halite crystals within the sabkha sediments and in the salt crusts. However, data also suggest that during winter the sabkha halite may be dissolved and sodium chloride may return to the lagoon.

(b) As may be expected, the 'mean' relative contents of Cl^- and Mg^{2+} and the Mg/Ca ratio increases continuously, while small amounts of Mg^{2+} are fixed in the lagoon by high Mg-calcite formation.

Considering the Mg/Ca versus SO_4/Cl maps (Fig. 6), it appears that the important flooding during the winter of 1975–76 generated a great diversity in the chemical composition of the waters of the lagoon but that the general tendency of the system is towards simplification. Furthermore, these maps clearly indicate the importance of El Mekhada and Sabkha bou Jmel in the general chemical evolution of the basin especially in its western part.

Conclusion

Our observations indicate that the following factors control the salinity and composition of the waters of Bahiret el Biban: rate of evaporation throughout the lagoon; input of continental waters; exchange with the open sea; exchange with peripheral sabkha brines.

In addition to being of local importance it is possible that such exchanges between a restricted basin and its evaporitic dependencies could play a major role in the early stages of the evolution of evaporitic basins (Perthuisot, 1980).

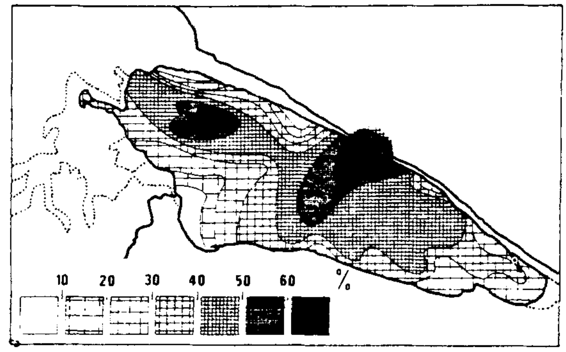

Fig. 7. Total sedimentary carbonate (weight %) of Bahiret el Biban. The proportion of carbonate grains (ooïds, pellets, debris, shells) is very limited and the total carbonate content tends to reflect the amount of matrix in the sediment.

PRESENT SEDIMENTATION IN BAHIRET EL BIBAN

Samples of surface sediments in the lagoon were collected at more than 40 points throughout the basin (Fig. 2) and were chemically analysed for carbonate, alumina and organic matter. The mineralogical composition of the carbonate matrix (particle size less than 40 μm) has been determined by X-ray diffractometry.

Around the periphery of the lagoon the present sediments are typically grey, fine siliciclastic sands with some ooïds, pellets and mollusc debris; the carbonate matrix is not abundant. In the deepest parts of the lagoon, the sediments are black carbonate muds with few debris or intraclasts. There are also intermediates between these two facies, such as on the tidal delta of El Biban.

Total carbonate contents of sediments

The carbonate content of surface sediments varies widely throughout the lagoon (Fig 7). It displays a roughly concentric pattern with a low concentration along the shore and a higher content in the deepest, central parts of the bahira. Because the carbonates occur essentially as matrix, several factors could account for this disposition:

(1) The rate of carbonate deposition is a function of water depth.

(2) The supply of siliciclastic particles of aeolian and fluviatile origin is more important near the basin margins.

(3) The winnowing of sediments around the margins tends to concentrate the fine carbonate particles in the deeper and quieter central parts of the lagoon. This mechanism also affects clay particles as is clearly shown in Fig. 8.

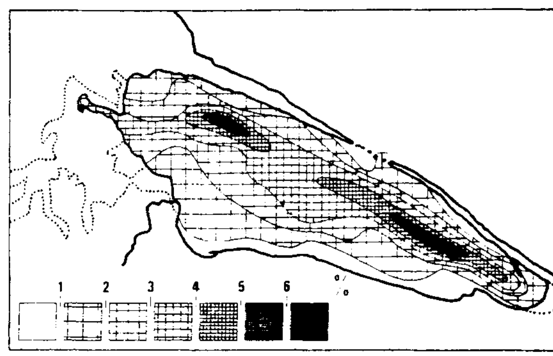

Fig. 8. Al_2O_3 content (weight %) of Bahiret el Biban sediments.

(4) Sea-grasses are more abundant in the central parts of the lagoon where they increase photosynthesis and epiphytic animal life.

Two particular areas are exceptions to the general pattern: one near El Biban inlet is an area of maximum carbonate deposition which corresponds to the area over which seawater, flowing into the lagoon, extends at high tide. This inflow is often turbid: large amounts of fine suspended carbonate formed mainly in the open marine areas are carried into the lagoon and deposited in its quieter waters. This would explain the localization of the tidal delta immediately south of El Biban pass. It is also likely that mixing of incoming HCO_3^- rich waters with the

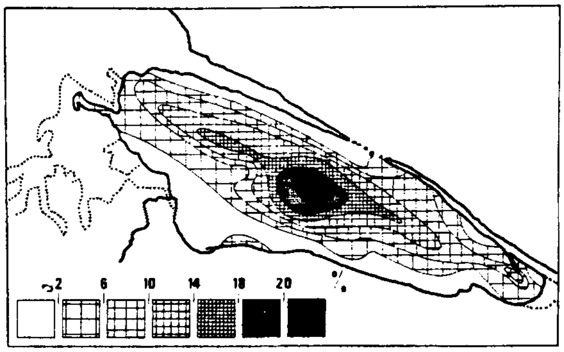

Fig. 9. Organic matter (fire loss weight %) content of Bahiret el Biban sediments.

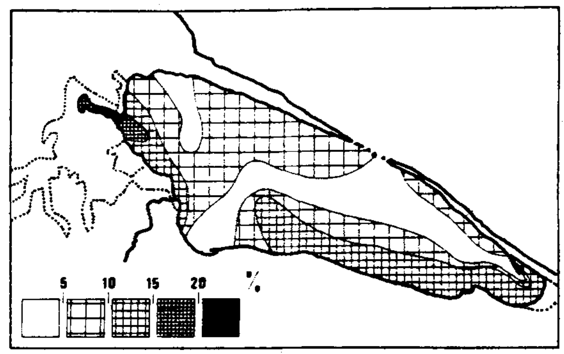

Fig. 11. Low-Mg calcite content (weight %) of the matrix of Bahiret el Biban sediments.

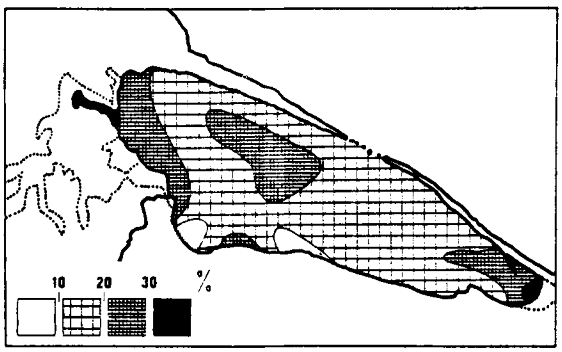

Fig. 10. Dolomite content (weight %) of the matrix of Bahiret el Biban sediments.

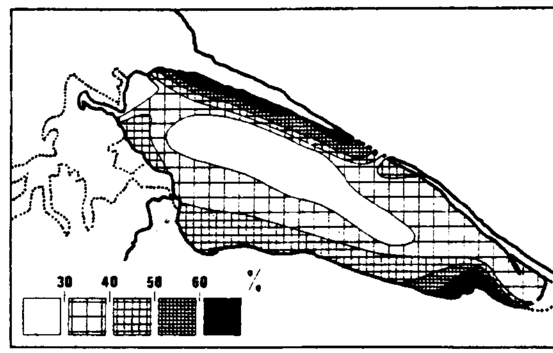

Fig. 12. Aragonite content (weight %) of the matrix of Bahiret el Biban sediments.

confined, highly saline and hotter waters of the lagoon favours carbonate precipitation in that peculiar area.

Another maximum of carbonate deposition occurs in the western central part of the lagoon. This is probably due to a similar process as described above: mixing of lagoon waters with the highly saline waters coming from El Mekhada and Sabkha bou Jmel.

Organic matter content of sediments

Distribution of the organic matter in the sediments is generally concentric (Fig. 9) and seems to be a function of depth for reasons already discussed: the distribution of sea-grass meadows and the winnowing of the sediments of the margins. Nevertheless, maximum organic concentration occurs immediately in front of the main pass where the depth is not particularly important nor sea-grasses especially abundant. This maximum is not shown by the repartition of clays which is mainly controlled by hydrodynamics. Hence, this anomalous repartition of the organic matter could be explained by a local mortality of marine organisms related to the junction of the inflow and the more saline and confined waters of the lagoon. Such a mechanism could have played a role in the production of source rocks in certain restricted ancient basins.

Composition of the carbonate matrix

Maps of the various carbonate components of the matrix of present sediments indicate:

Dolomite (Fig. 10) is especially abundant along the southern edges of the lagoon where Tertiary formations, sabkha sediments and red silts crop out. All these contain dolomite (and calcite). Dolomite is more abundant in the coarser fraction of the matrix of the sediments. Furthermore, the Mg/Ca ratio of the lagoonal waters is not high. Thus, we conclude that the dolomite is in all probability of detrital origin.

Low-Mg calcite has a similar distribution to the

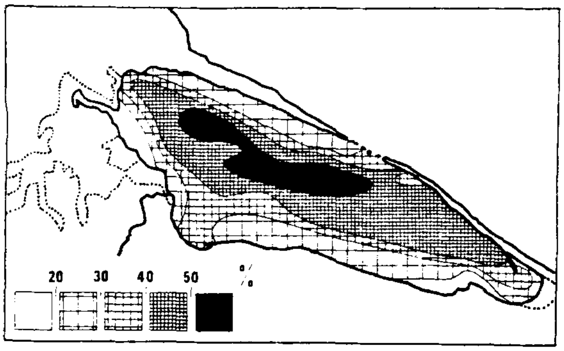

Fig. 13. High-Mg calcite content (weight %) of the matrix of Bahiret el Biban present sediments.

dolomite (Fig. 11) and thus is, at least partly, of the same origin. However it is also likely that a part of the low-Mg calcite forms by conversion of aragonite when the basin is submitted to freshwater flooding. Part is probably derived from organisms.

Aragonite (Fig. 12) and high-Mg calcite (Fig. 13) are the major components of the matrix of the sediments the aragonite being concentrated along the margins and the Mg calcite in the central part of the lagoon. Both minerals may be produced by biological activity (photosynthesis and calcareous organisms) but part of the aragonite may be precipitated chemically. As far as these two minerals are concerned, there still remains several unsolved problems:

The distribution of the two minerals suggests a significant difference between the western-central part of the lagoon where high-Mg calcite prevails and the margins where aragonite is more abundant. Whether this distribution is due to geochemistry, i.e. essentially the Mg/Ca ratio, or biological activity (epiphytic faunas or else) or both is difficult to say: Study of the lagoon ecology is not complete.

To what degree is the high-Mg calcite and aragonite syngenetic or early diagenetic? Is there a transformation from aragonite to high-Mg calcite as the comparison between geochemical maps and these two minerals' distribution may suggest? Further studies are needed.

CONCLUSION

Bahiret el Biban offers an interesting model of a restricted lagoon under arid conditions. Its chemical and sedimentological features depend upon several factors. In addition to input of continental waters, the balance between the exchanges with the open sea and the loss by evaporation, especially on peripheral sabkhas, plays a major role. It is likely that many of the subevaporitic or pre-evaporitic basins in the past have had adjacent supratidal sabkhas: these could have favoured salinity increase and water stratification within the basins, leading ultimately towards an evaporitic stage.

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