Hydrologic Framework of A Sabkha Along Arabian Gulf[1]

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ABSTRACT

During the last 4,000 to 5,000 years, sedimentary offlap and a relative fall in sea level have resulted in the development of broad, gently seaward sloping (about 1:3,000) planar areas, or sabkhas, along much of the south shore of the Arabian (Persian) Gulf. The depth of the water table below the sabkha surface increases with distance from the sea until it reaches 1.0 to 1.5 m, after which it remains constant. When the water table depth is in the range of 1.0 to 1.5 m, the sabkha surface has reached a state of deflational equilibrium. The water table beneath the sabkha always slopes seaward indicating that the direction of ground-water flow is toward the sea. The subsurface flow system beneath the sabkha is part of a regional seaward flowing ground-water regime.

In the seaward part of the sabkha, a downward flow component is superimposed on the general seaward ground-water flow pattern as a result of the infiltration and percolation of water from shallow bodies of seawater that are propelled inland over the sabkha surface by strong onshore winds. Farther inland where marine flooding does not occur, the vertical flow component is directed upward in response to evaporative losses at the sabkha surface. The net rate of evaporation from the central parts of the sabkha is on the order of 6 cm (± factor of 2) of ground water per year.

A regional ground-water flow system which causes the water table level to rise as the sabkha progrades appears to be a requirement for the development and the preservation of broad sabkhas. Fluctuations in sea level during sabkha development influence the rate of progradation and the thickness of sedimentary facies. The refluxing of sabkha brines beneath the lagoons in the Abu Dhabi area indicates a mechanism for preserving anhydrite during marine transgressions, thus permitting the development of stacked sabkha successions which are common in the rock record.

INTRODUCTION

Dolomite, magnesite, gypsum, and anhydrite are forming diagenetically in the sabkhas along the south shore of the Arabian Gulf (e.g., Illing et al, 1965; Kinsman, 1965, 1969; Butler, 1969; Patterson, 1972; Hsu and Schneider, 1973). The production of these minerals involves the movement of specific types of aqueous solutions and, thus, to understand the diagenetic processes completely it is necessary to define the hydrology of the sabkhas. In this paper, the hydrologic framework of a sabkha, as interpreted on the basis of water-table measurements and water chemistry data, is outlined. The implications of the hydrology for the development and preservation of sabkha sequences are considered in the discussion. Future papers will detail the individual diagenetic processes and their relations to the hydrology.

Location and Climate

The study area is situated near Abu Dhabi in the Union of Arab Emirates, formerly the Trucial States (Fig. 1).

The south shore of the Arabian Gulf is very hot. In Abu Dhabi the average annual temperature is 20°C, with average maximum daily temperatures in July of 45°C, and in February of 22°C (Patterson, 1972).

A regional, northwesterly, onshore wind pattern is modified by convective circulation near the coast where the main study was conducted. During the morning, a light offshore breeze generally prevails. This offshore wind progressively diminishes in strength until about 11:00 a.m., when for a short time, there may be no perceptible wind. Maximum temperatures and minimum relative humidities (20 to 50%) occur during this still period. As the afternoon proceeds, a stronger onshore wind pattern develops causing a slight drop in temperature and a sharp rise in the relative humidity (60 to 80%). At night when temperatures fall 10 to 15°C, relative humidities of 100% are common and early morning fogs may occur.

Strong, often gale-force, winds that periodically occur in the Arabian Gulf area are called "shamals." The shamals are north to northwest onshore winds that do not generally bring rain, but are accompanied by hazy conditions as a result of suspended dust. During rainstorms, onshore winds also prevail but they are

[1]Manuscript received, September 4, 1980; accepted, March 23, 1981.

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Grateful acknowledgement is extended to the donors of research grants awarded to Kinsman: The American Association of Petroleum Geologists (AAPG Persian Gulf Research Project); American Petroleum Institute (API Research Project 99); National Science Foundation (NSF Research Grants GA1170 and GA-13489); and Petroleum Research Fund of the American Chemical Society (PRF Grant 3009-42). We also thank the Government of Abu Dhabi, R. Park, K. Edworthy and the personnel of Phillips Petroleum Company, and Ray Geophysics for their assistance in the field. We thank L. S. Smith and C. J. Hodgson, Department of Geological Sciences, Queen's University, for critically reading the manuscript.

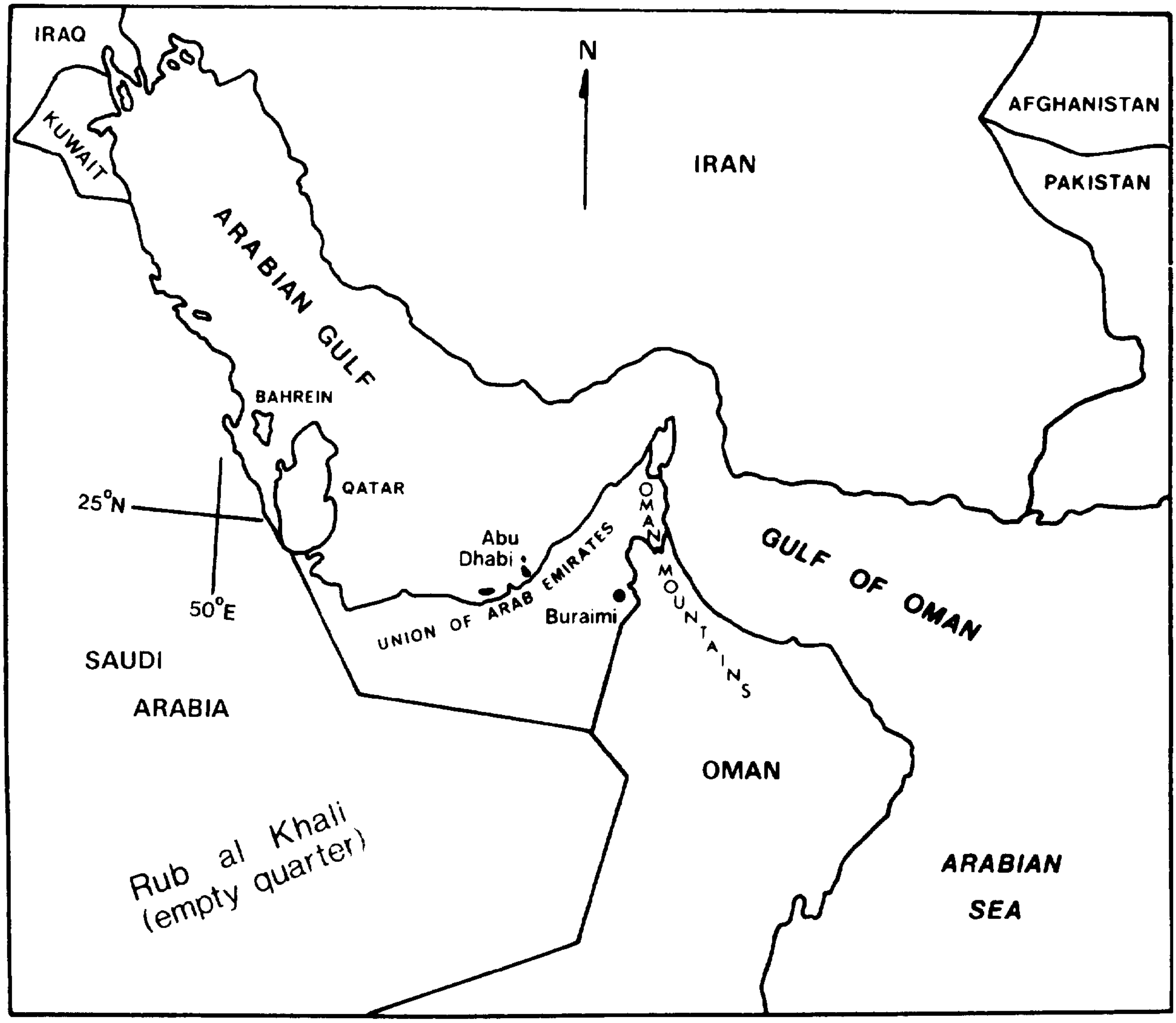

FIG. 1—Map of Arabian Gulf area.

generally not as strong as shamals. When strong onshore winds occur, exceptionally high tides are produced.

Rainfall is erratic and seasonal, usually occurring during the winter months. On average, the area receives 3 to 4 cm of rain annually but it is not unusual for a year to pass without any rain. The rainfall, though infrequent, is commonly very heavy when it does occur. The Oman Mountain region (Fig. 1) receives slightly more rainfall (10 to 20 cm annually).

Physiography and Stratigraphy of Arabian Gulf Sabkhas

The term "sabkha" is a transliteration of an Arabic word meaning "salt flat." Physiographically, sabkhas are very flat, though not necessarily level, areas. Surface relief is generally less than about 10 cm, but may reach 50 cm in some places. Most relief is associated with the development of evaporite crusts on the surface.

Figure 2 shows the physiography of the region surrounding the detailed study area. The recently formed carbonate sediment areas of the shelf, coastal barrier and lagoon environments are backed by extensive sabkhas which are bounded on their inland margins by dune sands. Farther inland, the dunes pass into alluvial gravels that mantle the Oman Mountain front.

Figure 3 is a composite stratigraphic section (based on about 600 core and pit sections) oriented northwest-southeast through the detailed study area shown in Figure 2. From surface downward, the section is:

1. Supratidal facies: 0 to 100 cm, wedge of detrital sandy sediments and evaporites thickening inland from shoreline. The detrital sediment is approximately 50% quartz and feldspar, 40% calcite, and 10% dolomite. Dominated by anhydrite in inland areas; may be magnesite-rich at base.
2. Upper intertidal facies: 60 cm, commonly an algal facies, but coarse skeletal sands or gravels are high-energy equivalent; anhydrite may be present in upper part; gypsum commonly abundant; intensely dolomitized in some areas.
3. Lower intertidal facies: 60 cm, cream, muddy, pellet sands with abundant cerithids; large gypsum crystals common; fairly intensively dolomitized in some areas.
4. Subtidal facies: 0 to 300 cm, gray-brown, peneroplid-and lamellibranch-rich muddy sands; thickens seaward. Minor dolomitization.

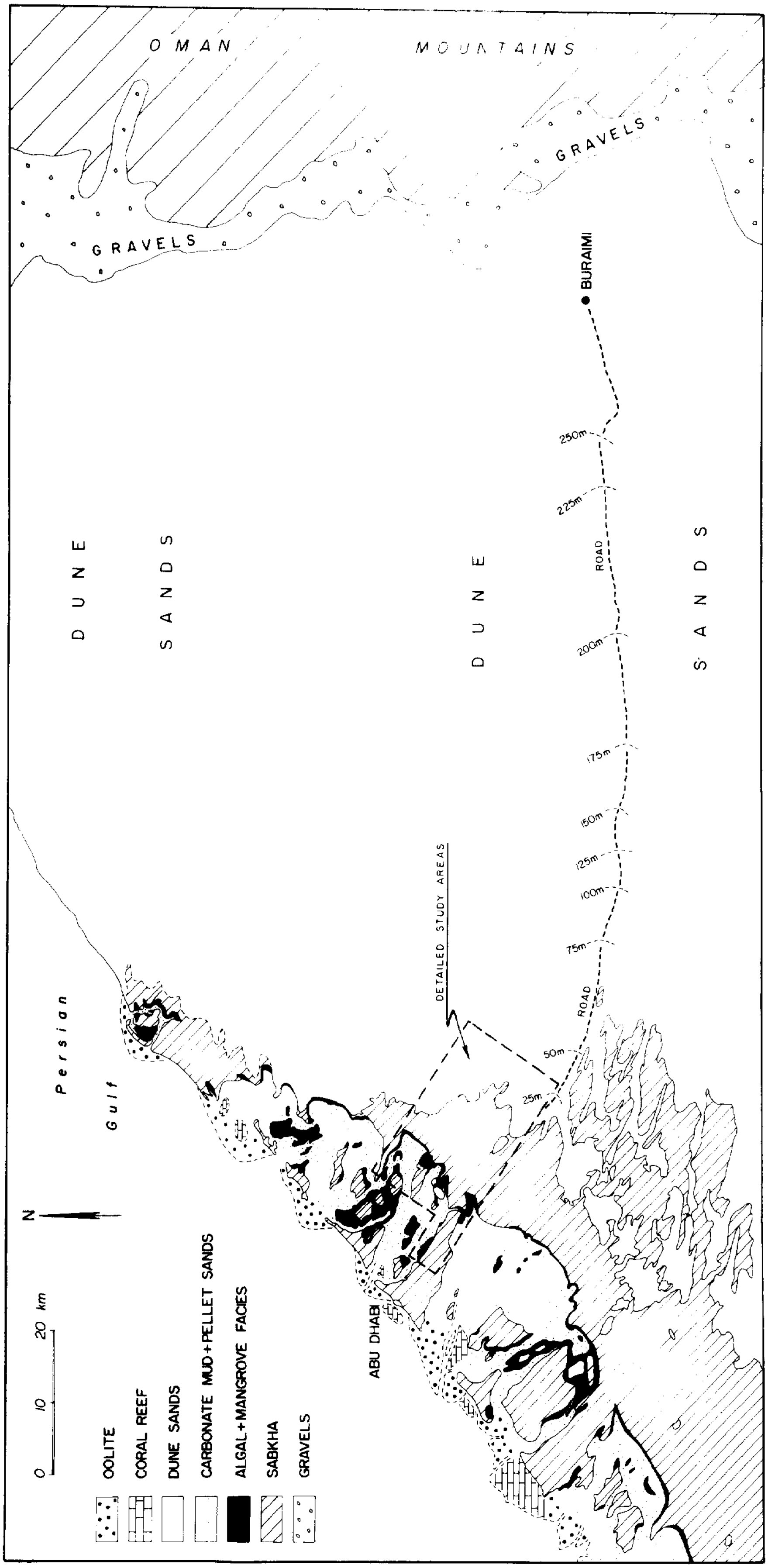

FIG. 2—Physiographic and sedimentary environments between Oman Mountains and coast of Arabian Gulf near town of Abu Dhabi.

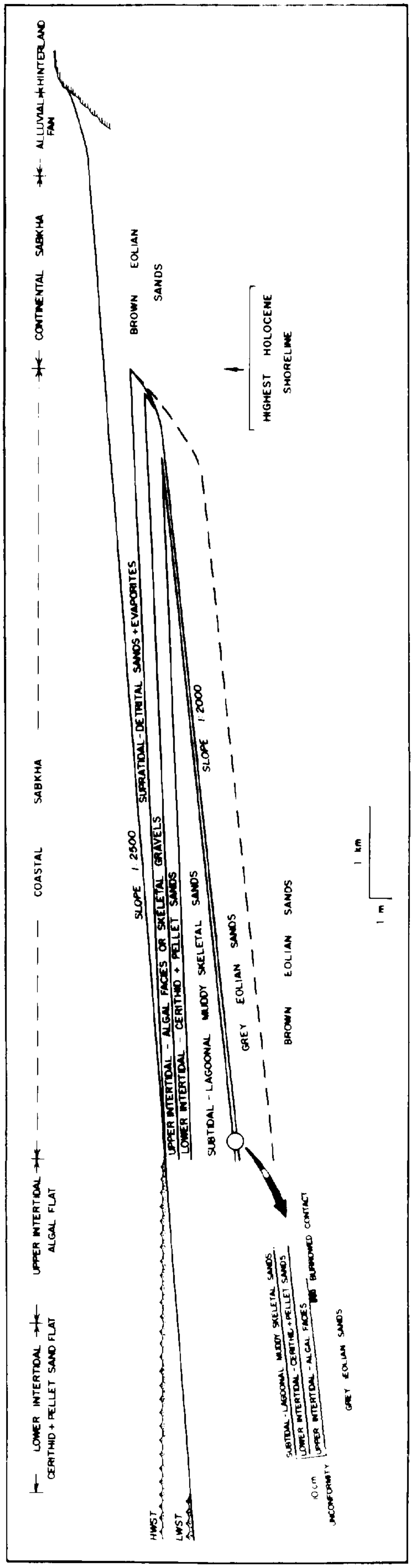

FIG. 3—Composite northwest-southeast stratigraphic section across Abu Dhabi coastal-continental sabkha belt in area of detailed study (Fig. 2). HWST and LWST are high and low water spring-tide levels, respectively.

5. Lower intertidal facies: 2 to 5 cm, cream, pellet sands with abundant cerithids.
6. Upper intertidal facies: 2 to 5 cm, algal facies in some places, otherwise mixed pellet and detrital sands. Unconformity: generally fairly sharp; some places burrowed.
7. Gray eolian sands: 50 to 150 cm, gray, cross-bedded eolian sands; original iron oxide film around grains now present as iron sulfide minerals; some gypsum.
8. Brown eolian sands: thickness unknown, but probably about 5 to 10 m; brown, cross-bedded eolian sands with some gypsum. Unconformity.
9. Miocene rocks.

The stratigraphy indicates that marine sedimentation began with a rapid transgression over an earlier sabkha. The rate of sediment production was insufficient to keep pace with the rate of sea level rise, and consequently only a thin intertidal unit was developed. The point of maximum marine transgression (highest Holocene shoreline) was reached about 4,000 to 5,000 years ago (Patterson, 1972). Since that time a much slower regression has been occurring as a combined result of sedimentary offlap and a relative fall in sea level of 120 ± 10 cm (Patterson, 1972). The average rate of strandline progradation during this regression has been about 2 m/year. A supratidal wedge of eolian, brown sands and diagenetic evaporites that thickens landward is accumulating above the regressive marine sediments.

Figure 3 also illustrates the two types of sabkha that have been defined on the basis of stratigraphy: marine, or coastal, sabkhas which have marine sediments in section, and continental sabkhas which are not underlain by marine sediments.

METHODS

Maps of the detailed study area were prepared from uncontrolled aerial photograph mosaics. Leveling of the sabkha surface was accomplished by a transit survey using the high and low water spring-tide positions as data. Surface elevations on the sabkha are accurate to within ±5 cm. Elevation data for points inland from the detailed study area were derived from topographic maps.

The elevation of the water table was determined by measuring the depth to the water surface in pits dug at leveled locations. At 5 leveled locations, sand points with 30-cm screened intervals were installed to depths between 3 and 5 m. Water elevations in the piezometers were periodically recorded. Data on water-table elevations inland from the detailed study area were obtained from 6 cased boreholes drilled by a highway construction company, water wells at Buraimi, and pits dug in continental sabkhas.

Ground-water samples were obtained from pits and piezometers, and by squeezing unconsolidated sediments. Pit water samples (about 600 in total) were secured by digging holes below the water table. The water which flowed into the pits was collected and sealed in glass bottles as quickly as possible to minimize evaporation and gaseous exchange with the atmosphere. Squeeze waters were obtained using a Siever type squeezer (Siever, 1962) and hydraulic press to extrude interstitial fluids from above and below the water table. Most sediments for squeezing were collected in plastic jars that were pressed into freshly exposed pit faces, but a smaller number were split from cores taken in the sabkha and beneath the lagoon.

Chloride concentrations were determined by titration with $AgNO_3$, and Ca and Mg were measured by atomic absorption using a Perkin Elmer 303 Spectrophotometer. Sulfate levels were determined gravimetrically by precipitation as $BaSO_4$. All concentrations are expressed as moles per kilogram (m/kg) of solution (formality). Uncertaintities associated with chloride, calcium, magnesium, and sulfate concentrations in percents are ±0.3, ±2, ±2, and ±5, respectively.

RESULTS

Surface Topography of Sabkha

Figure 4 illustrates the topography of the sabkha surface in the detailed study area. On average, the sabkha surface slopes seaward with a gradient of about 1:3,000.

Depth to Water Table

Figure 5 shows the depth to water table in the study area on August 29, 1968. The depth increases gradually with distance from the present high-tide strandline until it reaches about 1 to 1.5 m, after which it remains constant in this range. The water-table surface is never deeper than 1.5 m as a result of capillarity and deflation. In unconsolidated sediments the lowest level of deflation is approximately the top of the capillary fringe, below which the sediment is too moist to be moved by eolian action. Most continental sabkha surfaces lie at this base level of deflation, and any future raising or lowering of the water table will result in accretion or deflation, respectively, until equilibrium is reestablished. Consequently, sabkhas are defined as surfaces of deflational equilibrium (Kinsman, 1969) whose elevation and slope are determined by the water table.

In the seaward area where the depth to the water table is less than 1 m (Fig. 5), accretion is occurring to raise the surface to the equilibrium level. The brown, sandy, evaporite rich layer (Fig. 3) which overlies the regressive marine sediments and thickens landward represents this accretion.

Topography of Water Table

Figure 6 shows the topography of the water table in the study area. Contours are not drawn in the 1 to 2-km wide area adjacent to the lagoon because the levels vary in response to frequent tidal and wind-driven flooding which will be discussed later. Throughout most of this area the water table is at or very near the ground surface.

The water table is always above the high-tide level and slopes gently, but consistently, seaward across the entire study area, indicating that the direction of ground-water flow is toward the sea. Even in the seaward region that is periodically flooded, the water table was *never* found to slope inland. In the region corresponding roughly with the coastal sabkha (approximately seaward of the 80-cm contour in Fig. 5), the gradient on the water table

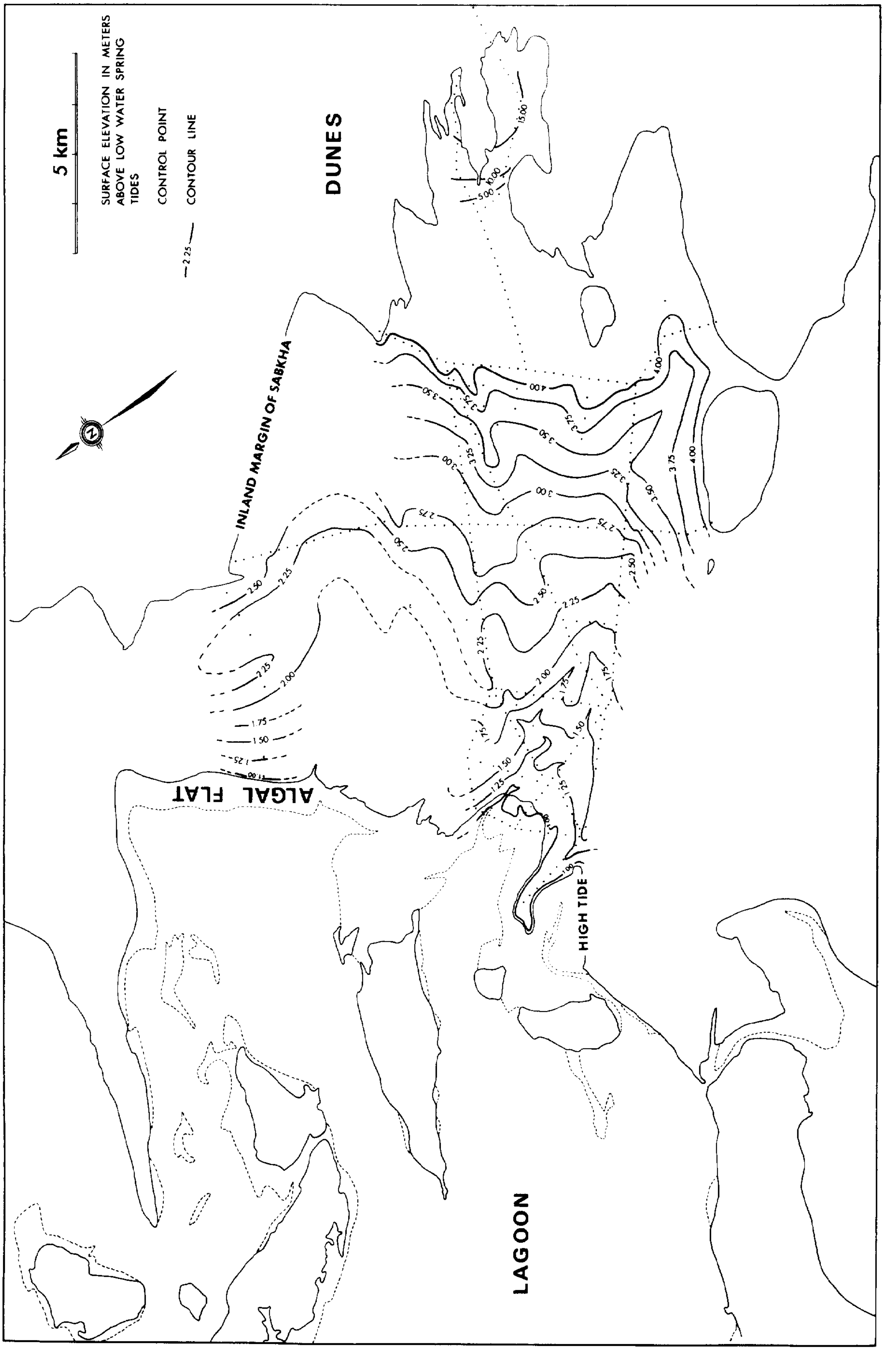

FIG. 4—Sabkha surface elevation in meters above low water spring tides. Maximum leveling error is ±5 cm. High water spring-tide elevation is ±122 cm.

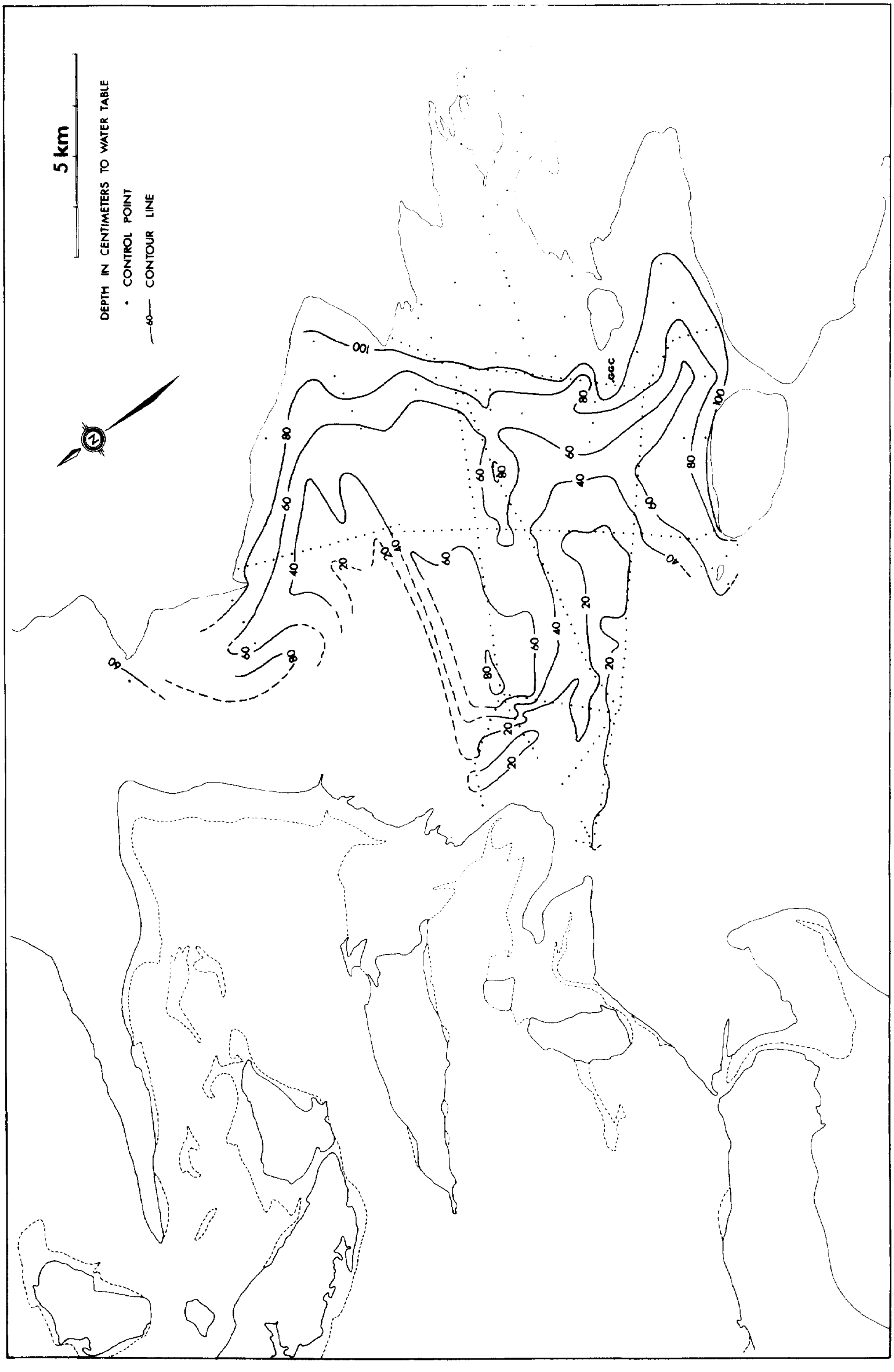

FIG. 5—Depth in centimeters to water table.

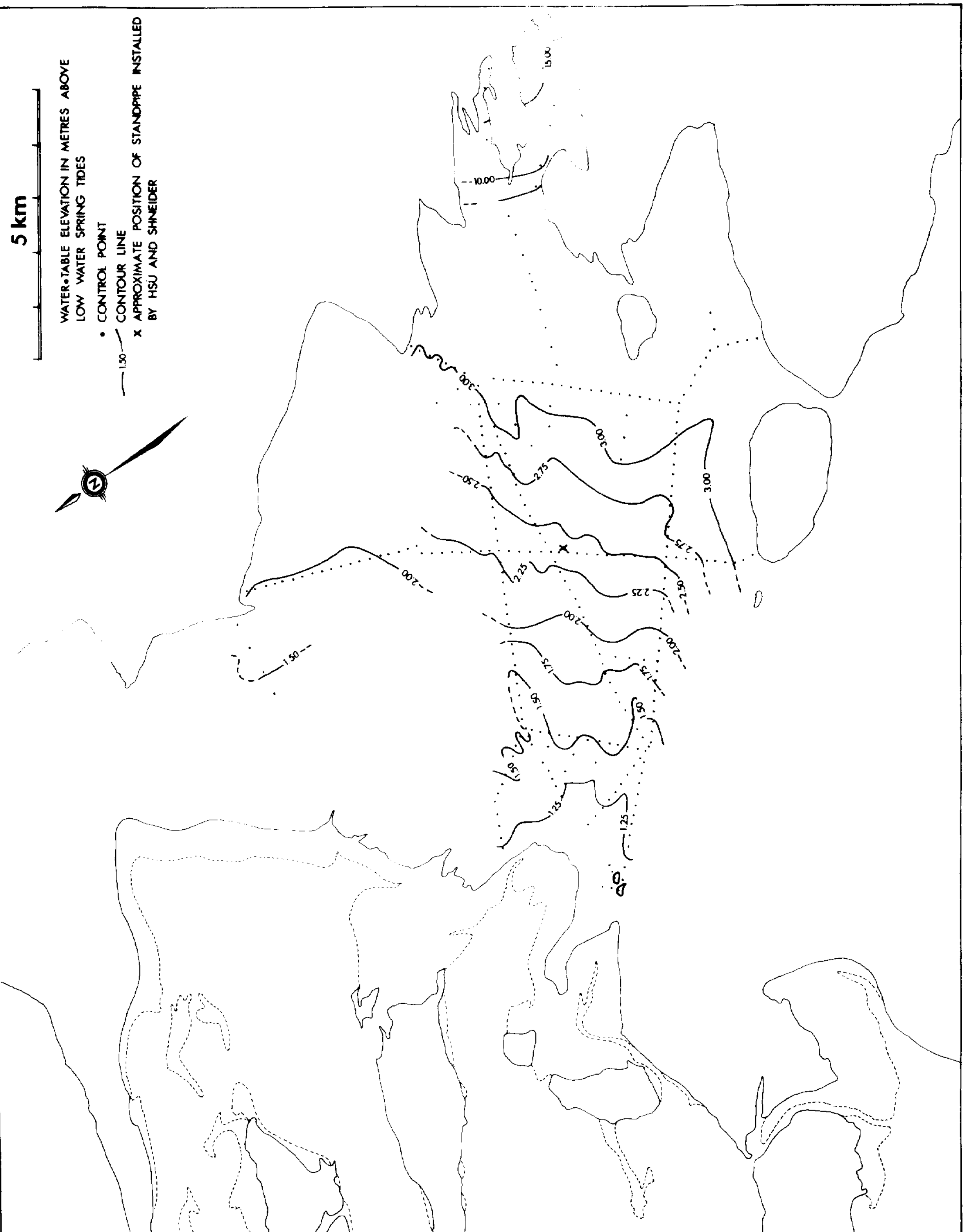

FIG. 6—Water-table elevation in meters above low water spring tides, August 29, 1968.

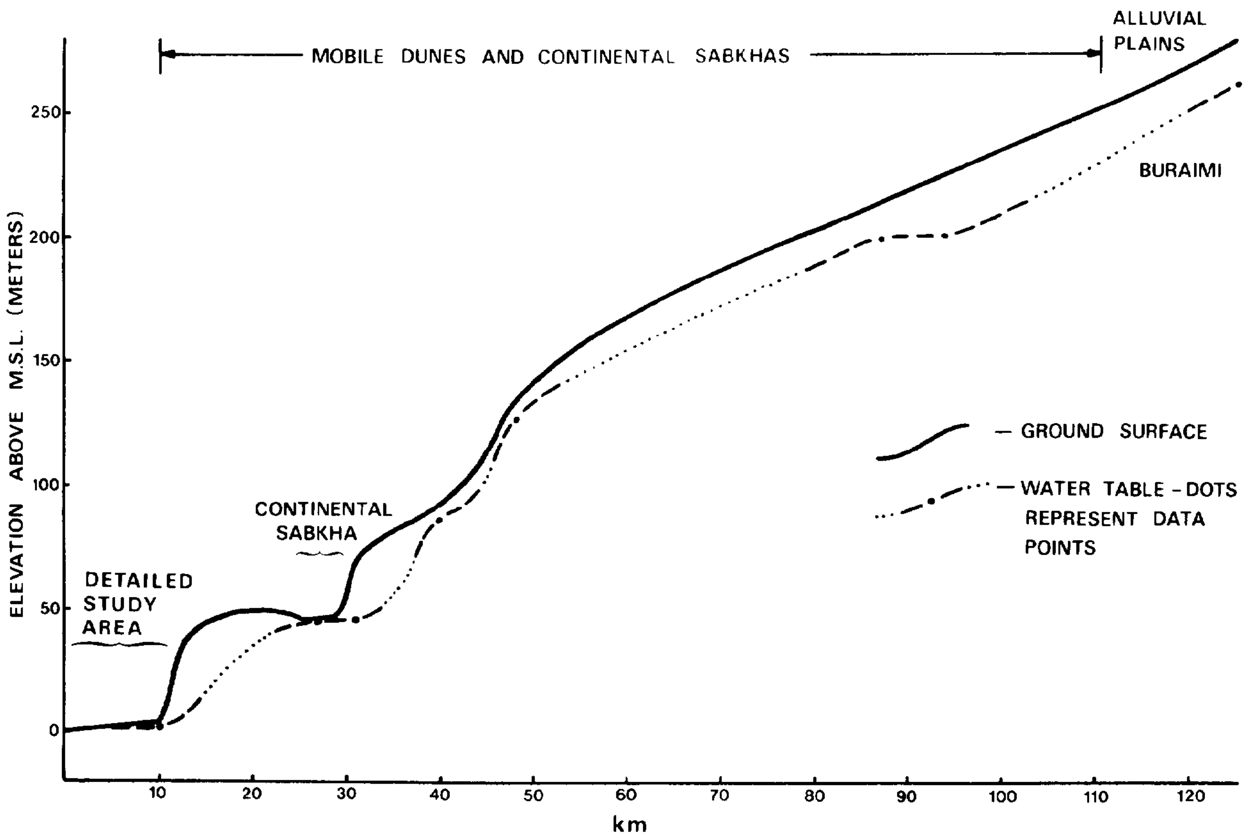

FIG. 7—Elevation of water-table surface between detailed study area and oasis of Buraimi at foot of Oman Mountains.

is about 1:4,000. Farther inland across most of the continental sabkha the gradient is even smaller, averaging about 1:20,000 to 1:30,000. Near the landward margin of the sabkha the water-table gradient and also the surface gradient (Fig. 4) are much steeper. Pits dug in this region revealed a very dense Miocene marl about 1 m below the sabkha surface. The sharp increase in water-table slope probably reflects the low permeability of the marl.

Water levels in the piezometers never differed by more than 1 or 2 cm from water levels in adjacent shallow pits, and the differences over time were not consistently in one direction. In addition, no variation in water level was noted between closely spaced holes of different depths, even though some of the holes were 2 m deep and penetrated lithified layers. These results are in contrast with those reported by Hsu and Schneider (1973) who concluded, on the basis of water-level measurements in a standpipe (approximate location shown on Fig. 6), that there is a significant increase in hydraulic potential with depth in the upper meter of the saturated zone. It is possible that the differences in results simply reflect changes in the ground-water flow system between the two periods of measurement. Alternately, as discussed later, the different results obtained by Hsu and Schneider may indicate significant variations in vertical gradient from place to place.

Although vertical hydraulic gradients were not measured, it should not be concluded that relatively significant vertical gradients are absent. A vertical gradient equivalent to the horizontal gradient (1:4,000) would produce a water-level difference of about 1 mm in a piezometer screened 5 m below the water table, and such a small difference would not be detectable. Thus, relatively significant vertical gradients may exist in the ground-water flow system beneath the sabkha.

Figure 7 shows the elevation of the water table between the detailed study area and the oasis of Buraimi (Fig. 2). The configuration of the water table indicates that the ground-water system in the detailed study area is the distal part of a regional seaward-flowing regime.

Temporal Variation of Water-Table Level

In November 1968, the water table was lower than on August 29, 1968, but the decline was not uniform throughout the sabkha. Across the part of the coastal sabkha that was not subject to tidal and wind-driven flooding (i.e., approximately the area between the 80-cm contour on Fig. 5 and the 1.25-m contour on Fig. 6), the water table declined uniformly about 8 cm. Farther inland in the continental sabkha, the water table only dropped an average of 4 cm. On January 5, 1969, a further drop of 6 cm and 3 cm had occurred in the two areas respectively. The observed rates of change in the water-table level, if projected, are equivalent to a decline of about 40 cm/year in the coastal sabkha and 20 cm/year in the continental sabkha.

Between January 5 and 11, 1969, approximately 7 cm of rainfall were measured at the laboratory in Abu

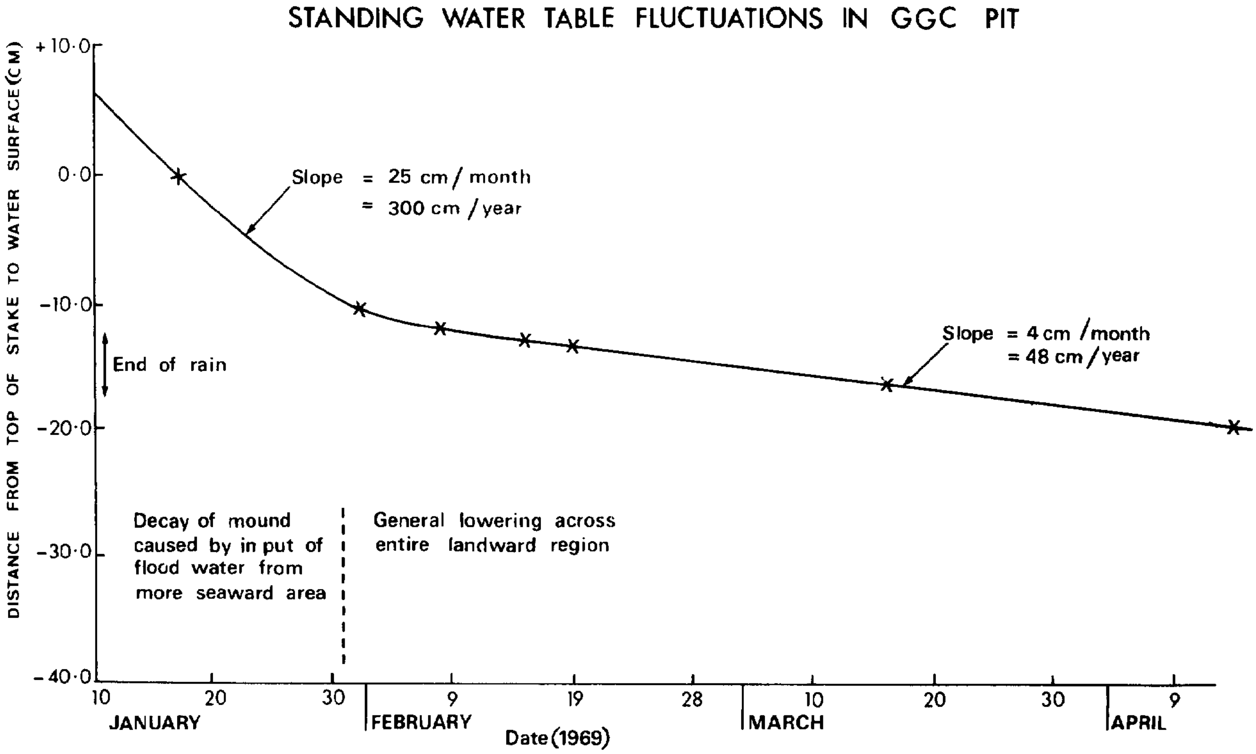

FIG. 8—Water-table elevation in GGC pit from January 11, 1969, to April 25, 1969. For location, see Figure 5.

Dhabi. Much of the precipitation occurred during thunderstorms and, therefore, the amount of rainfall in the study area may have varied somewhat, but probably not greatly, from that measured in town.

Following the rain, the surficial halite crust on the sabkha was completely dissolved, and strandlines around spoil heaps indicated that the coastal sabkha and some seaward parts of the continental sabkha were flooded to a depth of a few centimeters. Flooding occurred because this area is underlain by relatively impermeable anhydrite layers which retard percolation (Patterson, 1972). Current ripples in the seaward area indicated that some of the floodwater flowed over the surface to the sea. The orientation of sediment tails behind small projections and obstacles on the sabkha showed that moderate onshore winds impelled part of the floodwater inland beyond the area underlain by anhydrite where it infiltrated and percolated through the permeable eolian sands. Thus, maximum infiltration of rainfall occurred in a narrow zone that is located near the 100-cm contour on Figure 5.

On January 16 and 17, water-level measurements in the continental sabkha showed that the water-table level had changed dramatically as a result of the rain. Most levels had risen about 35 cm, except in the narrow zone where wind-driven floodwaters had infiltrated. In this zone, the water table was up to 50 cm above the January 5 level, indicating that the selective input of floodwater had produced a local ground-water mound. Figure 8 shows the change in water-table level in the GGC pit located in the area of the mound. The water table dropped rapidly following the rain, and then declined uniformly at a rate of 4 cm/month. This latter rate of lowering was similar to that measured simultaneously in pits several kilometers inland from the mound. Consequently, the local ground-water mound disappeared during the first month following the rain.

The 4-cm/month rate of water-table decline was too rapid to be entirely the result of evaporative losses because, during the hot, dry part of the year, the water table in this area dropped less than 2 cm/month. The increased rate of decline following the rain, therefore, must have been due to lateral flow, probably through the permeable eolian sands which crop out in the continental sabkha and underlie the marine sediments in the coastal sabkha (Fig. 3).

On March 18, 1969, water-table levels were measured in freshly dug pits in the part of the sabkha that had been flooded. New pits were required because the original holes had been filled with water and served as points of local recharge. The measurements in March indicated that the water table had risen by 35 to 50 cm as a result of the rain. Thus, the water-table level had been raised more than enough to offset the projected annual rate of decline of 40 cm and to maintain year to year stability. As much of the rain did not infiltrate but ran off to the sea or was propelled inland by winds, it is unlikely that direct infiltration and percolation of rainfall accounted for all the increase in water-table level. More probably, seaward ground-water flow from the upgradient continental sabkha where the water table declined rapidly following the rain was responsible for some of the water-table rise.

Relation of Mean Water-Table Position to Sediment Stratigraphy

Near the present strandline, the mean water-table level coincides closely with the top of the intertidal sediments, but with increasing distance inland it gradually rises above the intertidal units into the supratidal evaporite and eolian sediments. At the highest Holocene shoreline position (Fig. 3), the mean water table is about 30 cm above the intertidal units. Thus, as the sabkha progrades the mean position of the water table at a given location rises slowly through the stratigraphic succession. Accompanying the rise in the water table is the accretion of supratidal eolian and evaporite sediment to maintain a state of deflational equilibrium. This trend results in the marine sabkha facies becoming progressively more deeply buried as the sabkha progrades.

Water Chemistry

Pit waters—Figure 9 shows the variation in the chloride concentration of pit waters across the sabkha. The chloride concentration increases progressively from both the landward and seaward sides of the sabkha toward a large central area where concentrations range between 4.0 and 4.7 m Cl^-/kg. In this central region of uniform concentration called the "chloride plateau," ground waters are at, or near, saturation with respect to halite.

The increase in the concentration of chloride from the landward edge of the sabkha is the result of evaporative losses through the sediment section above the water table as the ground waters move seaward. At the seaward margin of the sabkha, the concentration gradient results from the infiltration and percolation of shallow, wind-driven masses of seawater that periodically flood an area extending inland as far as 5 km from the normal high-tide position. This type of marine flooding, which is distinct from that following heavy rains, occurs because the slope of the sabkha is so slight (1:3,000). On surfaces of such gentle gradient, wind friction replaces slope as the main influence on the direction of motion of shallow bodies of water. Thus, periodic strong onshore winds propel sheets of seawater, up to a few centimeters in depth, inland over the surface of the sabkha. These water masses continue to move landward until they are depleted by evaporation and infiltration, or the wind diminishes. The floodwaters move farthest inland along remnant, infilled, intertidal channel courses which are preserved as slight topographic depressions in the sabkha surface and are underlain by muddy sediments that restrict infiltration. Chloride concentrations of the ground waters beneath the flooded area reflect the extent to which the seawater masses are evaporated prior to infiltration. The maximum observed extent of marine flooding is shown on Figure 10. The flooding process plays a fundamental role in many of the diagenetic reactions, such as dolomitization (Patterson and Kinsman, 1981), in the sabkha environment.

The chloride results show that the shallow ground waters beneath the sabkha are more concentrated than seawater in the lagoon (0.65 to 0.85 m Cl^-/kg), and thus have a higher specific gravity. As a consequence, the hydraulic potential of sabkha ground waters with respect to the sea is even greater than indicated by the height of the water table above sea level.

Marine-derived and continentally derived ground waters may be differentiated using ion ratios such as mCl^-/mBr^- and mK^+/mBr^- (Patterson and Kinsman, 1977). The distribution of these ratios across the sabkha shows that continentally derived waters displace marine-derived brines seaward as the sabkha progrades. The present position of the zone of mixed marine and continental waters within the chloride plateau (Fig. 10) indicates a seaward ground-water flow rate in the central sabkha area of 0.3 to 1.0 m/year (Patterson and Kinsman, 1977).

Observations from a helicopter revealed that some of the surface of the most landward part of the chloride plateau is characterized by a pattern formed by discontinuous linear areas which are slightly different in color from the general sabkha. These linear features are oriented in either of two almost perpendicular directions; the pattern therefore resembles an incomplete net. From the ground these features are barely noticeable, as the color difference is slight and, in total, they do not represent a large proportion of the surface area. Excavations across the elongate features revealed that gypsum is the only sulfate mineral present and that much of the gypsum appears to have formed as a result of the hydration of nodular anhydrite. Similar gypsum is present just inland of the chloride plateau because the landward margin of the plateau is slowly moving seaward. The reticulate pattern on the surface is probably the result of relatively dilute ground waters seeping from joints and fractures in the underlying Miocene rocks. If seepage is occurring beneath the linear features, steep vertical hydraulic gradients may be present. It is possible that Hsu and Schneider (1973) obtained their water-level results from such an area.

Squeeze waters and piezometer waters—Figure 11 shows the variation in chloride concentration of groundwaters along a section extending from beneath the lagoon to the inland margin of the chloride plateau. Beneath the chloride plateau, there is a small decrease in chloride concentration with depth and a slight lateral increase in concentration at any given depth toward the center of the plateau. The upward increase in concentration reflects evaporation at the sabkha surface and indicates an upward ground-water flow component.

Seaward of the chloride plateau, the chloride concentration remains approximately constant with depth. This pattern occurs because the region is periodically flooded by marine waters and there is a net downward movement of water. Study of the process of dolomitization indicates that the average downward flow rate is about 4 cm/year (Patterson and Kinsman, 1981).

Beneath the lagoon the concentration contours (Fig. 11) define a tongue of high chloride waters that can be traced at least 2 km from the present strandline. This pattern indicates that dense brines from the sabkha are flowing, or refluxing, beneath the lagoon. Because the sabkha is prograding at about 2 m/year, the waters beneath the lagoon must be flowing seaward at a rate in excess of 2 m/year. Similar refluxing of brines is

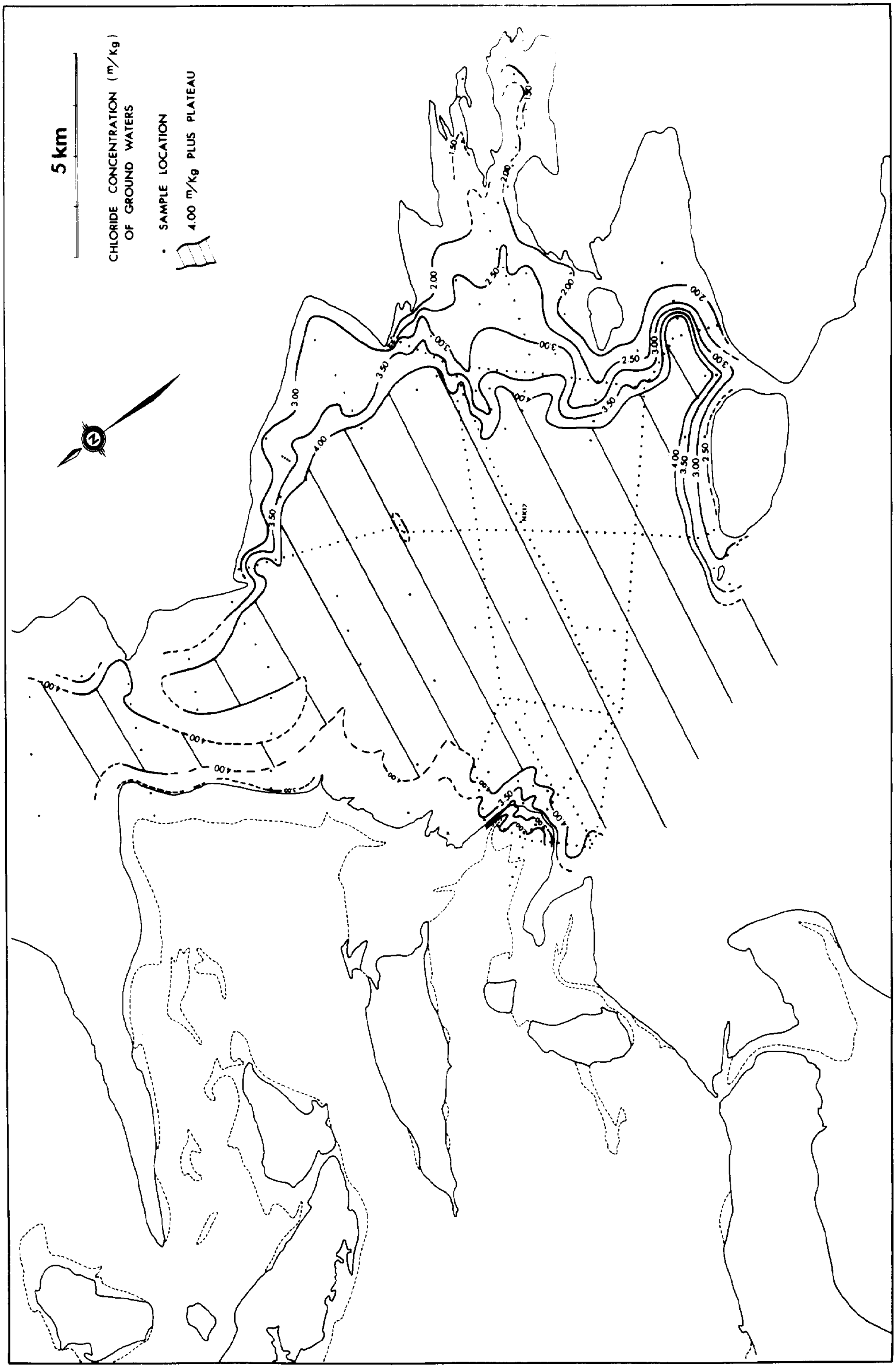

FIG. 9—Chloride concentration (m/kg) of shallow ground waters. Hachured area where chloride concentrations range from 4.0 to 4.7 m/kg is called "chloride plateau."

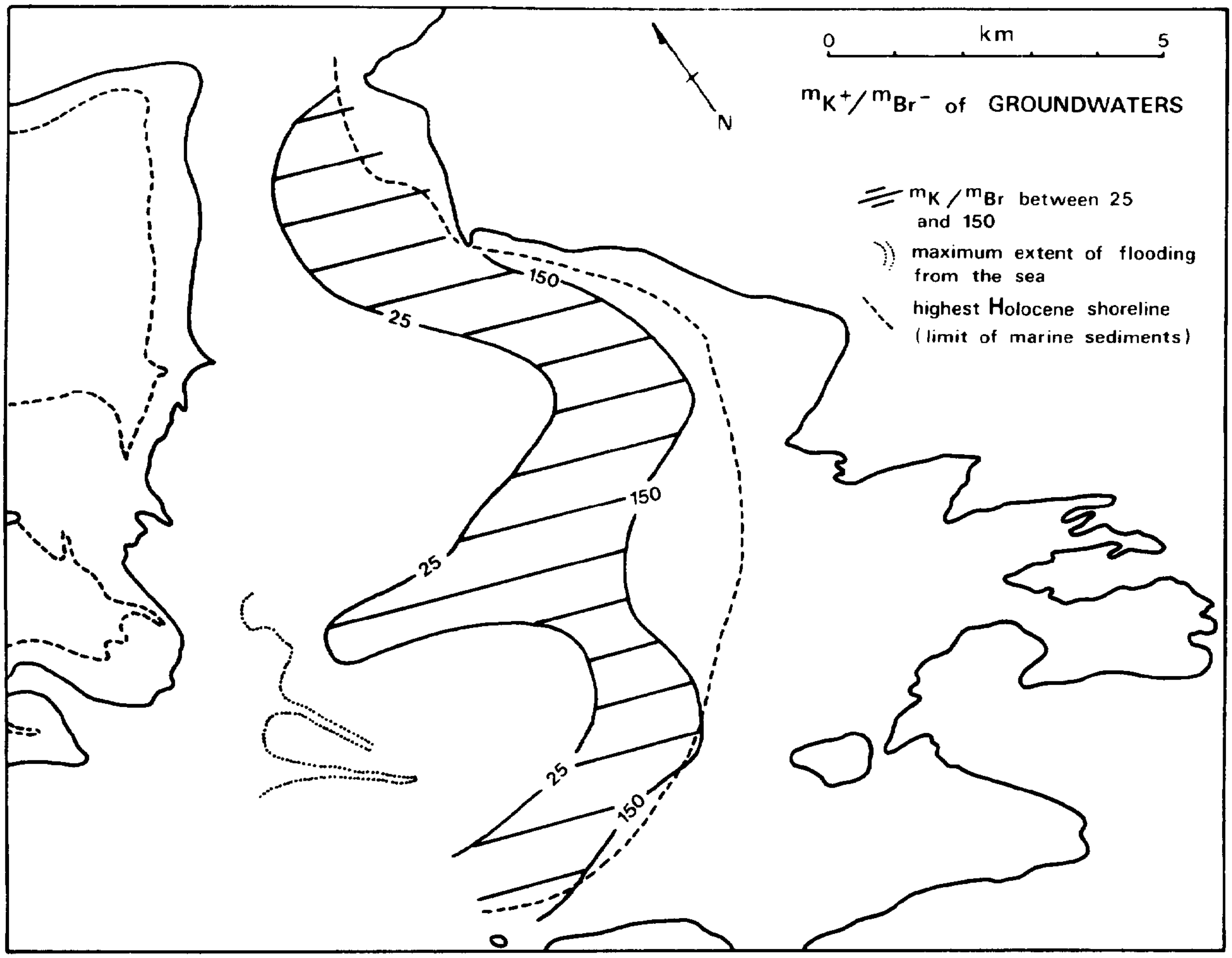

FIG. 10—m K+/m Br− ratio in ground waters of sabkha. Zone of mixed continental and marine brines lies between the 25 and 150 contours.

reported to be occurring in a dominantly quartz sand sabkha at Umm Said, Qatar (de Groot, 1973).

Evaporation Rates from Sabkha

The projected rates of water-table decline (40 cm/year in the coastal sabkha and 20 cm/year in the continental sabkha) may be employed to estimate annual evaporative losses from the sabkha. These estimates should be considered as very approximate, because the data cover less than half a year and inflow from the regional ground-water system undoubtedly offsets some of the evaporative losses, especially in the landward region. Also, only porosity rather than specific yield data are available for the sediments. The marine sediments have maximum measured porosities of 50 to 60%, but average about 40%, and the eolian sands have porosities on the order of 30%. Assuming average values for porosity, evaporation rates of 16 and 6 cm of fluid per year are indicated for the coastal and continental sabkhas respectively. The value of 16 cm for the coastal sabkha area is probably much too high because the specific yield of the fine-grained marine sediments should be significantly lower than the porosity. If rainfall (on average about 3 to 4 cm/year) is excluded because it may be considered as an addition and subtraction of distilled water, the net maximum evaporation rate for the coastal sabkha becomes about 12 cm of ground water per year.

A lower, but still comparable, net evaporation rate for the coastal sabkha is independently obtained from the amount of anhydrite in the section (Patterson, 1972). Ground waters throughout the coastal sabkha are saturated with respect to anhydrite and, therefore, a given evaporative loss should result in the precipitation of a specific amount of anhydrite. Also, because anhydrite forms in the subsurface it is likely that none has been removed. Calculations incorporating these assumptions indicate that the average net evaporation rate in the coastal sabkha during the last 4,000 to 5,000 years has been, to within a factor of 2, about 6 cm of ground water per year. It is felt that this figure is the most reliable estimate of the net evaporation rate because it represents an average over several thousand years.

The agreement between the net evaporation rates determined by water-table lowering and evaporite mineral accumulation suggests that the rate of ground-water inflow to the sabkha from the regional system must be relatively slow. If a good hydraulic connection

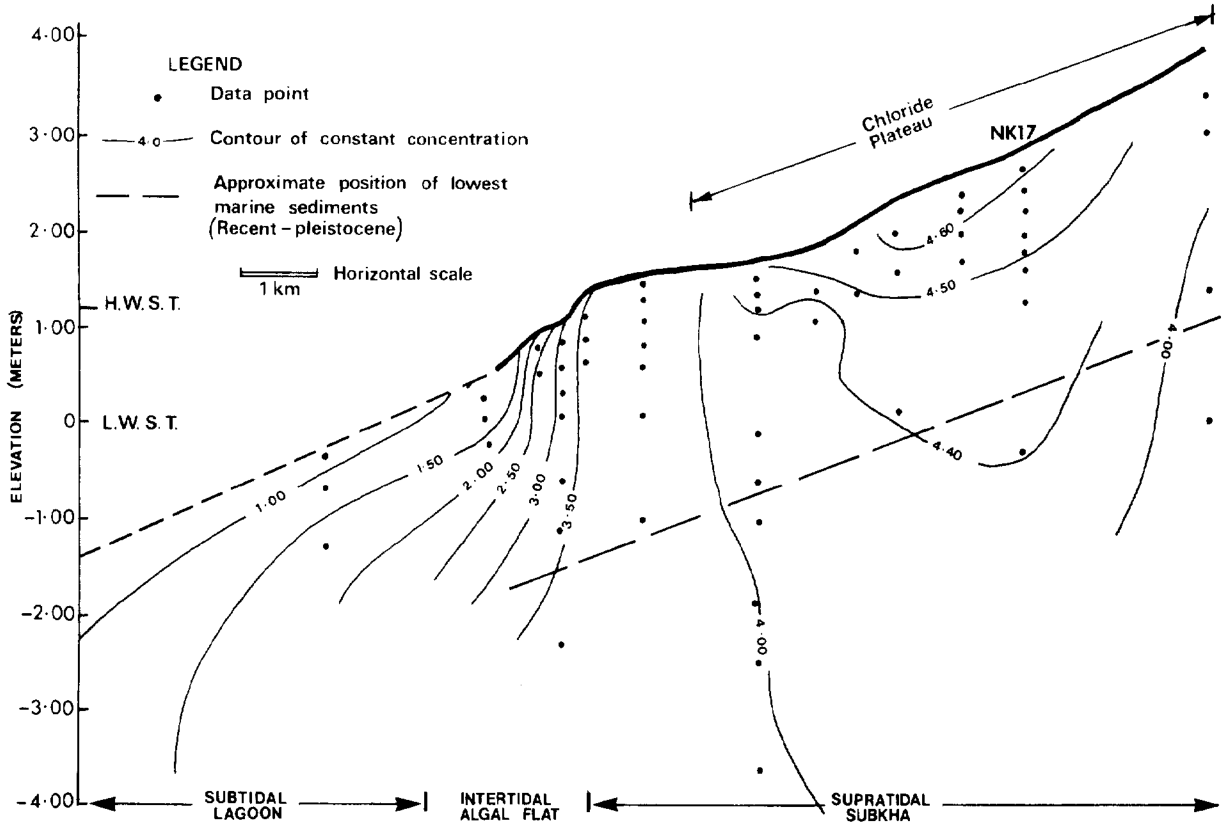

FIG. 11—Vertical variation in chloride concentration (m/kg) of ground waters along section through sabkha extending from beneath lagoon to inland margin of chloride plateau. Waters obtained from piezometers and by squeezing sediments.

with the regional ground-water system existed, the evaporation rate calculated from the water-table decline should have been much lower than that based on anhydrite accumulation.

A net evaporation rate of about 6 cm of ground water per year is relatively low compared with the mean annual evaporation rate of 124 cm/year for the south part of the Arabian Gulf (Privett, 1959). However, many factors, such as the sediment section above the water table, high ionic strength fluids, high average relative humidity, and vertical stratification of the air mass above the sabkha, significantly reduce the rate of evaporation from the sabkha compared with that from the Gulf.

The sediment section above the water table is a particularly important factor in reducing the rate of evaporation from the sabkha. Experimental data (Chow, 1964) show that if the water table is at a depth between 50 and 100 cm the rate of evaporation may be reduced by an order of magnitude compared to a free water surface. As the depth to the water table across most of the coastal sabkha ranges from 30 to 80 cm, this factor alone should significantly reduce the rate of evaporation, perhaps by as much as an order of magnitude. During field work, it was observed that halite accumulated much faster in water-filled pits than at the sabkha surface where only a thin crust developed, demonstrating that the sediment above the water table greatly retarded upward movement of ground water and thus reduced the evaporation rate.

A further reduction in the rate of evaporation occurs because the ground waters have high ionic strengths. On the basis of data presented by Bonython (1956), the evaporation rate of the brines beneath the chloride plateau should be lowered by about 25% compared with seawater.

The high average relative humidities in the region also lower the evaporation rate from the sabkha. Throughout the afternoon, the relative humidity is about 70 to 80% and at night commonly reaches 100%. When the humidity is in excess of 75%, a salt-encrusted surface such as the sabkha will not lose water by evaporation but will absorb moisture because the vapor pressure of water in the atmosphere exceeds the equilibrium value for a saturated sodium chloride solution. This process of absorption occurs on the sabkha during the night (Kinsman, 1976). By morning the surface is moist and shallow puddles commonly develop in some places. Thus, before any net evaporation of ground water can occur each day, the moisture which has been absorbed during the night must be reevaporated.

Finally, evaporation is retarded by well-developed stratification in the air above the sabkha (Patterson, 1972). Stratification occurs because there is little relief on the sabkha to encourage turbulence and vertical mixing.

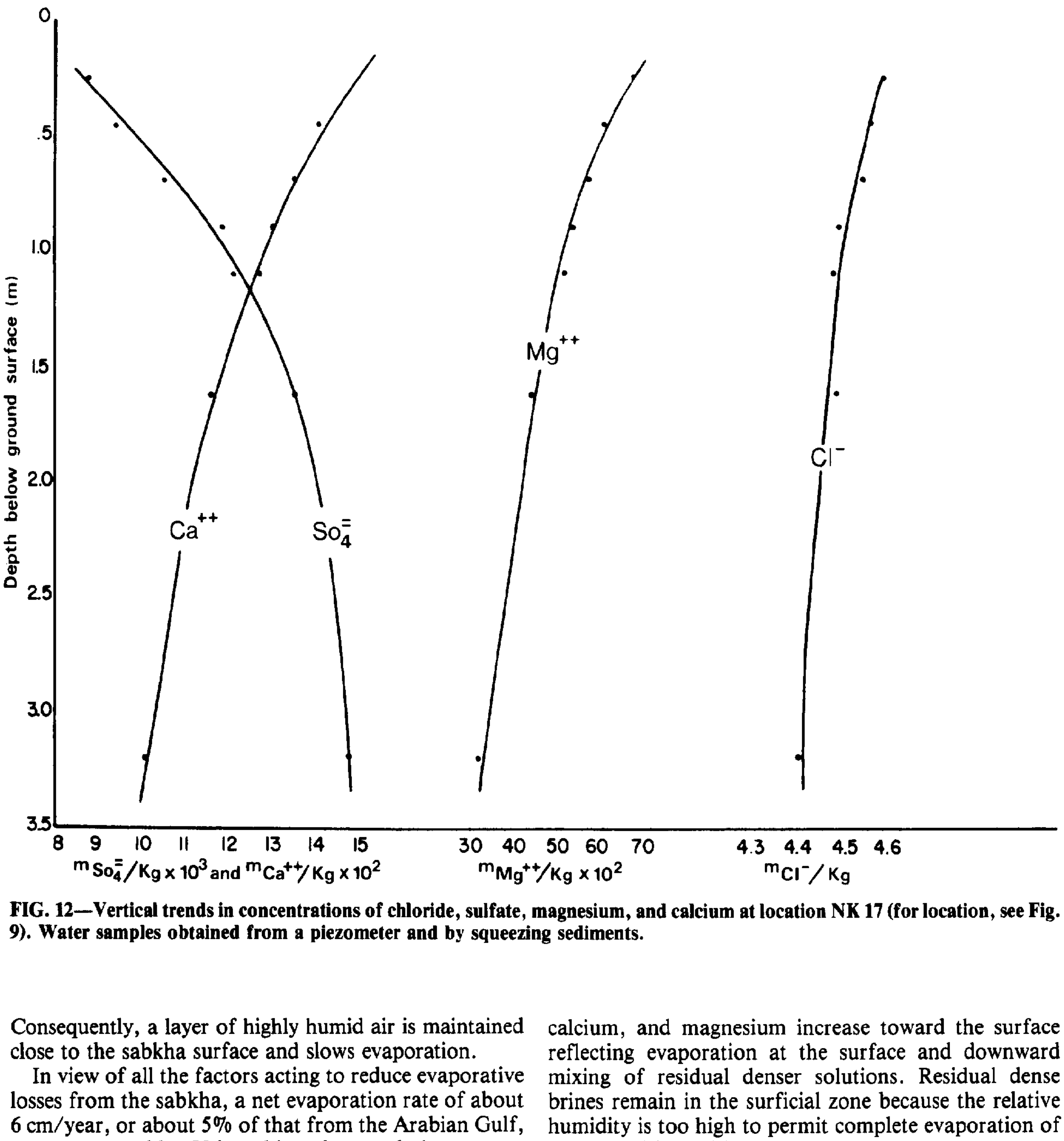

FIG. 12—Vertical trends in concentrations of chloride, sulfate, magnesium, and calcium at location NK 17 (for location, see Fig. 9). Water samples obtained from a piezometer and by squeezing sediments.

Consequently, a layer of highly humid air is maintained close to the sabkha surface and slows evaporation.

In view of all the factors acting to reduce evaporative losses from the sabkha, a net evaporation rate of about 6 cm/year, or about 5% of that from the Arabian Gulf, seems reasonable. Using this value, and the average porosity of about 40% for the marine sediments, the net average upward ground-water flow velocity across most of the coastal sabkha is on the order of 15 cm/year. Such a slow flow rate is consistent with the piezometer water-level data since it would not produce a measurable head difference over a depth interval of a few meters.

Vertical Concentration Gradients Beneath Chloride Plateau

Figure 12 shows the variation in concentrations of chloride, sulfate, magnesium, and calcium with depth at location NK17 (Figs. 9, 11) near the center of the chloride plateau. The concentrations of chloride, calcium, and magnesium increase toward the surface reflecting evaporation at the surface and downward mixing of residual denser solutions. Residual dense brines remain in the surficial zone because the relative humidity is too high to permit complete evaporation of the interstitial fluids.

Differences in the gradients for the various ions reflect the precipitation of diagenetic minerals. The solubilities of anhydrite and halite exert strong controls on the concentrations of sulfate, calcium, and chloride. Precipitation of anhydrite is responsible for the upward decrease in the sulfate concentration, however, the calcium concentration does not decrease similarly as the m Ca^{++}/m $SO_4^{=}$ ratio is always much greater than one. The solubility of halite limits the maximum chloride concentrations that may be achieved and, consequently, the maximum gradient for this ion. Magnesium does not participate in reactions involving solids (the m Mg^{++}/m Ca^{++} ratio is too low for dolomite or magnesite formation; Patterson, 1972) but its concentration may be influenced by ion exchange.

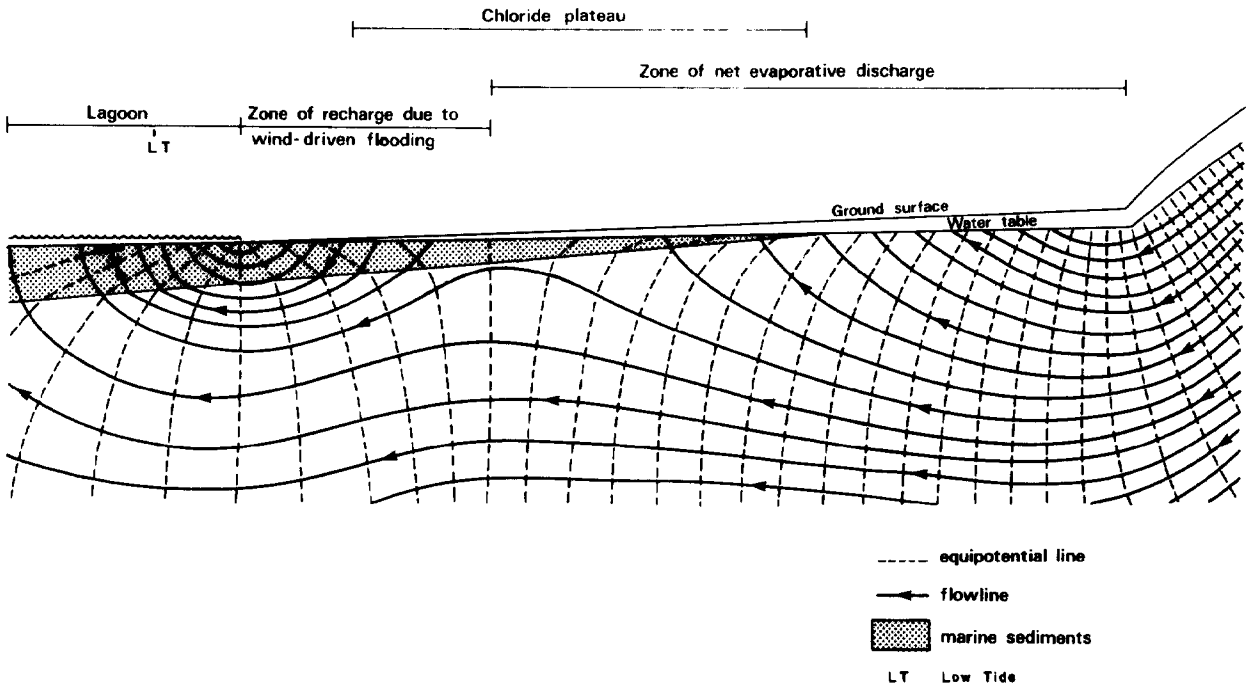

FIG. 13—Schematic flow net for section through sabkha oriented perpendicular to coastline. Marine sediments are assumed to be much less permeable than underlying materials which are not differentiated.

DISCUSSION

Figure 13 is a schematic flow net illustrating the inferred pattern of ground-water flow along a section through the sabkha perpendicular to the coastline. The flow pattern reflects inflow from the regional ground-water system, evaporative losses from the sabkha, recharge in the seaward areas as a result of wind-driven flooding, and reflux of sabkha brines beneath the lagoon. No attempt has been made to account for specific gravity differences in the ground waters or local variations in the infiltration of rainfall. Incorporation of these factors would result in more complexity, but the basic pattern probably would not be changed.

Along the south shore of the Arabian Gulf, the climatic, physiographic, hydrologic, and sedimentologic conditions are suitable for the formation of broad coastal sabkhas. The sabkha studied in the Abu Dhabi area is prograding seaward at approximately 2 m/year owing to sedimentary offlap and a slowly falling, relative mean sea level. As progradation continues, the water table in the sabkha rises in relation to the stratigraphy as a result of the hydraulic connection with the regional ground-water system. This rise in water table is matched by the accretion of eolian sands and diagenetic evaporites, progressively burying the marine sediments. Under these conditions continued development of the sabkha seems unrestricted and the sabkha facies that are formed should have a high potential for preservation because of their burial during progradation. The inferred pattern of development of the Abu Dhabi sabkha through time is schematically summarized in Figure 14.

Assuming suitable climatic conditions, it is apparent that two factors exert very fundamental controls on the rate and pattern of development of the sabkha in Abu Dhabi: hydraulic connection with a regional ground-water system and a slowly falling, relative sea level position. To gain a better understanding of sabkha development, it is necessary to evaluate the importance of these factors. The significance of a regional ground-water system connection is provided by the results of studies of a coastal sabkha in Qatar (Illing et al, 1965). Owing to low relief and low rainfall, the Qatar peninsula does not support a ground-water system with a strong seaward gradient. The water table in the Qatar sabkha is approximately horizontal at the high-tide position except near the inland margin where it falls rapidly in the landward direction. It is likely that the water-table level is falling in the inland areas because evaporative losses exceed the inputs by rainfall, occasional wind-driven marine flooding, and subsurface flow. In addition, the decline in the water table has probably been augmented by the late Holocene relative fall in sea level. The inferred differences in subsurface flow patterns in the Abu Dhabi and Qatar sabkhas are illustrated schematically in Figure 15.

Comparison of the stratigraphy in the Qatar and Abu Dhabi sabkhas indicates that surface deflation rather than accretion is taking place in the landward areas of the Qatar sabkha. The surficial, brown eolian layer in Qatar is thin (less than 4 cm) and gypsum discs and diagenetic dolomite, which are present only in the subsurface at Abu Dhabi, are exposed at the surface. The deflation is the result of the declining water-table level. This sabkha, therefore, does not have the same poten-

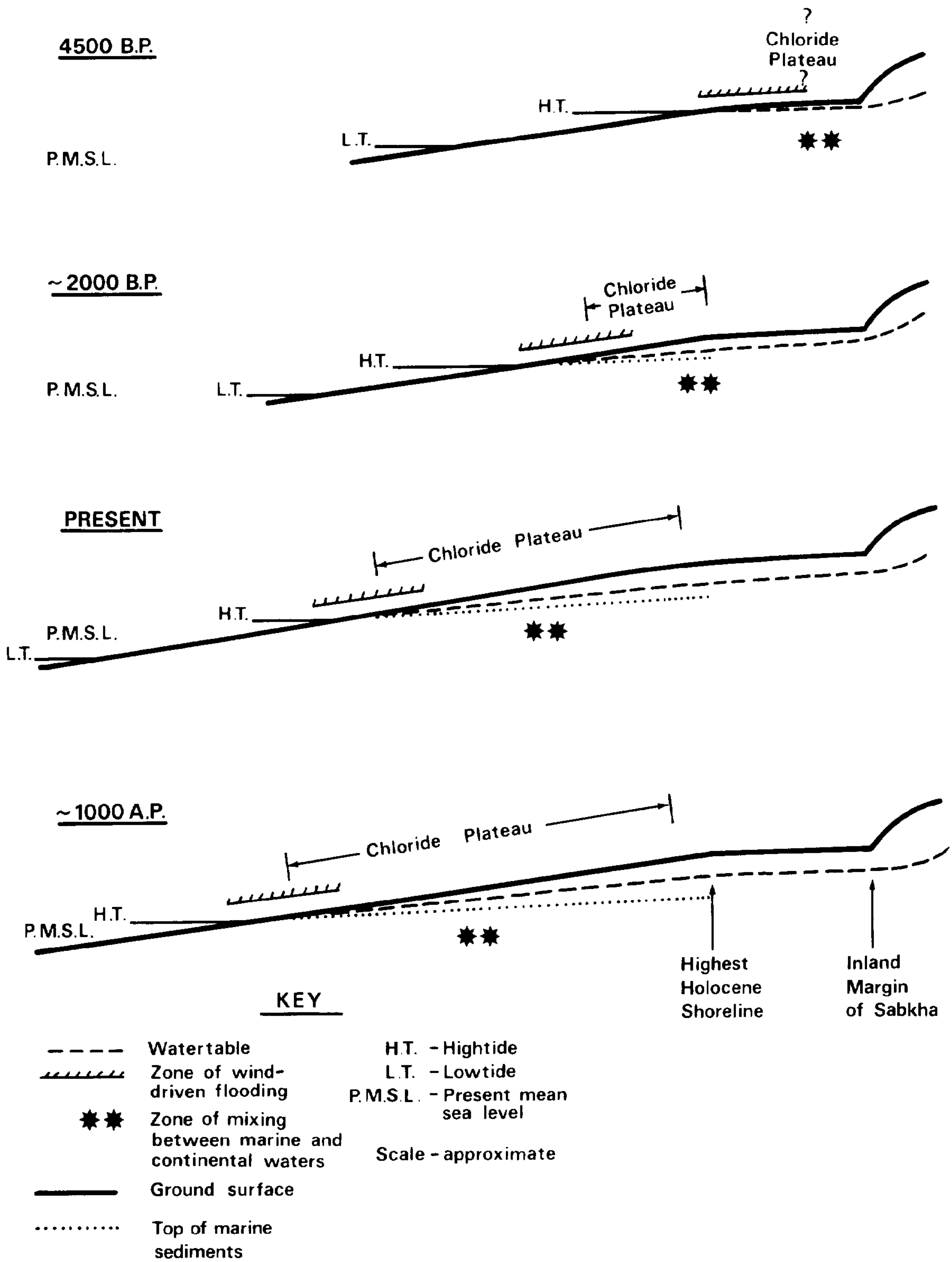

FIG. 14—Schematic diagram showing development of Abu Dhabi sabkha through time.

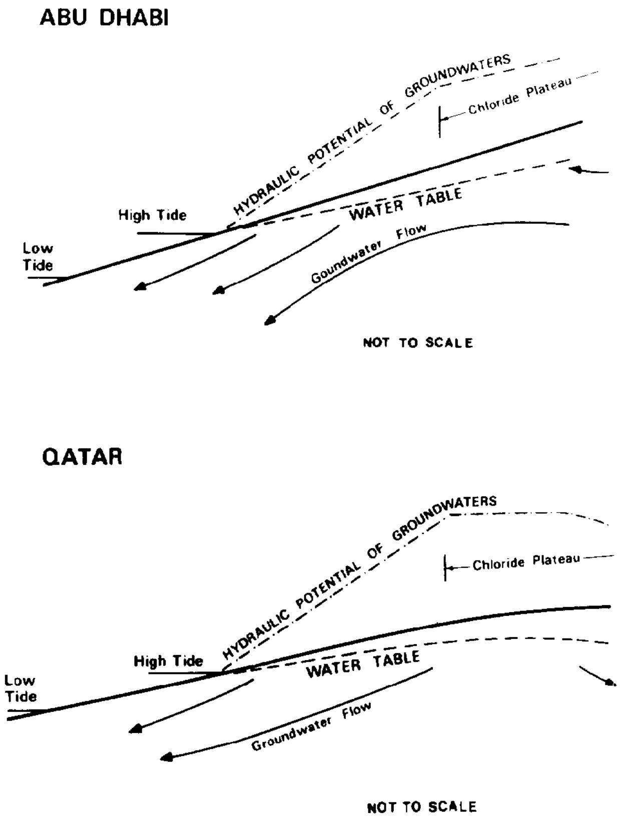

FIG. 15—Schematic diagram showing subsurface flow patterns in nearshore areas of Abu Dhabi and Qatar sabkhas.

tial for expansion and preservation as those in Abu Dhabi, for continued expansion will result in accelerating deflation in the landward areas and destruction of the underlying marine sediments. If the rate of deflation increases with additional progradation and exceeds the rate of sea level decline, the landward area will be reduced below sea level and marine flooding could recur. E. A. Shinn (personal commun.) indicates that this has occurred in local areas in Qatar. Thus, with a falling sea level, connection with a continental ground-water system which can maintain water-table levels and prevent deflation seems to be essential for the development and preservation of a broad sabkha.

Under steady sea level conditions, the rate of progradation of a sabkha would obviously be reduced, assuming a constant rate of sediment supply, compared to a falling sea level situation, but again connection with a regional ground-water system seems necessary to permit a broad sabkha to form and be preserved. Without a regional ground-water system, evaporative losses from the sabkha beyond the area of wind-driven flooding would eventually lower the water table and establish a ground-water potential gradient that slopes inland. As the sabkha becomes broader by sedimentary offlap the water-table elevation at inland locations would become progressively lower, resulting in deflation and loss of at least some of the marine sediments. At some point the sabkha surface in the inland areas would be reduced below sea level and marine flooding could occur. Consequently, it seems unlikely that sabkhas much broader than those in Qatar could develop and be preserved under steady sea level conditions without input from a continental ground-water system. However, with a continental ground-water system, development of broad sabkhas similar to those in Abu Dhabi would be possible.

Sabkha development under rising sea level conditions is more speculative. In this situation, the maximum rate at which the sea level could rise and still permit a sabkha to prograde is strictly limited by the rate of sediment accumulation. If the rate of sea level rise exceeds the rate of sediment accumulation, transgression would occur and a sabkha could not prograde. It is, perhaps, improbable that the rate of sea level rise would remain sufficiently slow for an extended period of time to permit prolonged sabkha progradation under rising sea level conditions. Such conditions would result in a sabkha that increases in width slowly and in which each sedimentary facies attains a considerable thickness. As before, it is probably possible to develop and preserve a broad sabkha only if a regional ground-water system is present. Without a regional ground-water system, increases in sea level would raise the water table near the strandline of the sabkha, but because the maximum rate of sea level rise could not be rapid, it is unlikely that a continuously rising water table could be maintained much farther inland than under steady sea level conditions. Once more, the inland area eventually would be subjected to deflation followed by marine flooding.

In summary, therefore, an important requirement for the development and preservation of broad sabkhas is a continental ground-water system with a seaward gradient. This requirement implies the presence of a large landmass and suggests that sediment accumulation on a shallow shoal could not produce a broad sabkha. Sea level conditions are not as significant in the development of sabkhas and influence mainly the rate of progradation and thicknesses of the sabkha facies. Only under the condition where sea level was rising faster than sediments were accumulating would sabkha progradation not be possible.

A flow pattern involving the shallow, subsurface, landward migration of seawater in response to evaporative losses from the sabkha surface (e.g., Kinsman, 1965) does not exist in Abu Dhabi. This conclusion is supported by the water-table elevation within the sabkha being always above the high-tide position and also by the presence of sabkha-derived brines beneath the lagoon. For subsurface landward flow of seawater to occur, landward-sloping hydraulic gradients would be required. Considering the high specific gravity of the sabkha brines relative to seawater, such a potential gradient would require a rather steep, landward-sloping water-table surface. As just discussed, such a water-table configuration would result in deflation in the landward parts of the sabkha ultimately limiting the process of sabkha development.

Within the sedimentary rock record, many units have features which indicate they probably represent sabkha facies (e.g., Choquette and Traut, 1963; Fischer, 1964; Schmidt, 1965; Schenk, 1967; Wilson, 1967; West et al, 1968; Fuller and Porter, 1969; Wood and Wolfe, 1969;

Bosellini and Hardie, 1973; Gill, 1977; Leeder and Zeidan, 1977). The most extensive (2×10^6 km^2) of the ancient sabkha units are the Upper Jurassic sulfate beds in the Arab and Hith formations of the Arabian Peninsula (Leeder and Zeidan, 1977). It is noteworthy, considering the requirements indicated earlier for the development of broad sabkhas, that these Late Jurassic sabkhas prograded eastward from the Arabian shield which could sustain a ground-water system with a seaward gradient.

A common characteristic of some of the ancient analogous units is cyclicity, or the apparent stacking of sabkha successions. Perhaps in Abu Dhabi, the present sabkhas are only the first of many that will be deposited. To stack successions containing anhydrite with characteristic sabkha structures and textures appears to be a serious preservation problem; if each regressive cycle is followed by a marine transgression, how is the anhydrite protected from contact with seawater and complete dissolution or hydration to gypsum with consequent changes in structure and texture? The hydrology of the sabkha suggests a mechanism for preserving anhydrite during marine transgression. Figure 11 shows that a tongue of saline water flows seaward beneath the present lagoon. Consequently, under transgressive conditions, as long as a sabkha is present, the refluxing of brines could keep the anhydrite in those parts of the sabkha that become covered by the sea in contact with concentrated solutions and maintain its stability with respect to gypsum. Also, the marine sediments deposited during the transgression would progressively bury the anhydrite more deeply and cause the brine-seawater mixing interface to rise, further insuring protection of the anhydrite. The fact that anhydrite with characteristics similar to those in present sabkhas has been preserved in transgressed analogous units in the geologic record is, of course, not conclusive proof that a hydrologic system similar to that in Abu Dhabi was present. However, it strongly suggests that hydrologic models involving the subsurface landward movement of normal seawater do not describe the flow systems that existed in the ancient sabkhas. If landward subsurface flow occurred, the anhydrite would have come into contact with seawater and would have been hydrated or dissolved.

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