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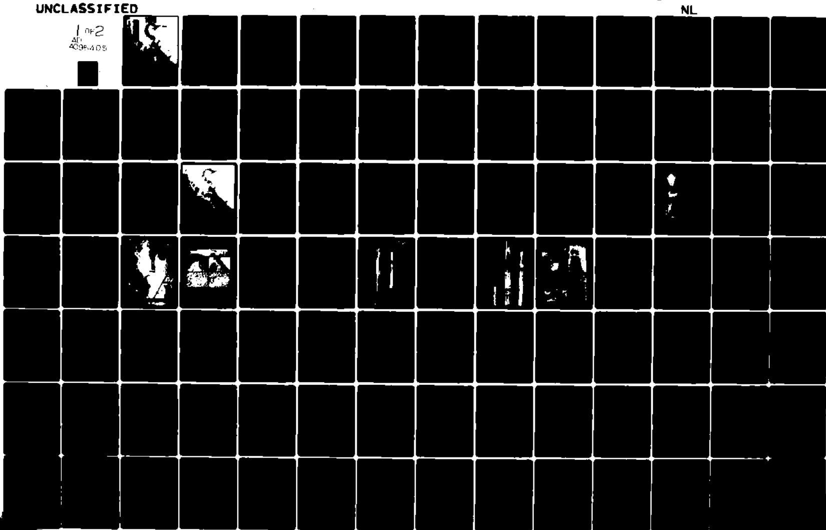

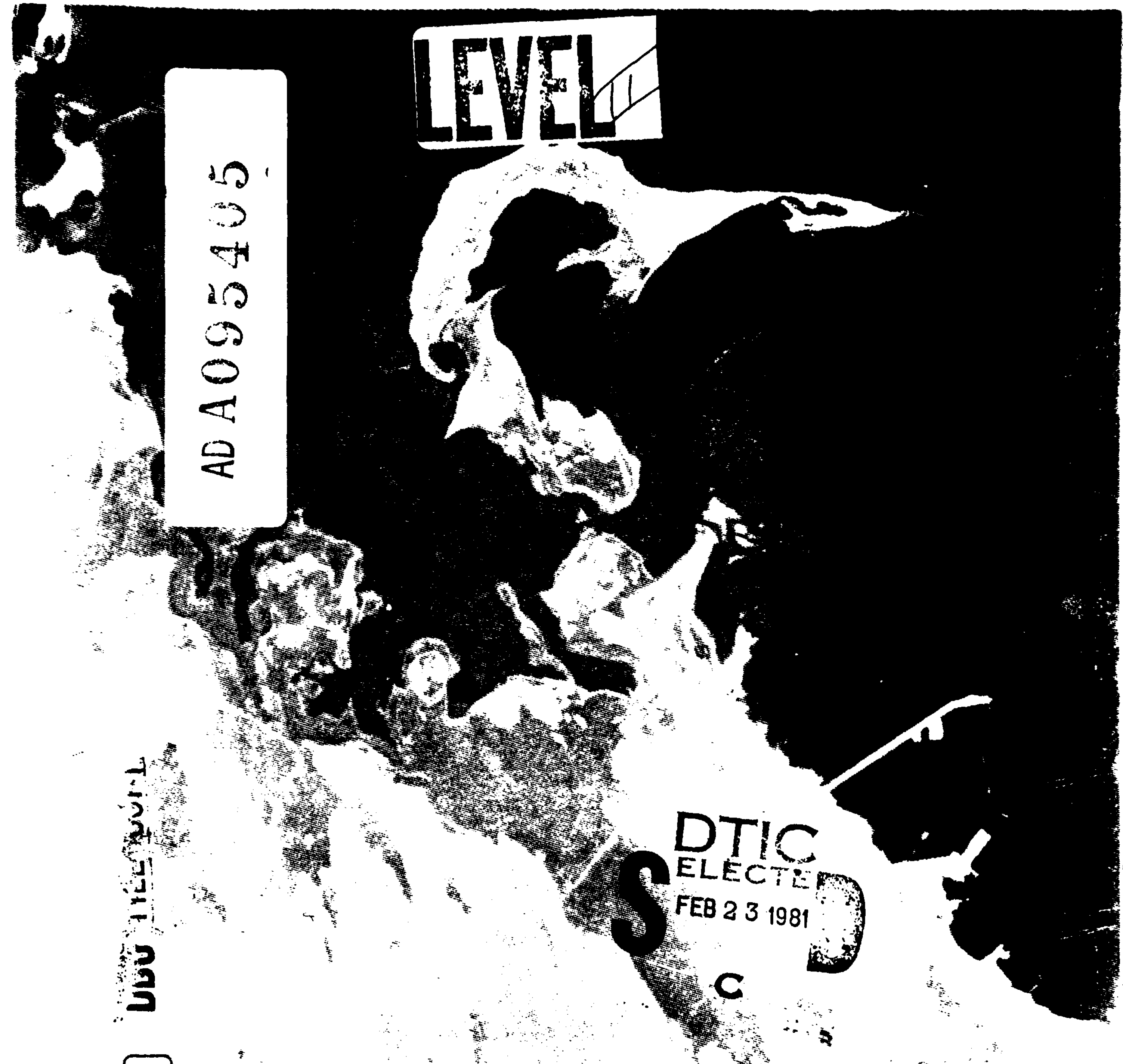

SABKHA TRAFFICABILITY

FRONTISPIECE

NASA LANDSAT color composite of the Jubail Region, 17 March 1979 at a scale of 1:1,000,000. Very dark to dark blue is the Arabian Gulf, whitish areas are sand dunes, light blue sabkha.

SABKHA TRAFFICABILITY

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INTRODUCTION

Many important human activities such as commerce require that goods be transported quickly and safely from one location to another. Historically, many major civilizations developed along both land and sea trade routes, routes which most efficiently linked producers and consumers. Ancient Mediterranean civilizations, from which Western civilization arose, are familiar to most Westerners. Few Westerners realize, however, that such trade routes were also extensive and, in fact, may have first originated in the Middle East (Bibby, 1970). Frankincense and myrrh, aromatic resins derived from several trees and shrubs native to the southern Arabian Peninsula, were transported through both the Red Sea and Arabian Gulf along marine trade routes which were well established thousands of years before Christ was born. Other products of the Arabian peninsula, such as pearls from the southern Arabian Gulf and copper from mines in Oman (which have since been depleted) also found their way into European markets.

That these Middle Eastern trade routes, particularly those in Arabia, were essentially marine, was no accident. Then, even more than now, goods could be transported more efficiently by sea. The Arabian Peninsula in general, and the central portion in particular was, and continues to be, very inhospitable. Potable water (although barely so by Western standards) is restricted to oases which are, in turn, separated by large expanses of barren sand desert. The various Bedouin tribes which inhabited the Arabian Peninsula were distrustful of one another in general and outsiders in particular. Until quite recently, this made land transportation a questionable undertaking.

From a practical point of view, Saudi Arabia did not enter the 20th century until the early 1930's when what is now known as the Arabian American Oil Company (Aramco) obtained concession rights to explore for oil in the eastern province of Saudi Arabia (Figure 1). The first Aramco geologists, two in number, arrived at Jubail via boat from Bahrain in the Fall of 1933 (Stegner, 1974). It was here that the initial exploration for oil in Saudi Arabia began. Outside of problems associated with obtaining what Westerners consider the basic amenities, the major difficulties encountered were associated with land transport. Bedouin guides were retained to identify trafficable routes for wheeled vehicles--not always, though, with notable success. Terrain requirements for wheeled or tracked transport are considerably different from those for camel transport.

Another characteristic feature of this portion of Arabia is large expanses of salt flats which are essentially devoid of vegetation. These regions, whose Arabic name *sabkha* has been applied generally to terrain of this type (Kinsman *et al.*, 1969), may extend inland for many miles and are often impassable to wheeled or tracked transport. The trafficability of sabkhas is a problem which, until now, has not been adequately assessed and which is addressed in this report.

Perhaps the most intriguing aspect of sabkhas relating to trafficability is the seemingly random manner in which the surface bearing capacity varies. During our initial exposure to sabkhas, it was observed that extensive sabkha flats were crossed by well traveled but isolated paths. These paths rarely followed a straight line but rather seemed to wander at random, often making 180° switchbacks within a few yards. Out of prudence, well traveled roads were normally followed when crossing sabkhas. The need for such caution has been frequently confirmed by the many pioneer roads which led from the older, well traveled roads

FIGURE 1 THE ARABIAN PENINSULA

and which frequently ended in an angry mound of mud, boards and old tires. Neither tracked nor ballooned tired vehicles were immune from miring since both types of vehicles have been observed deeply embedded in sabkha.

A working hypothesis for this research was that the original vehicle tracks across sabkhas followed meandering animal tracks, most likely those of camels. Since these original tracks across the sabkha show no apparent "wrong" turns, we further hypothesized that there must be some surficial characteristics of sabkha which camels and, possibly, bedouin tribesmen have learned to recognize. We, thus, endeavored to examine sabkhas to determine whether such surficial characteristics do indeed exist and, if so, then to quantify these characteristics in geotechnical-engineering terms for the benefit of future travelers. A glossary of scientific terms used in this paper is included as an addendum to this report.

SABKHA TERMINOLOGY AND DISTRIBUTION

There has not yet been a consistent acceptance in the geologic literature as to what constitutes a *sabkha*. Sabkhas, in accordance with the "type" areas of the Arabian (Persian) Gulf described by Curtis *et al.* (1963), are coastal (supratidal) or continental salt flats which may be underlain by clay, silt, and sand. These sedimentary features are considered to be equilibrium accretion-deflation surfaces whose elevation is often, if not always, controlled by the elevation of the groundwater table. The surface of sabkhas are evaporitic and may frequently be covered with a halite (salt) crust. Two types of sabkhas, continental and coastal, are found in Saudi Arabia. In most cases, continental and coastal sabkhas are internally (geologically) identical (Kendall, 1978). Some continental sabkhas may have had a marine origin, but the sole source of water for such areas is now terrestrial. In contrast, the primary source of water for coastal sabkhas appears to be marine, but coastal sabkhas may have a significant input of terrestrial water, particularly along their most landward edges. Coastal sabkhas, being supratidal, are also subject to periodic flooding at infrequent intervals.

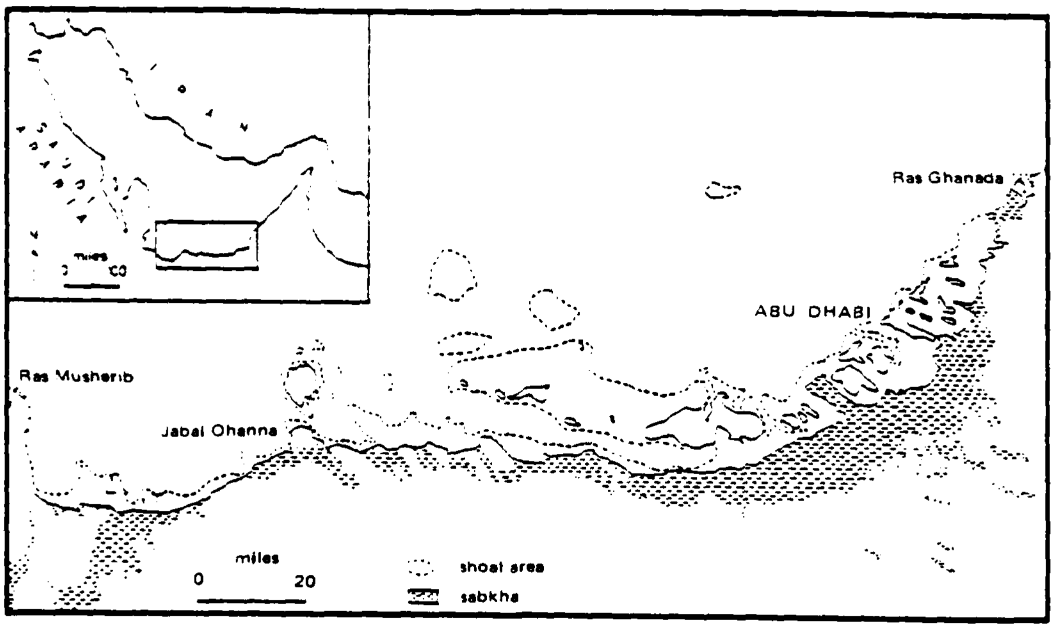
The Military Engineering Experimental Establishment (1969) defines a sabkha as the "Bottom of a closed depression....". The coastal sabkhas of the Arabian Peninsula are rarely closed depressions, but rather very gently sloping plains. The military definition is, though, applicable to continental sabkhas which is equivalent to the term "playa" (Reading, 1978). The term, itself, is also spelled in a number of different ways (sabka, sabkat, sebka, sebkha, sabkhah, sebkhah, sebkha, subkha, *etc.*). The spelling employed here as well as the definition of sabkha follows the standardization suggested originally by Kinsman (1969) and subsequently by Glennie (1970) and Whitten and Brooks (1972).

According to the definition employed by most investigators, modern sabkhas are to be found throughout the world. Pleistocene and recent carbonate deposits similar to sabkhas have been studied in Bermuda; the Bahamas; Laguna Madre, Texas; the Red Sea; Gulf of Aqaba; Gulf of Batabano, Cuba; Shark Bay, Australia; Campeche and Yucatan, Mexico; and Mallorca (Friedman, 1964); British Honduras (Kendall and Skipwith, 1969); the Sinai Peninsula (Gavish, 1971); and the North African coast along the Mediterranean (Shearman, 1966). Coastal playas closely akin to the predominantly carbonate Gulf sabkhas, but dominated by silicate sediments, have been studied in Baja California, Mexico at Laguna Mormona (Vonder Haar, 1975), Guerrero Negro, Ojo de Liebre and Manuela Lagoons (Phleger, 1965; 1969) and the Colorado river delta region in the upper Gulf of California (Thompson, 1968; Shearman, 1970).

SABKHA GEOLOGY

The most intensively studied sabkhas of the Arabian peninsula, if not in the world, are those of the Trucial coast, southwest Arabian Gulf (Figure 2). Between Ras Ghanda in the east to the Qatar peninsula on the west an essentially unbroken coastal sabkha stretches for almost 325 km and, in places, extends almost 30 km inland (Evans et al., 1964). Kinsman (1969) estimates that these Trucial States coastal sabkhas may cover an area of 2,000 km^2 while the continental sabkhas within a belt 100 km from the coast may cover an additional 4,000-6,000 km^2. Coastal sabkhas dominate the west coast of the Arabian Gulf as far north as the Shatt Al Arab.

Coastal sabkhas of the Arabian Gulf usually have at their seaward edge a blue-green algal mat (Figure 3). Similar algal mats are also associated with supratidal salt flats elsewhere in the world

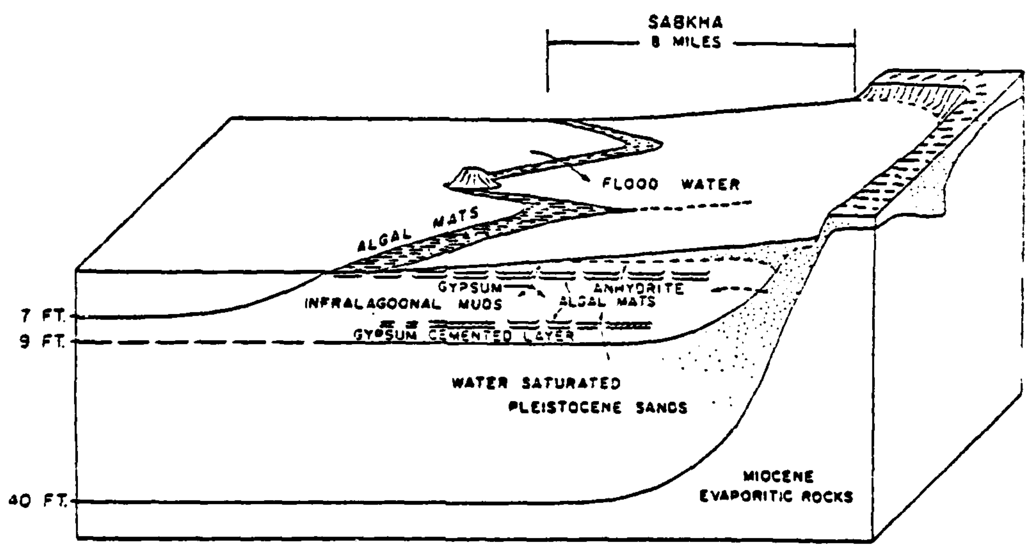


REF: EVANS ET AL, 1964

FIGURE 2 SABKHAS OF THE TRUCIAL COAST

such as the Bahamas (Black, 1933), Florida (Ginsburg *et al.*, 1954), Gulf of Mexico (Phleger and Ewing, 1962), the south coast of Texas (Fisk, 1959; Dalrymple, 1965), Great Salt Lake, Utah (Carozzi, 1962), Australian Salt Lakes (Clarke and Teichert, 1946), Baja California (Thompson, 1968), and Shark Bay on the west coast of Australia (Logan, 1961). Algal stromatolites are recognizably preserved in rocks as lamellae and are used by geologists as one diagnostic feature in defining ancient coastal evaporative environments (Lucia, 1972). The oldest fossils thus far dated 3.5 billion years B.P. are, in fact, algal stromatolites from Shark Bay, Australia (Anonymous, 1980).

The first major work published on Arabian Gulf algal mats was that of Kendall and Skipwith (1968). These authors studied the algal mats of Abu Dhabi, one of the Trucial States. They reported that the largest algal mat in this region extended unbroken along the coast for 42 km with an average width of some 2 km. A comparison of three algal mat classifications encountered in the



REF: BUTLER, 1969

FIGURE 3 IDEALIZED CROSS-SECTION OF COASTAL SABKHA

literature is presented in Table 1. Several authors report that these algal mats may be from 30 (Kendall and Skipwith, 1966) to as much as 50 cm thick (Kinsman and Park, 1976).

The origin of coastal sabkha plains has been attributed to extensive and prolonged seaward progradation through intertidal sedimentation (Evans *et al.*, 1964). One proposed mechanism for sabkha progradation in calm water areas is the direct precipitation of aragonite from sea water (Sugden, 1963; Bush, 1970). At a salinity of 68.5 ‰, 55 percent of the aragonite in sea water will have been precipitated, while at a salinity of 157.1 ‰ essentially all of the aragonite will have been precipitated (Borchert, 1969). As a point of reference, salinities in embayments of the Gulf frequently exceed 68.5 ‰. The sea water salinity adjacent to our sampling area was 67.2 ‰, while that of the study site ground water exceeded 300 ‰. Hence, direct precipitation or post-depositional precipitation of aragonitic muds is plausible at the Jubail site. Such precipitated muds should accumulate in the intertidal zone or as infills in the inner channels of lagoons (Evans, 1970). Algal mats would eventually grow over these muds. Mats of blue-green algae are thought (Shearman, 1965; 1966) to have played a major role in the formation and preservation of aragonite deposits. Before the rise of browsing gastropods, such algal mats may have been even more extensive and continuous than observed at present and in part, perhaps, explain why no modern analogs exist for the deposition of massive aragonite. The algal mats themselves may alter skeletal sands to a composition approaching that of aragonitic muds through boring and algal mat decay (Illing, 1954; Newell *et al.*, 1960; Purdy, 1963; Bathurst, 1966). According to Kendall and Skipwith (1969), "Nonskeletal calcium carbonate sediment types are related to wave energy; oölites form in the

TABLE I. COMPARISON OF CLASSIFICATIONS OF BLUE GREEN ALGAL MAT ZONATION

ZONES AS REPORTED BY:

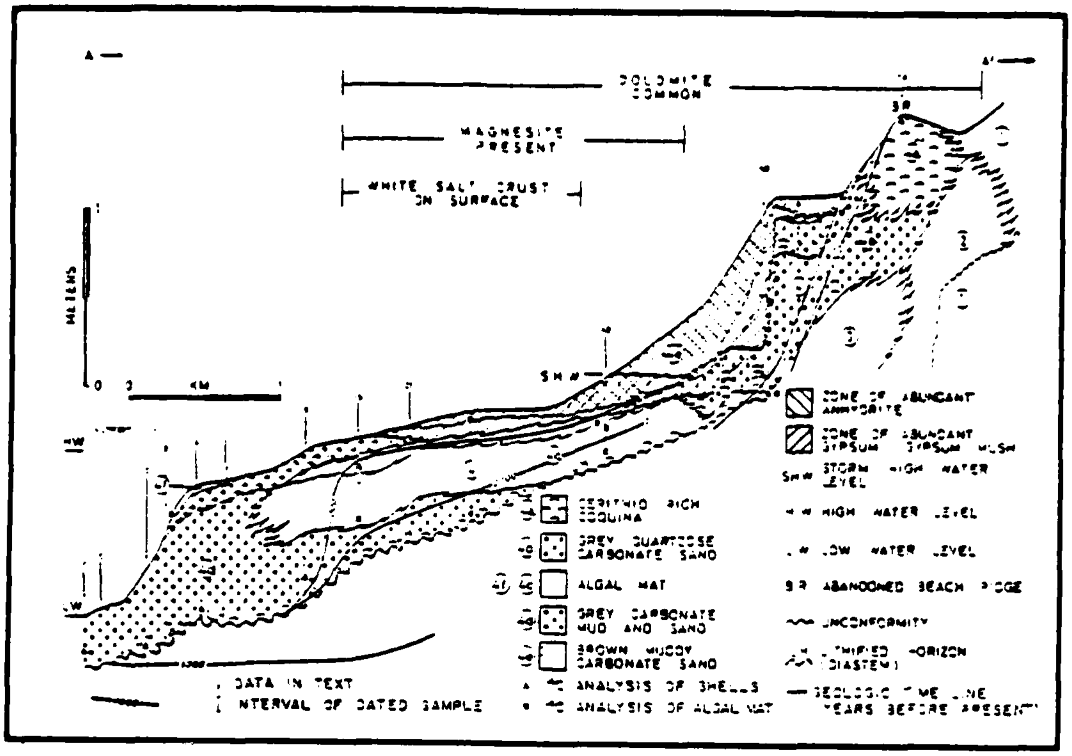
Kinsman and Park, 1976	Logan, et al., 1974	Kendall & Skipwith, 1968	Comments[1]
Pustular mat	Pustular mat	Cinder zone	+15 to +70 cm, underlain by large quantities of aragonitic mud, flooded daily. Seaward, depending on wave environment, skeletal and pelleted sands or muds accumulate.
Smooth mat	Smooth mat	Polygonal zone	+15 to +90 cm, but may extend to -40 cm in high salinity areas. Gives rise to algal peaks with minor sediment fraction. Commonly broken into polygons 2 cm to 2 m square. Daily flooding.
Pinnacle mat	Tufted mat	—	+60 to +100 cm. Found on higher, well drained areas between pools. Sediments are well oxygenated muds.
Blister mat	Blister mat	Crinkle zone	+80 to 100 cm. Gives rise to an identifiable stromatolitic structure. Underlain by aragonitic muds.
Wrinkle mat	—	—	+90 to +120 cm. Thin, surficial mat which forms no recognizable stromatolites. Underlain by gypsum crystal mush.
Flat mat		Flat zone	+110 to +140 cm. Poorly developed mat. Only flooded at extreme high tides. Usually underlain by a quartz rock carbonate sand or gray white mud composed predominantly of calcium sulphate hemihydrate.

[1] Elevations from Kinsman and Park, 1976
Other comments paraphrased from all three papers.

most turbulent environments, pellet aggregates in moderately sheltered environments, and pellets and muds in areas of low wave energy". In slightly deeper regions the sediments are primarily fine to coarse skeletal sand (Pilkey and Noble, 1966). Other components of sabkha sediments, such as limestones and dolomite, may be aeolian in origin since Sugden (1963) estimated that perhaps one-third of all sediment is transported into the Gulf by the wind.

As one moves inland from the tidal zone and algal mats, the subsurface geotechnical characteristics of the sabkha surface become more difficult to predict. Depending upon the sabkha region sampled, one may encounter "(1) brown quartzose carbonate sand; (2) grey quartzose carbonate sand; (3) grey muddy (lime) carbonate sand...(4) a complex composed of several types of primary sediments in which secondary minerals are especially abundant" (Evans *et al.*, 1969) or considerable quantities of unabraded shell (Evans *et al.*, 1969; Kendall and Skipwith, 1969; Johnson *et al.*, 1978; see Figure 4). This diversity of sediment types, according to numerous authors (Evans *et al.*, 1969; Evans, 1970; Butler, 1969; Kendall and Skipwith, 1969; Evans and Bush, 1970) is the result of the sequence of sedimentary processes which occurred in the Gulf region during the Holocene.

During the early Holocene (17,000 to 4,000 years B.P.), what is now the present coastal zone consisted of unconsolidated or weakly cemented brown sand and relict sand dunes of Pleistocene age. The regional climate during this period was milder and more humid than at present (Hötzl and Zötl, 1978). As sea level rose, this landscape was gradually flooded and 1) the Pleistocene sediments were reworked and 2) deposition of sediments occurred in the intertidal zone. These dunes, surrounded by water and thus cut off from their aeolian sediment sources, were eroded. The



REF: EVANS ET AL, 1969

FIGURE 4 STRATIGRAPHIC CROSS-SECTION OF COASTAL SABKHA,ABU DHABI, TRUCIAL STATES

Holocene sea transgression apparently reached areas which are now tens of kilometers farther inland and several meters higher than the present shoreline. During the subsequent regression, an cff-lap sequence was deposited and subtidal zones became intertidal and finally supratidal. These supratidal sediments were exposed to an increasingly dry climate, and wind deflation quickly leveled them to a surface at which the zone of capillary wetting was reached and at which point the adhesion of the moist sediments retarded further erosion. Aeolian sediments accumulated in depressions until a delicate balance between the subsurface water level, capillary wetting, and aeolian deflation—accretion was reached. Once this transient stability point had been achieved, the sabkha surface took on the appearance of a very flat plain. Photographs in the following sections will show that this is the case for the sabkha examined during this investigation.

Massive evaporite deposits millions or hundreds of millions of years old are found buried under thousands of feet of sediments in many parts of the world. The extent of many of these deposits, thousands of square kilometers in area and hundreds of meters thick, have no analogs in modern deposits. To gain insight as to how these ancient deposits may have been formed, scientists have conducted extensive tests of modern sabkhas on the Trucial Coast. Presented below is a summary of those aspects of these studies relating to sabkha trafficability.

Air temperatures in the northwest Arabian Gulf often exceed 50°C (122°F) in the shade during the summer. These high air temperatures, in conjunction with intense and prolonged solar radiation and a dark, damp sediment surface may result in surficial sabkha temperatures of 60°C or higher (Kinsman, 1966). Such high temperatures, as well as persistent wind, should efficiently drive surficial evaporation on sabkhas. Borchert (1969), however, pointed out that surface evaporation rates actually decrease as interstitial brines become more concentrated. Brines have a lower specific heat than sea water and the effect of prolonged solar radiation is to increase brine temperature, not evaporation. In addition, the saline surface of the sabkha would be hygroscopic and would absorb moisture from the higher humidity of the air while also losing heat during the night. Nevertheless, the presence of dense brines underlying sabkha suggests that a considerable amount of evaporation has occurred in the past. Since sabkha surfaces characteristically remain damp, if not wet, water must move through the sabkha to replace any lost through evaporation.

There are four possible sources of subsurface sabkha water: 1) rain or condensation, 2) continental ground water and 3) sea water which may enter sabkhas either horizontally through the sediments or 4) vertically following surface flooding. The average rainfall in the eastern province of Saudi Arabia as well as the Trucial States is only about 10 cm/yr (Schyfsma, 1978). The average evaporation, on the other hand, is some 124 cm per year (Privett, 1959). Since evaporation exceeds precipitation, it is unlikely that rain plays an important part in maintaining sabkha water content.

Numerous studies have shown that coastal water tables lie at depths of from 30 to 130 cm below the sabkha surface (Kinsman, 1966; Gavish, 1974; Johnson *et al.*, 1978 and others). Further, groundwater levels for the seaward two-thirds of coastal sabkhas are essentially that of mean sea level (Kinsman, 1966).

The flow of continental groundwaters into sabkhas, at least along the most shoreward fringe of sabkhas, has been demonstrated by Patterson and Kinsman (1977) based on the difference in ionic ratios between continental and Arabian Gulf waters. These authors estimate that continental brines are displacing marine brines at the rate of 0.3 to 1 m/yr in a seaward direction along the Trucial Coast. The seaward progradation of the marine/continental groundwater interface within the Trucial Coast sabkhas is certainly related to the rate of sabkha sedimentary progradation but even more indicative of the rate of groundwater movement through the sabkha sediments.

Butler (1969) suggested that the periodic flooding of coastal sabkhas has two effects. First, these thin sheets of water percolate downward into the upper sediment layers and rejuvenate the near surface interstitial brines. Butler (1969) termed this phenomenon "flood recharge". Second, the flood waters dissolve halite crystals and other soluble salts which may have formed on the sabkha surface. Most of the resulting brines which do not percolate downward flow back into the sea carrying the dissolved salts. This may account for the lack of significant surface salt deposits on sabkhas which are typical of salt flats in many other locations.

Adams and Rhodes (1969) proposed that the concentrated brines formed by such processes as evaporation and "flood recharge" may sink downward through the sediments and into the water table and eventually flow back into the sea. This process termed "seepage reflux" may be important in the eventual dolomitization of coastal evaporitic deposits.

Shinn *et al.* (1965) and Hsü and Siegenthaler (1969) have proposed two mechanisms by which ground water is supplied to surface sediments. Shinn and his associates proposed that surface sediments are maintained in a damp state (even in the absence of evaporation) via the capillary action of water amongst sand grains. Hsü and Siegenthaler proposed that sediments are maintained in a damp state at an elevation greater than that which can be explained by simple capillary action due to an "induced... vertical hydraulic gradient under the evaporated area".

It is interesting to note that these two hypotheses beg the question as to how subsurface waters penetrate deep into sabkha in the first place. They seek only to explain the process of vertical water movement. Seepage reflux and flood recharge, on the other hand, explain the movement and replenishment of the groundwaters themselves. From a trafficability point of view, being able to explain and, ultimately, to predict groundwater flow is crucial since, as succeeding sections of this report will endeavor to explain, trafficability seems intimately related to the water content of soils.

SABKHA MINERALOGY

Clark (1924) performed experiments to determine which chemical species precipitated from sea water under evaporative conditions. He listed a total of 51 chemical species; however, the dominant minerals were, in order, aragonite (calcite), gypsum and halite. There are a number of mechanisms by which sea water can be concentrated in sabkha sediments, as previously discussed. Most authors studying subsurface sabkha waters note increasing salinity with distance from the closest sea water source. Based on actual field work, Butler (1969, 1970) listed the diagenetic minerals observed in sabkha sediments from the intertidal zone to the high supratidal zone of the Trucial Coast.

> Intertidal zone: Subject to diurnal or semi-diurnal flooding. Aragonitic lime muds beneath algal mat. Some small gypsum crystals with minor, if any, cementing by aragonite, magnesite and protodolomite.
>
> Inner Flood Recharge zone: Subject to monthly or more frequent flooding. Surface layer of gypsum crystals up to 30 cm thick. Aragonitic muds may still be present.
>
> Intermediate Flood Recharge zone: Flooding occurs at intervals of more than a month. Gypsum mush partially or totally replaced by anhydrite, gypsum being precipitated as crystals, possibly localized dolomitization.
>
> High Supratidal zone: Flooding once every four or five years. Alternating bands of anhydrite and detrital sands, interstitial precipitation of gypsum forming cemented layers, local traces of polyhalites and sylvite in halite surface crusts.

Other major evaporitic minerals may include calcite, dolomite, magnesite and celestite (Bush, 1970).

Two of the most abundant of the evaporitic minerals found in sabkhas are gypsum ($CaSO_4 \cdot 2H_2O$) and anhydrite ($CaSO_4$). Ellis (1973) reports that gypsum and anhydrite make up the bulk (62 percent) of the uppermost seaward sabkha sediments at Abu Dhabi. Gypsum appears to have the following mechanisms of formation in sabkhas: primary precipitation, replacement of aragonite, replacement of aragonite through dolomitization processes, and hydration of anhydrite (Butler, 1970). The dehydration of gypsum into anhydrite normally occurs in the vadose (aerated soil) zone above the water table (Butler *et al.*, 1965; Hardie and Eugsler, 1971). This process is hastened by elevated temperatures and burial. Butler (1970) lists the following mechanisms for the formation of anhydrite in sabkhas: replacement of primary gypsum, replacement of aragonite, and possibly as a by-product of dolomitization processes with or without an intermediate gypsum phase. These mechanisms reflect a predominantly, if not exclusive, secondary origin for anhydrite. Dellwig (1955) argues, however, that primary anhydrite would be precipitated directly from vadose solutions if the ambient temperatures were at or above 42°C.

GEOLOGY OF THE JUBAIL REGION

The Jubail region of Saudi Arabia contains extensive coastal sabkhas, coastal and inland sand dunes, open and protected coastal environments, offshore islands and extensive intertidal exposure of cap rock. A study of the Quaternary period in Saudi Arabia, edited by Al-Sayari and Zötl (1978), contains details of geochemistry, geology, and culture not covered here.

The Eastern Province of Saudi Arabia has experienced numerous episodes of sediment deposition since the Pre-Cambrian. Paleozoic and Mesozoic strata are buried by thick Tertiary and younger deposits in the Jubail region (Chapman, 1978). Further inland are outcrops of barren limestones which date from the Eocene, Miocene or Pliocene. Many of the slightly raised terraces (1 to 4 m above high tide) in the Jubail region represent Quaternary beach deposits of shell debris, sand, and chert (Johnson, 1978). Many of these terraces are locally cemented.

The Gulf sea level has risen and fallen numerous times in concert with eustatic (worldwide) sea level fluctuations over the past several million years. Of primary interest to our investigations is the last complete cycle.

Prior to the last major glaciation (40,000-26,000 years B.P.), the maximum sea level in the Gulf region may have stood somewhat higher than at present. C^{14} determinations from a wave cut terrace at 10 m elevation in the eastern province of Saudi Arabia showed an age of 38,800 B.P. (Felber et al., 1978). During the glaciation thereafter, sea level fell, reaching a maximum regression some 25,000-12,000 years B.P. At this time the sea level stood 105-125 m lower than at present (Sarnthein, 1972) and the Gulf was essentially dry except for the confluence of streams and rivers which flowed out through the present Strait of Hormuz.

Between 20,000-15,000 years B.P., the last major (Flandrian) rise in sea level and transgression began. Several transgression standstills are indicated in the Gulf at 61-64 m, 40-53 m and around 30 m below the present sea level (Sarnthein, 1972). There is some controversy regarding the extent of the rise of worldwide sea level during the past 10,000 years. Workers such as Shepard (1960), Curray (1961), Milliman and Emery (1968), and Scholl *et al.* (1969) contend that eustatic sea level during this period never exceeded its present position and that sea level has essentially levelled off during the past 3,000-5,000 years. Others (Fairbridge, 1961; Coleman and Smith, 1964; Block, 1965) state that Recent sea level has been higher than at present; these high stands usually correlated to "climatic optima". This controversy is further complicated by the Recent tectonic histories at the sites of evidence on both sides of this controversy. The Flandrian transgression reached its greatest extent in the Gulf region some 6,000-4,000 years B.P. to a relative level 2-3 m above the present sea level. About 3,750 years B.P. the relative sea level dropped rapidly by one meter. A cemented layer was formed 1-2 m above sea level with radiocarbon dates of about 1,000 years B.P. (Sarnthein, 1972). Thereafter, an additional regression of about a meter then brought sea level to its present elevation which began a period of sedimentary deposition and coastline regression over the past 1,000 years which resulted in the present configuration of sabkhas.

It is generally accepted that cemented horizons, such as coquina, beach or cap rock may be formed in supratidal/intertidal environments. At, or very near, the air-sea interface, sufficiently rigorous evaporitive or precipitative environments exist which could result in cementation of beach face material (sand, shell, gravel, *etc.*) by chemicals such as aragonite or calcite. According to this argument, the presence of cap rock whether it be located above or below the present sea level would approximate a stable sea level or standstill. One should, however, be cautious in making assumptions equating lithification and sea levels, at least in the Gulf. Shinn (1969) and

Taylor and Illing (1969) make very strong cases for submarine lithification of carbonate sediments in the Gulf, although neither propose a process whereby submarine lithification occurs. Shinn (1969) further pointed out that.... "age is not related to [water] depth nor is the degree of lithification always related to age." For instance, well lithified sediments lying in 10-20 m of water were found to have ages varying from less than 240 years to greater than 8,000 based on radiocarbon dates. Lithification can apparently proceed rather rapidly since contemporary artifacts (glass, iron bolts, etc.) were found embedded in lightly cemented surficial crusts of the end of a 20 year old jetty in Qatar. It may also be of interest to note that beer cans were observed to have been incorporated into lithified supratidal cap rock on Jana Island off Jubail (Burchard, Pers. Comm.). It is not assumed, therefore, that cap rock is indicative of past sea levels.

Although the Eastern Province of Saudi Arabia is extremely arid, a considerable amount of water flows underground in aquifers. The uppermost aquifer in Jubail is the Neogene Formation, surficial unconsolidated aeolian and marine calcareous sand with interspersed regions of mixed composition (sabkhas). The water level is generally less than 2 m below the surface, highly saline and related to both local precipitation and sea water intrusions (Dames and Moore and Basil Geotechnical, S.A., 1976). Under extremely wet conditions, the water table may rise locally above the ground.

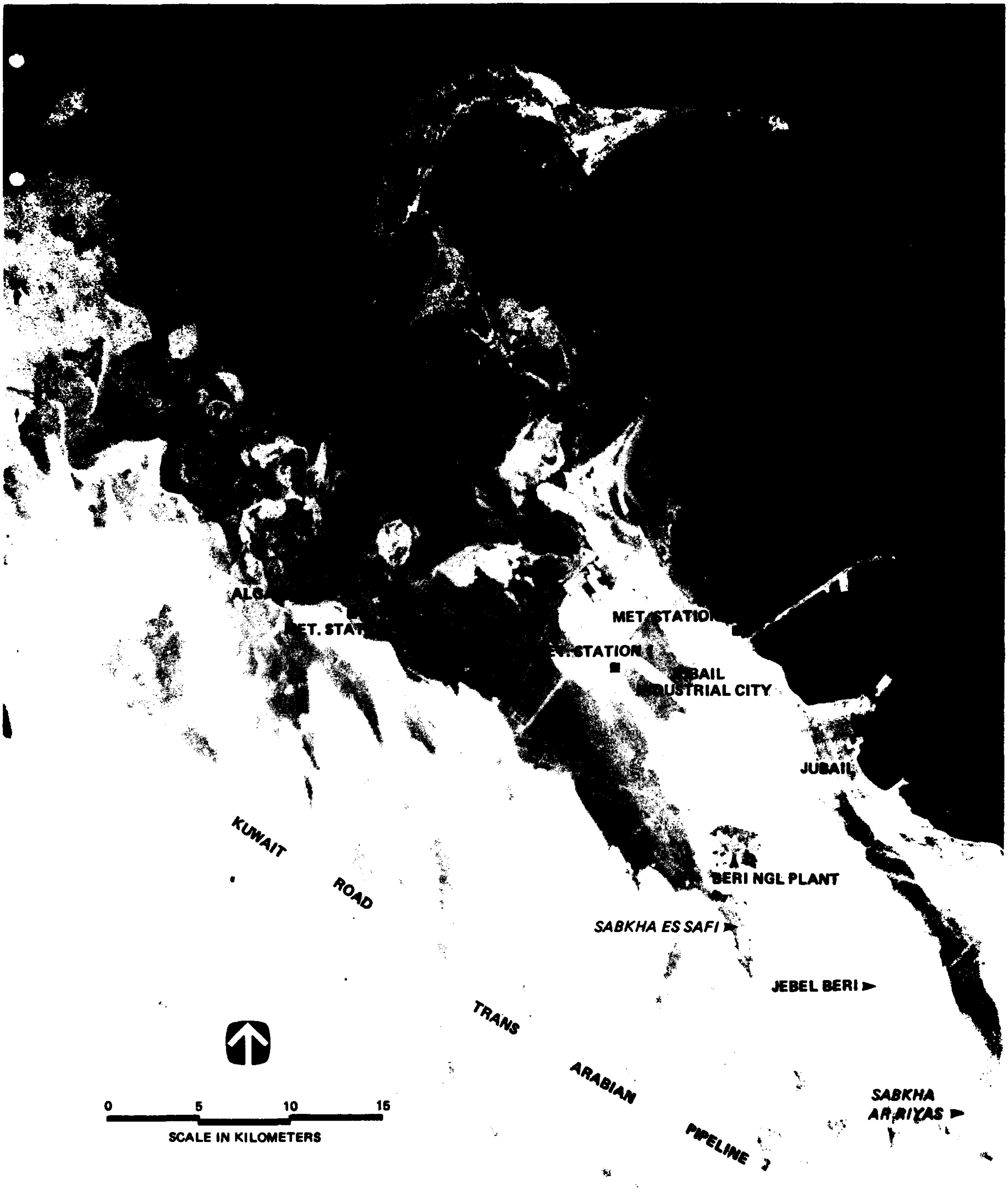
The upper Quaternary deposits are underlain by the Eocene Dammam Formation. The Dammam Formation has, in turn, been subdivided into shale, limestone, and mixed calcareous members. Only the two uppermost members, Alat and Khobar, are reliable aquifers, the remaining being impermeable. Flow from these aquifers varies regionally from less than 1 to in excess of 25,000 m^2/day. These are the aquifers presently being used for city water in the Jubail region. By Western standards, however, the water is of poor quality, containing 3,000 mg/l total dissolved solids with a hardness of 1,300 mg/l (James F. MacLaren, Ltd., 1979). Several deeper formations are also water bearing but have a water quality (total dissolved solids which may approach 5,000 mg/l) lower than the Alat and Khobar aquifers.

There are several areas in the Eastern Province where groundwaters flow to the surface results in oases. One of the largest oasis is at Al Qatif, a series of palm gardens about 10 km long and 2 to 3 km wide (Job, 1978) located some 50 km southeast of Jubail. There are many wells here, the oldest having been dug by hand to a depth of 10-35 m. These withdraw water from the Alat aquifer of the Dammam Formation.

Jubail is somewhat unique in that it does not have an oasis *per se*. Rather, the town owes its existence to one of the few naturally protected harbors along the Arabian Peninsula and to an offshore source of fresh water, the Al Ghumisa submarine spring (Figure 5). This spring, lying in 3 m of water 6 km offshore, releases potable water at a flow rate of about 260 m^3/day (Tetra Tech, 1978). Historically, local fishermen would dive on this spring and fill goat skin bags to obtain their fresh water supply.

GEOMORPHOLOGY OF THE JUBAIL REGION

The major surficial geological features of the Jubail region are discernible in the LANDSAT imagery presented as Figure 5. In general, the area can be broadly classified as either salt

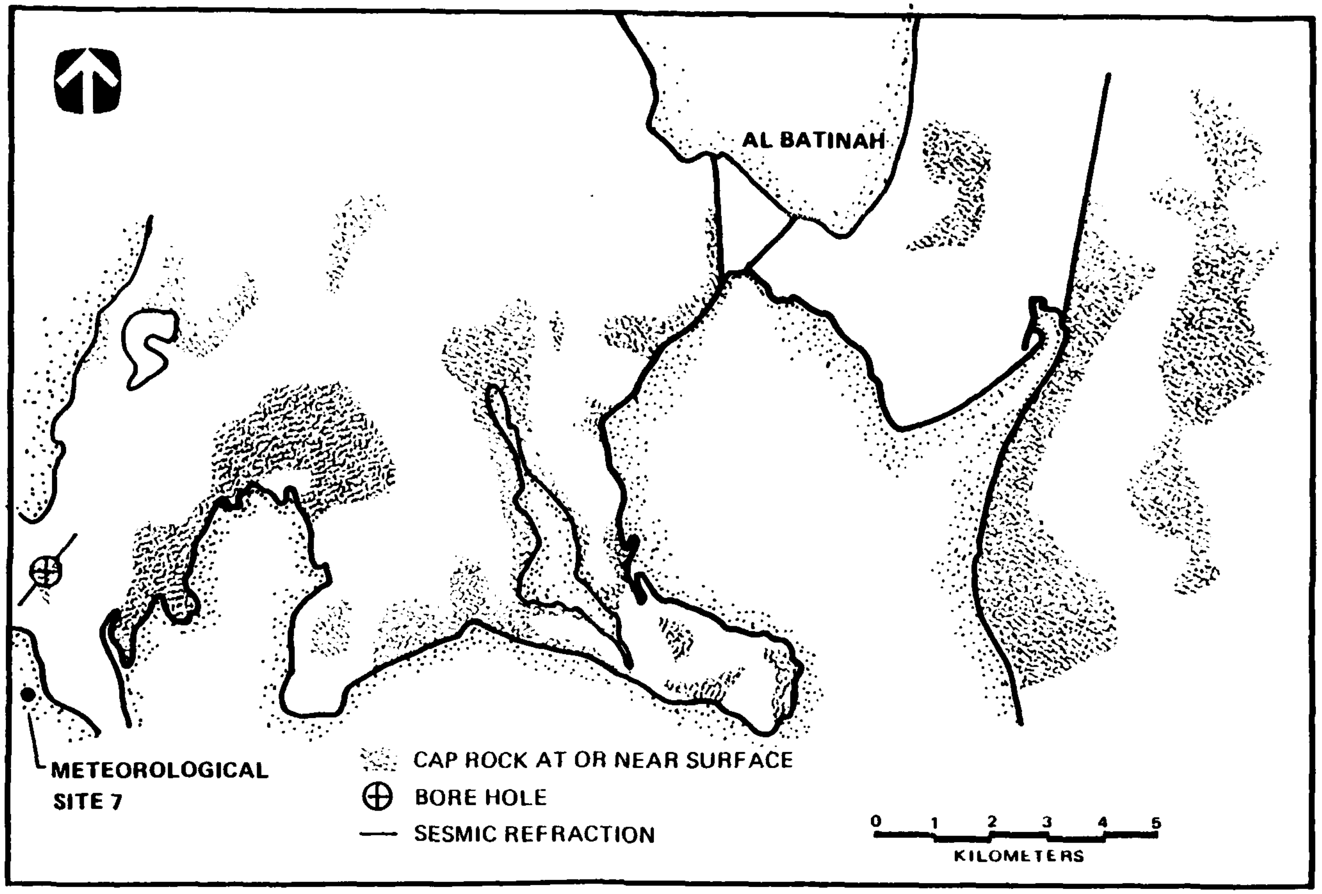


LANDSAT IMAGE OF JUBAIL 17 MARCH 1979, BAND 7 flat (sabkha) or sand dune (dikaka). The latter may either be marginally stabilized by vegetation or barren, in which case dune movement is usually observable. Barely distinguishable in this photograph is Jebel Beri, the highest (91 m) landmark for some 80 km. This feature is slowly being removed for breakwater rip-rap and roadbed marl. No specific information on the age of this formation was found, but it may be a part of the Dammam Formation which dates from the Eocene. In addition, an important geologic feature which also cannot be easily delineated on this or other aerial photographs is the extensive intertidal cap rock which the Arabs call *faroush*. Cap rock, as opposed to sabkha and even dunes, is easily trafficked.

Cap rock, sometimes several meters thick, is found near the surface throughout the Jubail region. These strata, exposed locally along the shore, may extend a considerable distance offshore. On the north side of the Jubail Industrial Causeway, for instance, cap rock extends at least 10 km offshore as a very flat plain overlain by a thin and patchy veneer of sand. Small and large coral formations can be found growing on top of the cap rock.

Figure 6 shows the locations in the Jubail region in which cap rock was found at or within 1 m of the sediment surface. These outcrops were delineated by a combination of acoustical sub-bottom profiling equipment and direct sampling with coring devices. Not shown on Figure 6 are the massive outcrops of well cemented cap rock at depths of from 5 to 12 meters which were encountered in and subsequently dredged from the Jubail harbor. Figure 6 does indicate, however, that while the surface cap rock deposits are widespread, they are not continuous.

The porosity of these cap rock formations was not directly investigated. During the present investigations, sampling pits



REF: TETRA TECH, 1979

FIGURE 6 OCCURRENCE OF CAP ROCK AT OR NEAR SEABOTTOM SURFACE were dug to cap rock. At several of these sites, hydrogen sulfide gas was observed percolating out of the cap rock. When diving on the offshore cap rock ledges, it was observed that air exhausted from SCUBA regulators percolated rapidly through the rock. These observations indicate that locally, cap rock may be permeable. Adams and Rhodes (1960) described the limestone formations of South Florida as being "...only slightly less permeable than a sponge." This is an apt description for the shallow cap rock formations we investigated. Some of the older marl deposits may, however, be far less porous since many, such as those of Jebal Beri, have had interstices filled by post-depositional crystallization.

In summary, the geomorphology of the Jubail region is dominated by coarse to fine grain supratidal deposits (sabkhas) or medium to medium coarse aeolian deposits (sand dunes). Outcrops of cap rock are observed at several elevations above and below sea level. The shallow subsurface geology is likewise dominated by sea level regressions and transgressions which occurred within the past 40,000 years.

METHODS AND MATERIALS

The area chosen for this study was the Sabkha al Fasl, north of Jubail and roughly bounded by 27°03' to 27°06' north latitude and 49°24' to 49°30' east longitude (see Figure 5). This particular site was selected because of our familiarity with the area and because an established infrastructure existed to support the survey including laboratories, meteorological stations, local benchmarks and land surveys, logistics, and background data. In addition, the Sabkha as Summ, south of Jubail, had already been investigated (Johnson *et al.*, 1978) and this information was available for comparison.

The specific site studied represents as much of the varied sabkha environments as possible. It is in an area which should stay peripheral to planned construction at the Jubail Industrial Complex for many years. The field work for this survey was performed during May, June and July, 1980, during which local temperatures reached 50°C.

In order to maintain maximum flexibility, sample sites were occupied in such a manner as to allow for the complete physical analysis and initial assessment and interpretation of data prior to sampling additional sites. This allowed hypotheses to be developed that could be tested at subsequent sample sites.

The methods and materials chosen for this field effort were dictated by the preliminary nature of the investigation. Although previous experience indicated that sabkha trafficability varied in a seemingly unpredictable manner, localized variability in sediment character and temporal changes in water content of the soil were suspected causative agents for these changes.

SEDIMENT SAMPLING

Two methods were used to obtain sediment samples. The first method employed a Phleger corer (Khalsico Scientific) modified for manual sampling of sediments. This device consisted of a heavy metal tube into which a 3.4 cm x 125 cm clear plastic core liner was inserted. A stainless steel nose cone and core catcher was placed on the terminal end, the upper end being capped with another piece of pipe around which was a circular weight with two handles. Once assembled, the device was positioned vertically at the point to be sampled and manually driven into the sediments to the greatest depth possible. The entire device was then withdrawn and the plastic core liner extracted, capped, and taken to the laboratory for analysis. Immediately after the Phleger corer was removed, a fresh core liner was inserted in the hole until it reached cap rock or was flush with the sediment surface. This was done to mark the holes and to keep them open for later measurements.

The Phleger corer proved to be of limited use for sampling very fluid or unconsolidated sand or shell. In the former case, the upper few centimeters of cohesive sediment became embedded in the core catcher while the lower fluid muds actually flowed away from, rather than into, the core. Samples of such sediments were obtained by sampling the walls of trenches dug by hand.

On occasion, a heavy metal digging bar was required to loosen and penetrate dense or cemented horizons. After a hole of the desired dimensions was dug, the sides were trimmed to near vertical, and the various horizons identified, described, sampled and photographed *in situ*. Samples obtained in this manner were immediately placed in 530 ml capacity Whirl-Pak® plastic bags and sealed. A plastic core liner was inserted into the hole level with the surrounding surface and the hole was then filled around the tube.

In the laboratory, the plastic core liner was split longitudinally along its entire length and one half photographed adjacent to a meter stick in conservative, overlapping, 10-15 cm sections. Each photograph was identified with the site number. Thereafter a visual description of each core was entered into a laboratory notebook and the core sampled at sedimentary interfaces (changes in sediment color or character) and, on occasion, arbitrarily to determine whether sediment changes were occurring over what otherwise appeared to be a homogeneous horizon. Samples were removed from both halves of the core with a flat-bladed spatula and placed in either one or more (depending on the quantity of sediment) tared, numbered, disposable aluminum pans. Sediment samples were catalogued and a quantity of sediment from each horizon photographed. Each photograph included the site number and horizon represented.

PHYSICAL SEDIMENT DESCRIPTION

Sediments were described in the field and laboratory using standard nomenclature in general accordance with ASTM D2487-69. Colorimetric descriptions follow those established for previous geotechnical investigations in Jubail conducted by Fugro-Cesco (1977).

Moisture content analysis was conducted in accordance with ASTM D2216-71. Any deviations involved less than minimum sample weights as might be necessitated by the same sample size available from core samples. This would also affect the method of preparing the samples for sieving (ASTM D421-58) and the actual sieving as well (ASTM D422-63). The sieve sizes used for these investigations were in half φ (-log 2) intervals from 4.0 to 0.063 mm.

After sieving, all identifiable shell and larger shell fragments were removed from the 2.0 mm and larger sieves and weighed separately. The shell fraction is reported as a percentage of the total dry weight of the sample. Sieve size sediment percentages are reported on the total dry weight of the sediments after removal of the shell debris.

Atterberg limit determinations were performed by McClelland-Schaimi, Ltd. soils laboratory in Jubail in accordance with ASTM D423.

IN SITU SEDIMENT TESTING

Several *in situ* soil parameters were also measured for these studies. Shear strength was measured using a Pilcon Engineering shear vane. A U.S. Army Corps of Engineers penetrometer used by the Corps for their trafficability studies and manufactured by Soiltest, Inc., was also used (Figure 7). Finally, a Soiltest, Inc., Model MC-300B Moisture-Temperature Meter was used to take moisture-temperature measurements at various depths by emplanting *in situ* probes in the soil (Figure 8). An ASTM Grade mercury thermometer, graduated in 0.1° divisions and calibrated against an NBS-certified master, was used to calibrate the individual temperature thermistors of the Soiltest unit as well as for taking air, surface and shallow subsurface soil temperature measurements. Each instrument was calibrated and used in accordance with the manufacturer's directions.

Of these three instruments, the shear vane seemed the most practical, yielding replicable results with an ease of operation not matched by the others. This instrument is also

FIGURE 7

U.S. ARMY CORPS OF ENGINEERS PENETROMETER IN USE AT SITE 18.

FIGURE 8

IN–SITU SAMPLING AT SITE 18. SHOWN ARE THE METER STICK USED FOR WATER LEVEL DETERMINATIONS, VACUUM DEVICE FOR EXTRACTING WATER SAMPLES, 300 ml BOD SAMPLE BOTTLE AND WIRES FOR THE SOIL TEST MOISTURE–TEMPERATURE METER. VERTICAL WOOD STICK MARKS HOLE LOCATION.

designed to be operated by one person and its feature of retaining the final maximum reading until manually reset was a decided advantage.

The use of the Soiltest penetrometer required two persons, one to push it down with a constant pressure (a difficult task when passing through horizons of differing strength) and the other to record the results. Also, the soil strength measurement was an instantaneous reading not retained by the instrument and the dial scale was small, hard to read and covered a range of 0-300 pounds per square inch (PSI). Consequently, the results obtained with this instrument were much less useful than those obtained with the shear vane.

Only the thermistor on the soil moisture-temperature unit worked adequately in the field. The moisture portion of the probe failed to obtain information on groundwater fluctuations and percent moisture. The principal difficulty with this probe was that it was designed to measure resistivity in soils containing fresh or only moderately saline groundwater. As will be seen in later sections, the salinity of sabkha waters is extremely high. The soil moisture meter readings were, as a result, off scale even at the lowest salinity tested.

WATER-LEVEL MEASUREMENTS

Water levels were monitored in two types of holes--cased and open--and for two periods of time, short term (essentially hourly over a semi-diurnal tidal cycle) and long-term (over several weeks at infrequent intervals). All measurements were taken with a meter stick.

In regions with shallow cap rock water level was recorded as the depth of water above cap rock. Where no cap rock was present water level was recorded as depth below the sediment surface. These values then corrected to a common datum plane. The accuracy of this technique probably lies within ± 2 mm for successive measurements at a given hole.

CHEMICAL ANALYSES

Chemical analyses were performed on seawater and subsurface sabkha waters for salinity and sulfate. Salinity determinations were performed by Tetra Tech in accordance with Method 209C for argentometric titrations (Standard Methods, 1979). Replicate samples were also given to McClelland-Schaimi Ltd. for verification. This same laboratory also performed the sulfate analyses. Water samples were removed from the open pits by submersion of a 300 ml BOD bottle or by aspiration from the lined holes (Figure 8). In all cases, several hours before sampling the standing water in the holes was removed. Only "fresh" sabkha groundwater was tested.

SURVEYING

After completion of all field sampling, the surveying firm of Saudi-Comet, Ltd. was retained to accurately determine the location and elevation of each sample site. These sites were tied into the existing bench marks which serve as the basis for all local surveying.

METEOROLOGICAL DATA

Meteorological data were obtained from meteorological stations in Jubail. Unless otherwise specified, all meteorological data are from Meteorological Station 7, located within the sabkha sampling area occupied during this survey.

PHOTOGRAPHIC COVERAGE

NASA LANDSAT coverage of the Jubail region for all seasons and years was requested from the EROS Data Center, Sioux Falls, South Dakota. Coverage of this particular region of the world is poor, only one photograph appeared to be of suitable quality and scale for our purposes. Accordingly, we obtained large photographs (70 x 70 cm) of the Jubail region in four bands (bands 4, 5, 6 and 7) and a color composite. The photograph (EROS image identification No. 82151506185X0) was taken 17 March 1979, is at a scale of 1:1,000,000 and has a resolution of approximately 80 m. An uncontrolled black and white photomosaic dated 1976 was also obtained. The resolution for this photomosaic is far better than that of the NASA photographs.

RESULTS

SITE DESCRIPTIONS

The locations of the 18 primary (surveyed and numbered) and four secondary (named) sample sites are shown in Figure 9. Details of the topography surrounding these sites are shown in Charts 1-3 which accompany this report. The locations and elevations of these sites and other referenced locations are given in Appendix Table A-1.

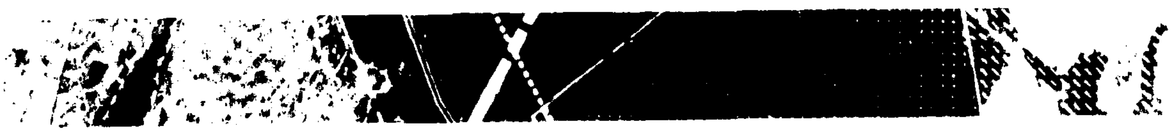
As is evident from the topographic charts, the region surrounding the sample sites is quite flat. The maximum elevation difference between the 18 surveyed sites is 1.09 m (between Sites 2 and 16). The most widely separated sites (2 and 18) are 4.3 km apart and the slope of the sabkha between them averages less than 18 cm/km.

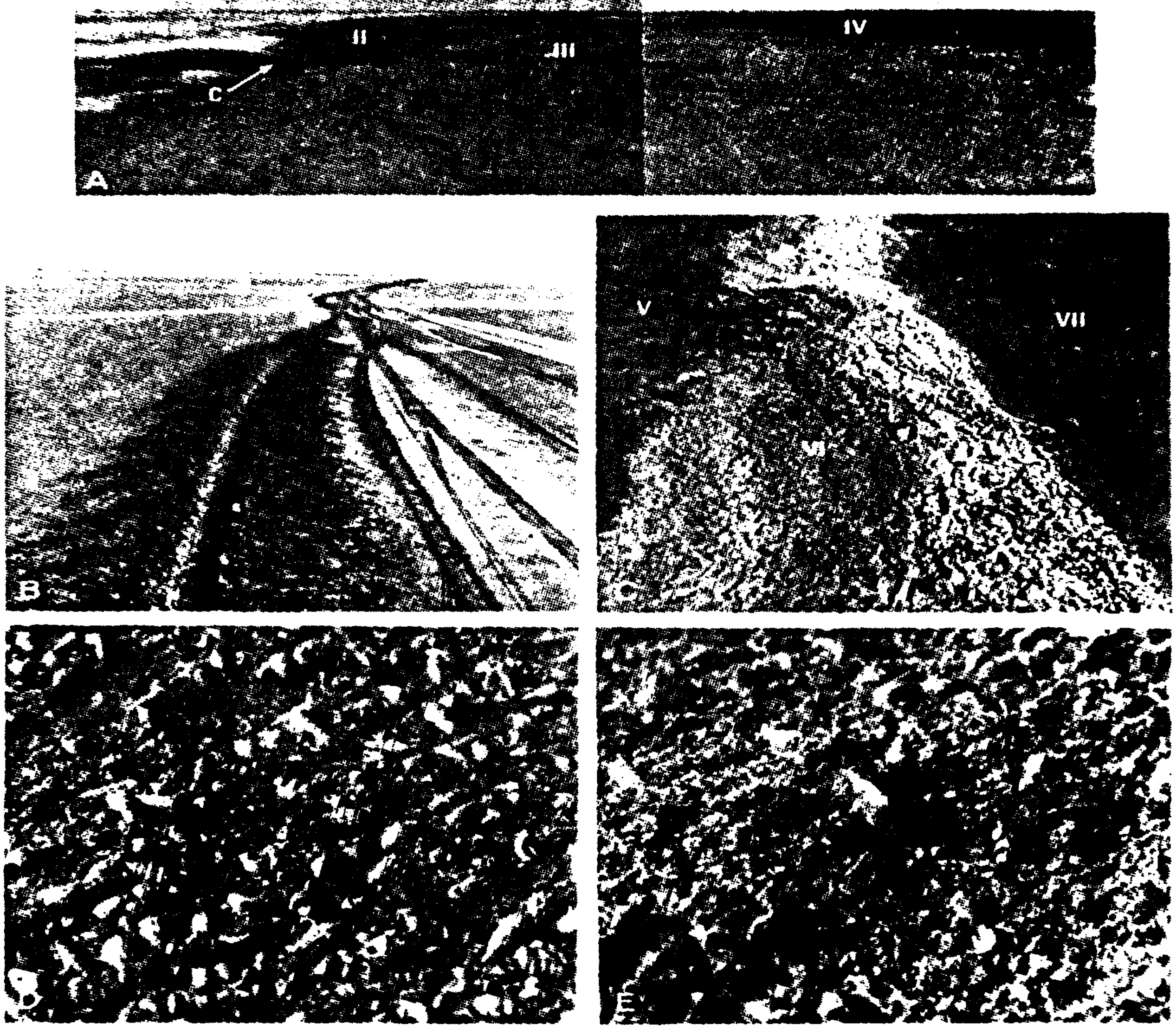
The sample sites were selected to sample the diversity of sabkha types which were observed within the study region. The study sabkha was divided into two basic types termed *"brown"* and *"white"* sabkhas.

Figure 10 consists of a series of photographs taken in the immediate vicinity of Site 11. Photo A was taken in a northwest direction. Location 1 in this partial panorama shows the *"white"* sabkha, whose actual color varied from off-white or cream to very light tan (as in the present case). The perception of color varies as a function of the incident light and quantity of surficial shell and other constituents.

Location 2 in Photo A shows a feature which only occurs along the immediate shoreline. This, apparently, represents the shoreward excursion of wind blown sea foam. The rich tan color and high content of sea and wind carried detritus is

AERIAL PHOTOGRAPH OF STUDY AREA, 1976





A VIEW LOOKING NORTHWEST FROM ACCESS ROAD
B VIEW LOOKING NORTHEAST ALONG ACCESS ROAD TO COASTAL SABKHA SAMPLE SITES
C CLOSE UP OF WIND DRIVEN FOAM AT LOCATION 3 IN PHOTO "A"
D CLOSE UP OF "WHITE" SABKHA SURFACE
E CLOSE UP OF "TAN" OR "DARK TAN" SABKHA SURFACE

FIGURE 10 SABKHA COLORATION IN THE VICINITY OF SAMPLE SITES 6 THROUGH 11 characteristic of this rather narrow band. Sample Site 11 was located in this band while sample Site 12 was located in the *"white"* sabkha.

To the right can be seen the more typical *"brown"* sabkha (Location 3). This area flooded several days before this photo was taken and was in the process of drying out. The color is, however, typical of *"brown"* sabkha which is devoid of surface shell and fine layers of halite crystals. Location 4, although also *"brown"* sabkha, is much darker because the surface is water saturated, although there is no standing water present.

Photo B in Figure 10 was taken several days after Photo A. Note that the darker color (as noted at Location 4 in Photo A) has faded into a uniform brown. Additional points to be noted in Photo B are as follows: there is standing water in wheel ruts, the vehicle didn't sink into the well traveled sabkha but sank to a depth of about 6 cm in the adjacent, untraveled sabkha, and no surficial layer of halite was deposited on the sabkha surface as a result of flooding. Evaporation of a subsequent flood, however, did result in thin halite deposits which were still evident after two months.

Photo C of Figure 10 was taken at the same location shown in Photo A. It was also taken the morning after the sabkha flooded and the very dark brown (grey in this photo) zone extends to the foam line (Location 6). A comparison of this photo with Photos A and B (in the order C, A, B) shows the effect of gradual drying on the sabkha. Location 5 shows the tan slightly supratidal sabkha zone and Location 6 shows the accumulation of wind blown foam.

Photographs D and E in this series are both close-up shots of the *"white"* and *"brown"* sabkhas, respectively. They were taken immediately adjacent to sample Sites 11 and 12. The apparent white coloration observed in Photo D is due, at least in part, to an abundance of bleached shells of the genus *Cerithidea* on the surface and to the very dry nature of the sediment surface itself. The surface of the "tan" sabkha, on the other hand, has far fewer shells and its sediments are wetter and frequently adhere to the shells.

It is interesting to note that there are few shells on the surface of the sabkha flats although these flats appear to be frequently inundated. One hypothesis is that when the sabkha floods, the flood water is preceded by the foam line which incorporates and carries the shells to the farthest extent of the flooding. Another possible mechanism is that the elongated, conical *Cerithidea* shells may be rolled by the wind across the flat sabkhas to collect as windrows at the base of the first topographic relief feature encountered. No strictly aeolian "rolling" shells were observed on the sabkhas. Significant accumulations were observed collecting only in the distinctive "foam" deposits. Over hundreds of years, however, such mechanisms could move a considerable quantity of shell, resulting in shell rich and shell poor regions lying adjacent to one another.

Figure 11 is a panorama of the most seaward location studied; the sequence was photographed adjacent to Site 5 situated atop a sand berm with relief of 50 cm above that of the surrounding terrain. From this vantage point an algal mat extends from approximately 10 m inland of Site 2 seaward. Sampling Sites 1, 2, 3 and 4 were all located within this algal mat. In this region, extreme difficulty was encountered in coring due to the extreme thixotropy (fluidity) of the silty sediments encountered about 4 cm below the algal mat. Barely visible in back of sample Site 10 in the direction of meteorological Site 7 is a thin surface layer of halite.

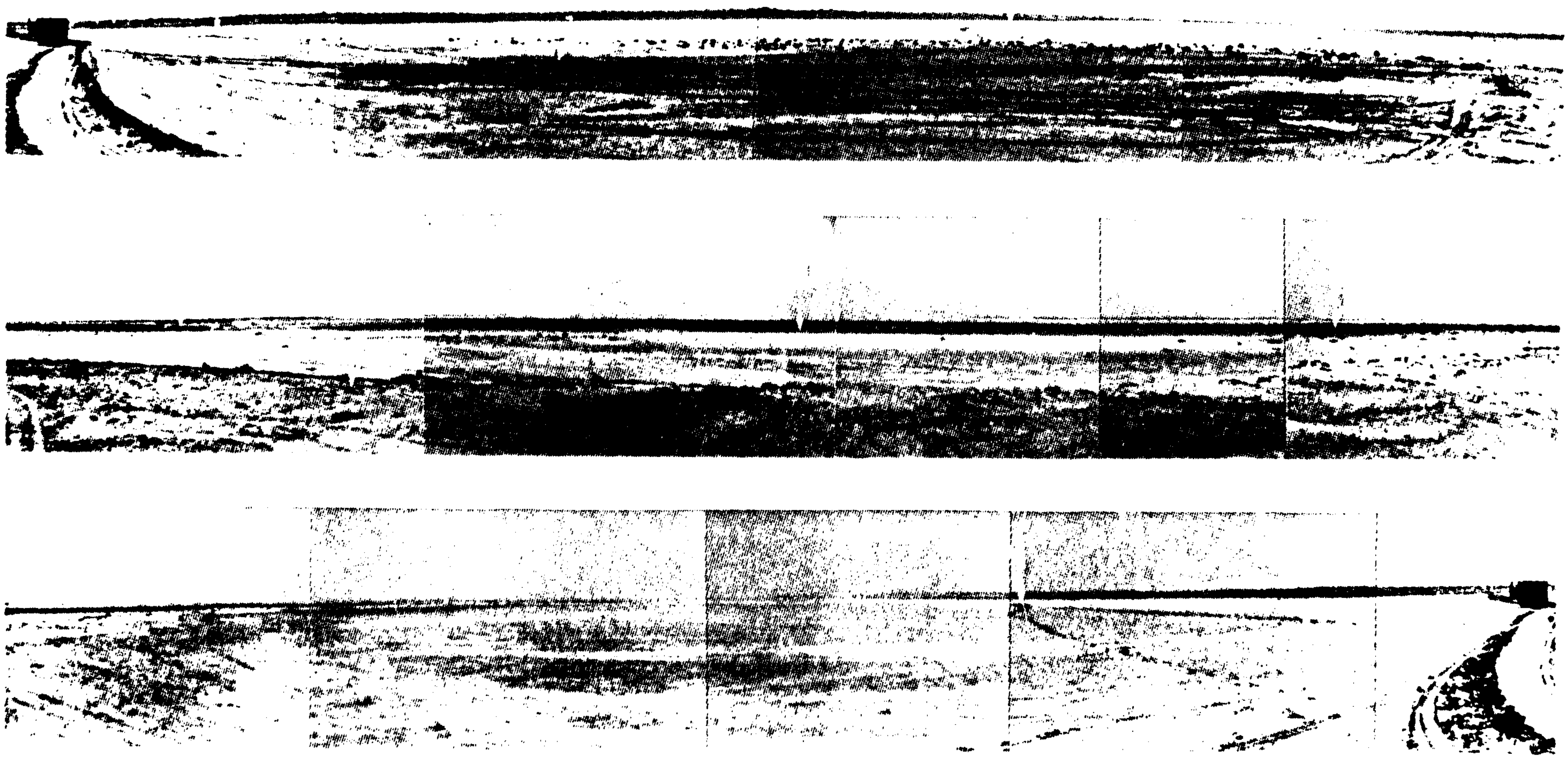


FIGURE 11 STUDY AREA AND SAMPLING SITES AS VIEWED FROM NEAR SITE 5

Figure 12 presents a panorama taken from the roof of Meteorological Station 7. The rise on which this station is situated is at an elevation of approximately 4 m. Hard native cap rock forms the foundation for this station, although there appears to be no such cap rock in the sand dunes immediately to the south and west.

All samples inland from Site 13 on, including the last four uncontrolled (named) sites, were dug using a shovel. It was thus not possible to delineate detailed stratigraphy. We did, however, photograph the walls of these sampling pits.

Figure 13 presents a series of six photographs depicting Sites 14, 15 and 16. Photo A shows Sites 14 and 15, located only 16 m apart to take advantage of the close proximity of both *"brown"* and *"white"* sabkha. The next two photographs show the individual characteristics of Sites 14 and 15. The surface surrounding Site 14 (Photo B) is hard and smooth with an abundance of loose shell (predominantly *Cerithidea*) lying on the surface. The surface at Site 15 (Photo C) on the other hand, contains far fewer shells and the "blistered" surface is typical of evaporitic mud flats.

Photos D and E show the subsurface characteristics of Sites 14 and 15, respectively. Differences in surficial characteristics were found to extend downward and are discussed in more detail below. Finally, the subsurface characteristics of Site 16 are shown in Photo F. While the surficial characteristics of Sites 14 (Photo B) and 16 are very similar, the subsurface characteristics are markedly different. A consolidated sediment layer 2 cm thick was encountered at the 7.0 cm level at Site 14; no such layer was found at Site 16. These two sites are located 148 m apart. The sediments at Site 16 were much easier to dig than those at Site 14, perhaps less compacted

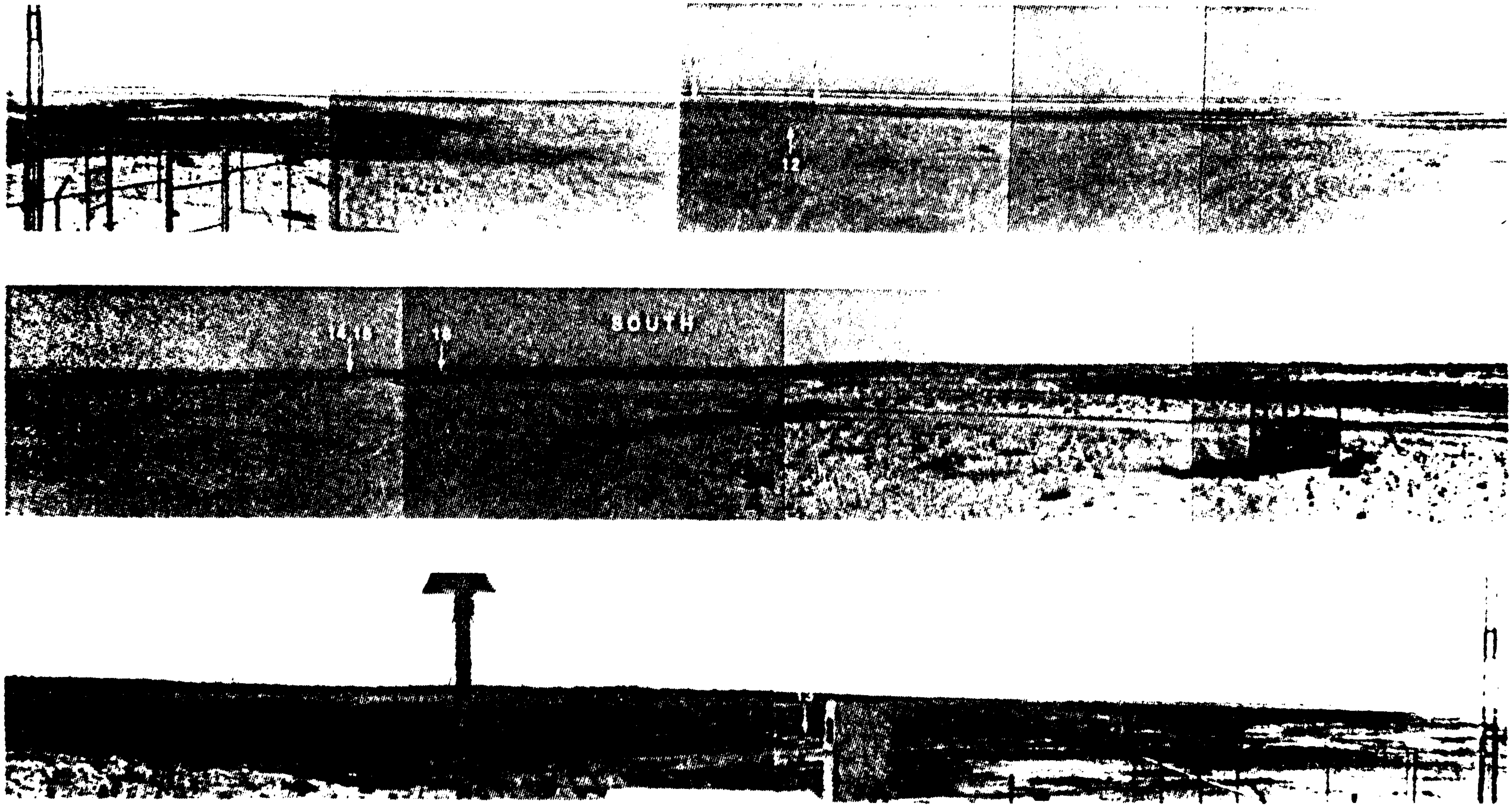


FIGURE 12 STUDY AREA AND SAMPLING SITES AS VIEWED FROM METEOROLOGICAL STATION 7

FIGURE 13 SAMPLE SITES 14 15 AND 16

although this difference is not apparent in the penetrometer data to be presented below.

Sites 17 and 18 were chosen to sample representative "[illegible]" sabkha inland from the bay to the north. The surface character of the sites is indistinguishable based on visual examination of Photos A and B of Figure 14. Photo C, a close-up photograph of Site 17, shows a thin (~ 1 mm) friable crust of halite which was typical of both sites. The surficial resemblance of both sites extends below the surface to the -6.5 cm level with regard to a lack of shell material and low water, silt, and clay content. Below -6.5 cm, however, the differences in sediments are pronounced. The lower strata at Site 17, down to the limits of the excavation (-122 cm), contain a high percentage of shell, approaching 40 percent in one location. Site 18, on the other hand, contains no shell from the surface to -122 cm.

Figure 15 is photos of the uncontrolled sites. Photo A, called "Road Cut", shows a poorly indurated sand capping the top of road cut. This sand can be crumbled with a moderate amount of effort. This sand was sampled, as was the unconsolidated sand immediately beneath it. Photo B, located in an abandoned borrow pit similar to that sampled, represents a cross section of a sand dune stabilized by vegetation. A poorly indurated sand layer can be seen capping the dune and several layers which have been sculpted by blowing sand. These consolidated layers crumble readily when touched.

Photos C and D of Figure 15 are of the sites called Dry Side and Wet Side, respectively. These two sites are less than 60 m apart, on opposite sides of a 4 lane compacted dirt haul road built within the past year and are several kilometers from the bay of the Gulf north of the study area. Superficially, the sedimentary characteristics at both sites appeared quite

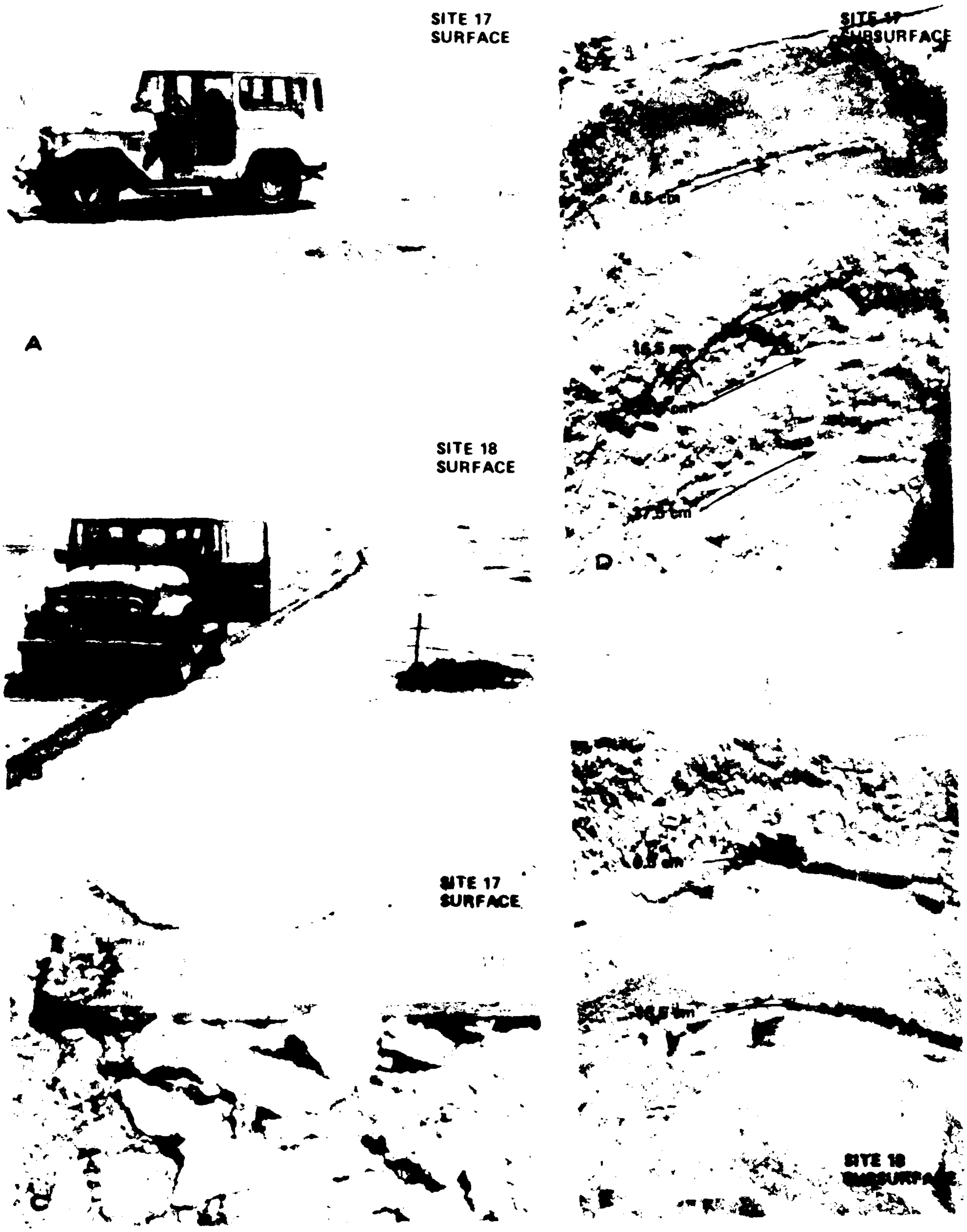
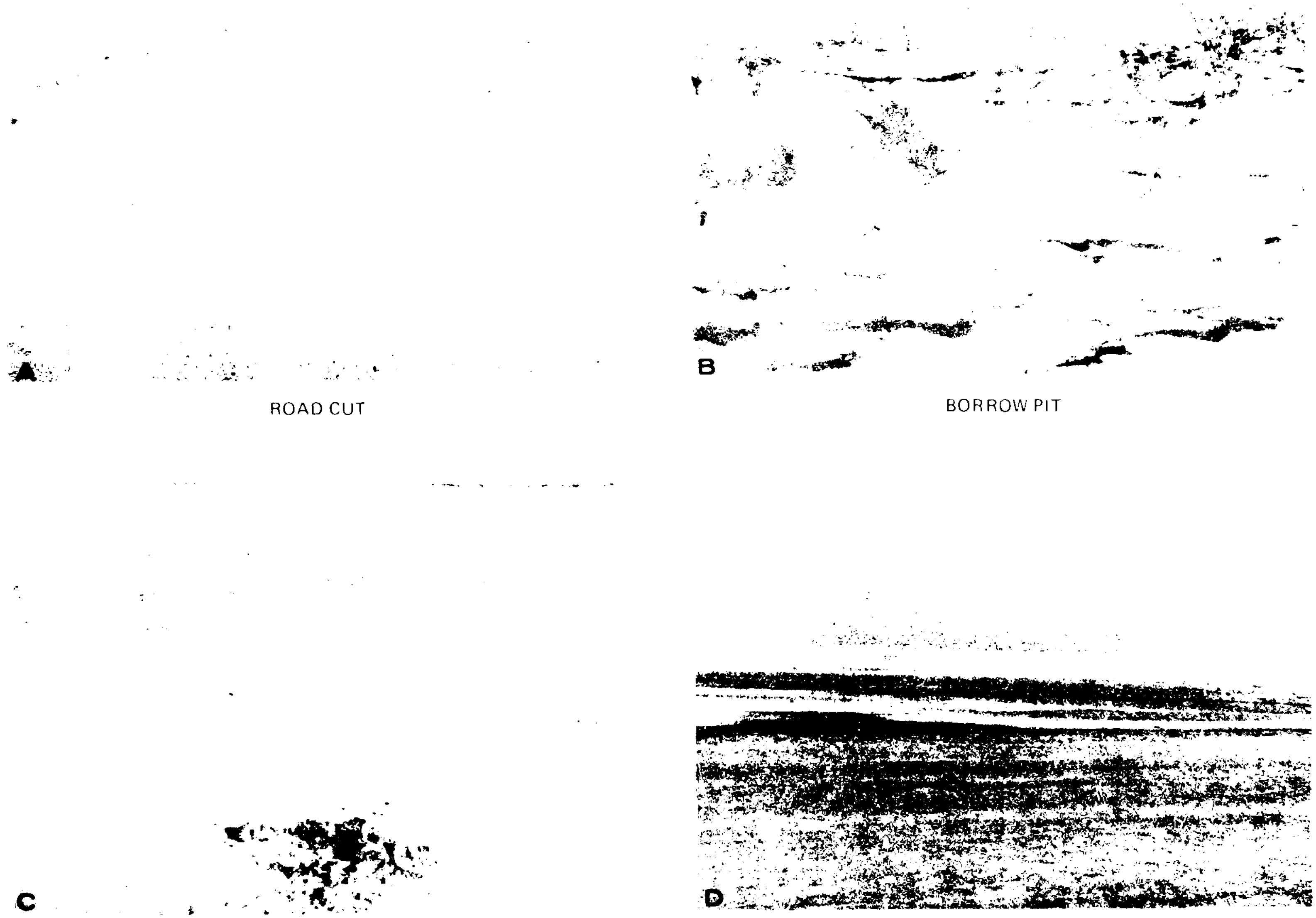


FIGURE 14 SAMPLE SITES 17 AND 18



A ROAD CUT

B BORROW PIT

C DRY SIDE

D WET SIDE

FIGURE 15 UNCONTROLLED SAMPLE SITES

similar. The sediments at Dry Side offered more resistance when excavated than those at Wet Side. In addition, initial measurements found the water table to be 15-20 cm higher at Wet Side than at Dry Side. However, several days after the samples holes were dug (primarily for testing the salinity of the groundwater) the area was flooded up to the haul road. Thus Wet Side, quite literally, became wet. Several days after this flooding occurred, the photographs in Figure 15 were taken, at which time the water had receded (it was never more than 2 cm deep at the site), leaving the white halite layer observable in Photo D.

The observational data just presented for the 18 sample sites is summarized in Table 2. This table is presented to reiterate the color description of each site and the surficial characteristics which may partially account for these colors. We have also included our tentative estimates of flooding frequency based on observational information.

SEDIMENT GRAIN SIZE

Grain size distributions were determined for all sediment samples. All of these data are presented in Appendix Table A-2. A composite summary of the stratigraphy at each of the 16 sampled sites is presented in Figure 16. The sedimentary divisions are based on percentage of silt and clay and of shell material in each sample as determined by sieve analysis. The elevations of the stratigraphy at each site are adjusted in Figure 16 to the Jubail datum. A summary of the sieve results is presented in Table 3. Cap rock underlies the sabkha surface at a constant elevation below Sites 1-9. Below Site 10, the elevation of the cap rock was 15 cm higher than the cap rock below Sites 1-9. At Site 12, a thin (2 cm) coquina layer (shell, worm tubes and quartz sand cemented by carbonate) was sampled 0.7 m above the present high water mark and over a meter higher than the cap rock layer.

TABLE 2 SUMMARY OF OBSERVATIONAL DATA FOR SURFICIAL SABKHA DEFINITIONS USED IN TEXT

Site	Color Type	Predicted[1] Flooding Frequency	Percent Water in Upper Sediment Layer	Surficial Visual Distinguishing Characteristics
1	Brown	Frequent	36	Blue green algal mat
2	Brown	Frequent	34	Blue green algal mat
3	Brown	Frequent	35	Blue green algal mat
4	Brown	Frequent	35	Blue green algal mat
5	White	Infrequent	8	Loose sand, few shells
6	Brown	Occasional	31	Rare shells
7	White	Occasional	25	Compacted sand, few shells
8	Brown	Occasional	33	Rare shells
9	Brown	Occasional	41	Rare shells
10	Brown	Occasional	26	Rare shells
11	Brown	Infrequent	18	Moderately abundant shells
12	White	Rare	2	Abundant shells
13	Brown	Rare	17	Few shells
14	White	Rare	1	Abundant shells
15	Brown	Rare	26	Few shells
16	White	Rare	2	Abundant shells
17	Brown	Rare	30	Rare to no shells
18	Brown	Rare	27	Rare to no shells

[1] Frequent: Flooding monthly or more frequently, with spring tides or moderate winds.

Occasional: Flooding several times a year with high tides and high winds.

Infrequent: Flooding once or twice a year but only when the highest tides are coupled with high, persistent, winds.

Rare: Flooding once every several years to once a decade or more, but only under catastrophic weather conditions.

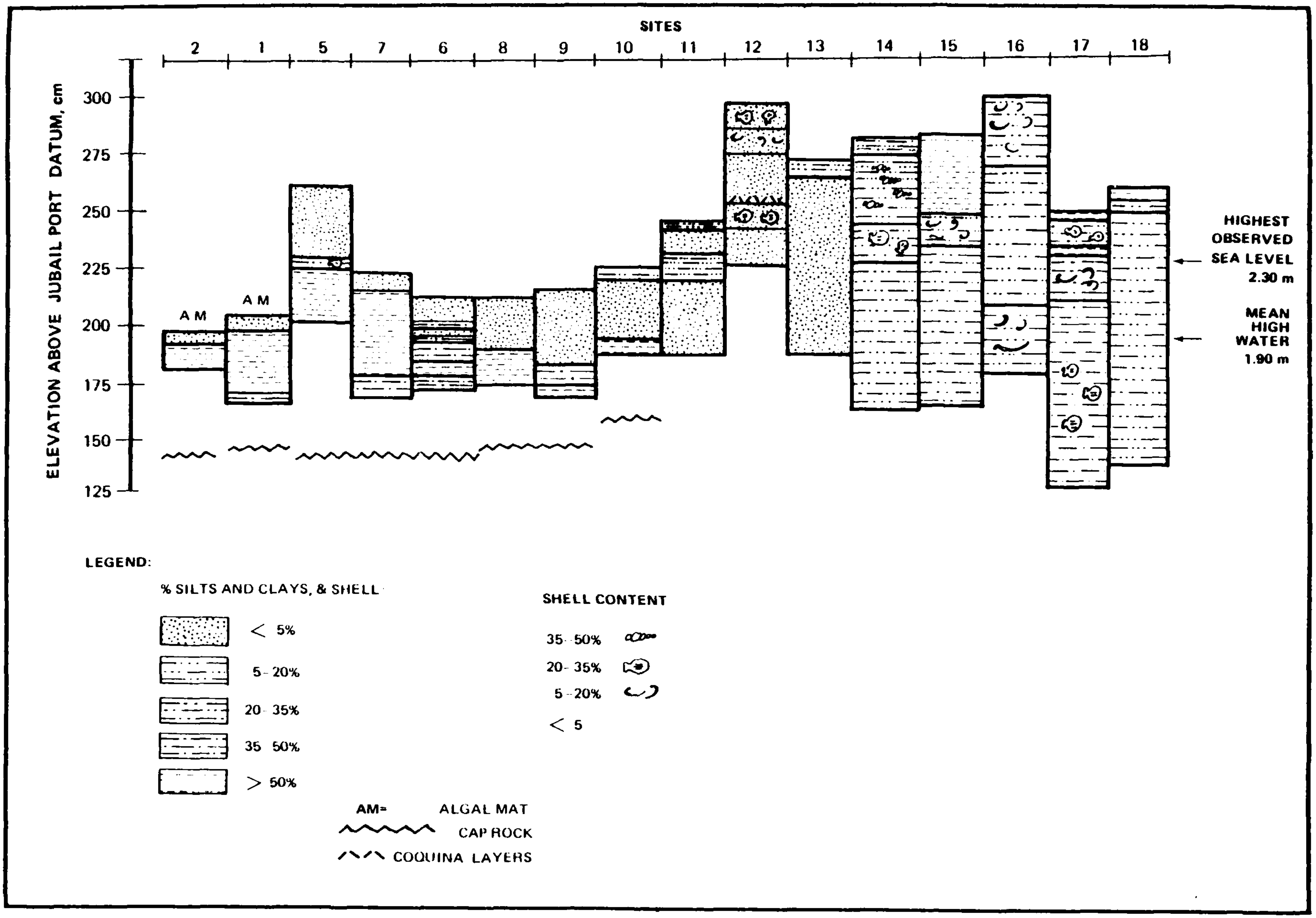


FIGURE 16 SABKHA STRATIGRAPHY

TABLE 3: SIEVE ANALYSIS SUMMARY

Site Number and Depth Strata, cm	PERCENT Shell	PERCENT Passing 0.063 mm Sieve	PERCENT Water
Site 1			
0.0 - 1.0	Blue Green	Algal Mat	36.2
1.0 - 3.0	0.0	0.3	33.3
3.0 - 37.0	0.0	51.2	54.6
37.0 - 39.0	3.2	44.4	48.5
Site 2			
0.0 - 0.6	Blue Green	Algal Mat	33.8
0.6 - 4.5	0.0	0.0	35.6
4.5 - 16.0	0.0	49.8	55.6
Sites 3 and 4	Not Sieved		
Site 5			
0.0 - 17.0	3.8	1.0	7.9
17.0 - 34.5	3.6	0.4	13.6
34.5 - 37.5	14.1	1.9	17.1
37.5 - 62.5	1.5	35.8	46.7
Site 6			
0.0 - 1.5	0	2.5	30.7
1.5 - 9.5	0	0.1	38.1
9.5 - 13.0	0	48.0	37.0
13.0 - 14.5	8.3	0.3	19.3
14.5 - 19.5	1.2	24.2	42.8
19.5 - 26.5	0	36.9	57.4
26.5 - 31.6	0	55.7	38.5
31.6 - 38.7	0.6	45.0	31.9
Site 7			
0.0 - 10.5	4.0	0.0	24.9
10.5 - 44.0	0.0	51.5	37.8
44.0 - 55.5	0.3	44.6	61.2
Site 8			
0.0 - 5.0	0.2	0.0	32.6
5.0 - 21.5	0.1	0.7	39.3
21.5 - 26.0	1.0	50.4	41.0
Site 9			
0.0 - 4.5	0.8	0.7	40.6
4.5 - 22.5	0.2	2.7	40.5
22.5 - 40.6	0	48.5	39.0
40.6 - 43.5	0	76.0	28.6
Site 10			
0.0 - 5.0	0	28.1	26.0
5.0 - 33.0	4.6	4.5	32.5
33.0 - 37.0	0.1	56.0	33.8
Site 11			
0.0 - 3.5	0.2	12.0	15.0
3.5 - 14.5	0.1	0.5	13.0
14.5 - 29.5	0.9	5.5	[illegible]
[illegible] - 55.5	1.4	[illegible]	[illegible]
55.5 - [illegible]	14.5	[illegible]	[illegible]
Site 12			
0.0 - 11.5	15.6	0.1	[illegible]
11.5 - 22.0	19.3	0.6	3.3
22.0 - 41.0	2.4	0.8	17.1
41.0 - 42.5	0.	1.4	15.6
42.5 - 44.5	Calcarenate		
44.5 - 56.0	25.2	0.2	10.4
56.0 - 72.0	1.2	0.1	14.0
Site 13			
0 - 5.5	0	7.8	17.1
5.5 - 28.0	0	0.7	12.4
28.0 - 53.0	0	0.4	16.1
53.0 - 87.5	0	0.0	19.1
Site 14			
0.0 - 2.0	4.5	35.2	1.0
2.0 - 7.0	17.2	12.9	2.7
7.0 - 9.0	2.4	65.2	5.0
9.0 - 40.0	41.5	15.7	14.5
40.0 - 65.0	29.7	14.2	20.0
65.0 -121.0	6.0	19.9	37.9
Site 15			
0.0 - 6.0	0.6	81.0	25.9
6.0 - 37.0	0.9	61.9	23.9
37.0 - 50.0	17.4	18.0	19.4
50.0 - 66.0	0.6	15.0	26.7
66.0 -122.0	4.8	19.8	17.0
Site 16			
0.0 - 33.0	17.4	19.1	1.9
33.0 - 88.0	1.9	15.6	5.9
88.0 -122.0	15.6	6.8	19.4
Site 17			
0.0 - 6.5	0	73.0	11.4
6.5 - 16.0	4.6	15.7	11.0
16.0 - 22.0	19.1	50.4	16.0
22.0 - 37.5	13.4	34.1	28.6
37.5 -122.0	34.9	17.4	10.6
Site 18			
0.0 - 6.5	0	61.5	26.6
6.5 - 13.5	0	19.4	13.5
13.5 - 52.0	0	6.8	14.4
52.0 -122.0	0	15.2	15.0
Sand Dune Cemented Surface	0	1.0	1.0
Sand Dune Uncemented Subsurface	0	1.0	1.0

The recognizable shell extracted from the sediments were all molluscs and the bulk of these were of the genera *Cerithium* and *Cerithidea* with lesser representation by *Mitrella*, *Nassarius* and a rare *Umbonium*. Further, all are gastropod molluscs (snails) rather than pelecypod molluscs (clams). The present distribution of these genera includes both bays (such as the embayment north of the study site) and the open coast. In the sheltered bays, these epifaunal (surficial) genera are usually associated with infaunal (near surface) pelecypod molluscs and silty sands whereas on the open coast of the Jubail Region they are found on fine to coarse grained sands and on thinly veneered cap rock with few, if any, pelecypods. Thus, the assemblages found, regardless of burial depth, are more indicative of high energy open coastal environments than the more protected environs in which they were found.

PENETROMETER DATA

Penetrometer readings for each sample site are summarized in Table 4, the unreduced data are presented in Appendix Table A-3. As previously mentioned, these data were not consistent; replicate readings were highly variable and the instrument itself was difficult to read accurately in this application. However, some correlation between these data and our observations permit the following generalizations on trafficability; sabkhas with surface (0-15 cm) penetrometer readings below 271 Pascals or 200 pounds per square inch (PSI) are not trafficable. Sabkhas with penetrometer readings below 135 Pascals are often difficult to walk across. Sites 1 through 4 and Sites 6 through 9 are in this non-trafficable category. Regions covered with blue-green algal mats are untrafficable by standard tracked or wheeled vehicles unless shallowly underlain by cap rock. Such algal mat areas have, in general, penetrometer readings of 68 Pascals or less and are thixotropic

TABLE 4: MEAN PENETROMETER READINGS IN PASCALS (NEWTONS PER SQUARE METER)

Sites	Color Type	Depth, cm 15	30	45	400 Pascals @ cm
1	Brown	53.6	52.9	69.8	
2	Brown	24.4	39.3	29.8	
3	Brown	57.6	73.9	60.3	
4	Brown	72.5	73.2	67.1	
5	White	350(6)[2]	156[1]	149[1]	15(9)[3]
6	Brown	85.4	49.5	44.1	
7	White	193.2	134(5)	44.7(5)	22.5(5)
8	Brown	200	70(9)	68(9)	22.5[1]
9	Brown	84.7	52.2	47.4	
10	Brown				12.45
11	Brown	266.4	208.1	274(8)	43(2)
12	White				2.2
13	Brown				S[4]
14	White				3.4
15	Brown	227.8	108.5	247(7)	20[3]
16	White				7
17	Brown				5.6
18	Brown				7

(1) Mean of ten replicate readings taken at random around sample site.

(2) Where 10 readings could not be taken due to lack of penetration, the number of replicate samples taken to the given depth.

(3) Mean depth (and number of replicates) at which 400 Pascals were met or exceeded.

(4) S = Surface, no penetration

(5) All readings converted to metric system; 100 PSI = 135.6 Pascals.

from the surface to the limit of sampling. A compact and trafficable surface layer of sand, sufficiently strong to support a quarter-ton four-wheel drive vehicle, may be underlain by thixotropic muds which are incapable of supporting any traffic. If the supportive surface layer is breached, traction is immediately lost. Very low speeds or quick changes in speed or direction often result in breaching the surface. The sabkhas sampled at Sites 5, 7 and 8 fall into this category.

SHEAR VANE DATA

Table 5 summarizes shear vane data. All unreduced shear vane data are presented in Appendix Table A-4. As mentioned previously, the shear vane data are more consistent than those obtained with the penetrometer. This consistency, however, is restricted to silts and clays, the sediments for which the shear vane was designed. In addition, the two types of soils strength measurements (shear vane and penetrometer) were made at slightly different depths and the resultant data are not strictly comparable. Based on our experience with standard four-wheel drive vehicles, sediments with surface shear vane readings above 25 kiloPascals are marginally trafficable. This breakpoint is, though, at least partially dependent upon the dampness of surface sediments.

WATER LEVELS AND FLOODING

Several kinds of measurements were taken involving sabkha groundwater. A series of measurements were made in cased core holes to determine if fluctuations in water level occurred over time. These measurements, made at irregular intervals, suggested that water levels at Sites 1 through 4 might fluctuate as much as 15 cm over a given week. Irregular flooding of some of these sites, however, prevented a rigorous long-term

TABLE 5: MEAN SHEAR VANE READINGS IN KILOPASCALS[1]

Sites	Color Type	Depth, cm[2]			Comments
		6	22	52	
1	Brown	12.3	13.5	13.3	
2	Brown	7.0	7.9	6.2	
3	Brown	13.6	11.9	7.8	
4	Brown	14.1	22.3	8.2	
5	White				Sand[3]
6	Brown	(25.3)[4]	22.2	14.6	
7	White	(20.5)			NFPP[5]
8	Brown	(14.6)		10.6	
9	Brown	(20.1)	(24.5)	9.7	
10	Brown	(10.2)	(66.6)	14.2	
11	Brown	(22.6)	(20.8)	(18.6)	
12-18					Sand

(1) Mean of 5 replicate samples.

(2) From surface to top of shear vane.

(3) Sites which were predominantly sand and not tested.

(4) ( ) value was derived from a horizon which, from core data, is predominantly sand.

(5) No further penetration possible past the 6 cm depth.

analysis of these groundwater fluctuations. In order to examine the potential correlation of water levels with time, water levels in each of the 18 cased sampling holes were measured over a semidiurnal tidal cycle. This was initiated during the early morning hours of 31 May 1980. The last time that any of these sites had been flooded was 24 May 1980. The interim period was assumed to be adequate to allow water levels to equilibrate. In addition, pits were dug within 5 cm of several sampling sites to examine the underlying cap rock layer and, in several instances, to obtain samples of sabkha groundwater. The water levels in these pits were also monitored. Unexpectedly, we found that changes in measured water height between the open pits and cased sampling holes were asynchronous.

The water levels in all of the open pits showed a net increase in water height with time while the cased holes showed a net decline in water level except at Site 7, where the net change was a 0.2 cm increase. These water levels were measured as distance below the sediment surface; therefore, a decrease in the recorded number indicates that the water level is rising and *vice versa*. The cause for this behavior is not immediately evident. The two factors assumed to be major contributors to short-term fluctuations in sabkha water heights are changes in barometric pressure and sea level. These two factors are plotted against time and sabkha water heights in Figure 17 for Site 4. For these data, at least, there appears to be no obvious correlation of water level to either sea level or barometric pressure. One explanation of the disparity in the water height data is that the core liners were pushed into the sabkha until cap rock was encountered. The impermeable nature of the plastic casing requires that any water level changes in cased holes occur through entry of water through the base of the hole. The liner itself is also too large for any significant capillary action to occur.

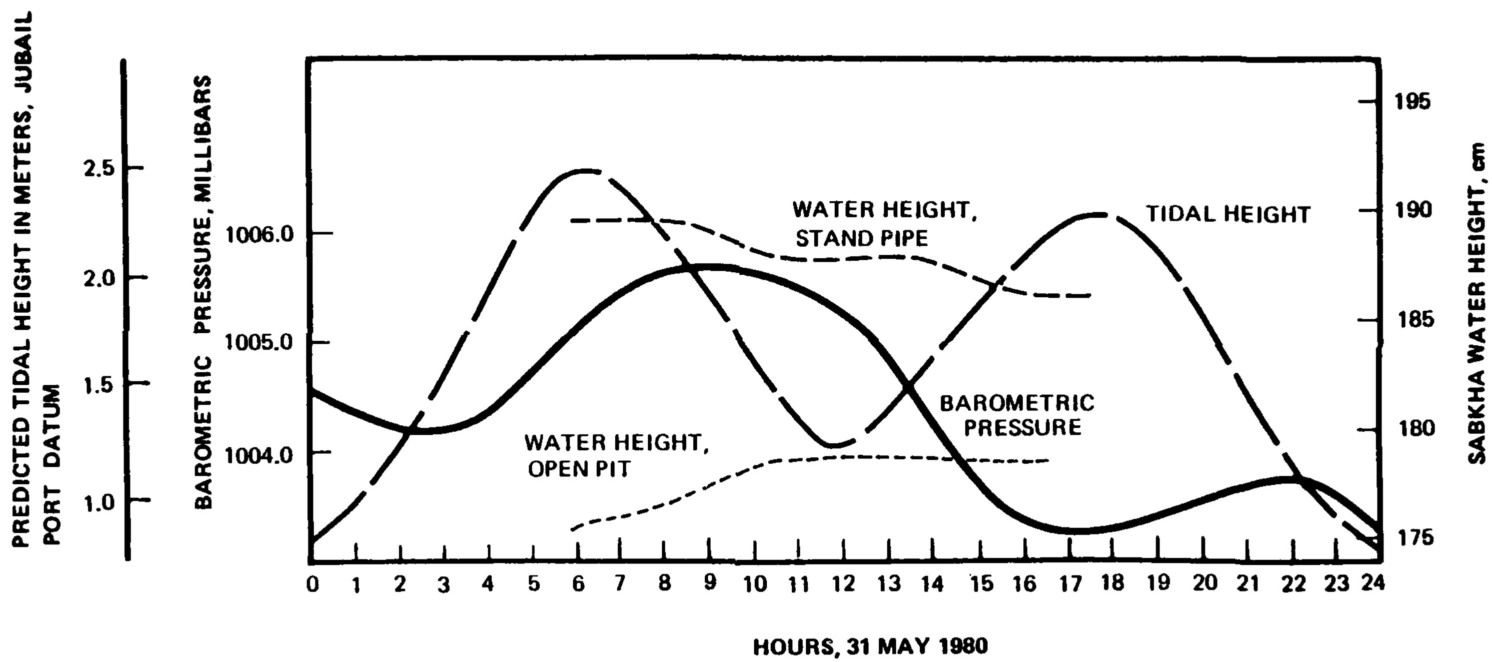


FIGURE 17 POSSIBLE ENVIRONMENTAL FACTORS CONTROLLING SABKHA WATER LEVELS

Water can enter an open pit, however, at any location along the sides. There is no obvious reason why the water level as measured in the cased holes is characteristically higher than that measured in the open pits. This is a problem in need of obvious clarification since, as will become evident, the trafficability of sabkha depends to a great extent on groundwater elevation.

The unreduced groundwater elevation data for all sites are presented in Appendix Table A-5 while the reduced and plotted data are presented in Table 6 and Figure 18, respectively. Figure 18 also summarizes physical observations and groundwater measurements made for all sites. Of interest is that Sites 1 through 4 and 7 through 10 were observed to have been flooded on at least one occasion during the study. This flooding never exceeded a few centimeters in depth and was always accompanied by relatively high winds.

The observed flooding saturated the surface sediment layer to a depth of perhaps 6 cm. At Sites 1 through 4 saturation resulted in a liquified mud down to cap rock. Under "normal" (non-flooded) conditions, a person walking on sediments covered by a blue-green algal mat might sink to a depth of 4-6 cm. During or immediately following a flood, however, one might sink to a depth of up to 30-40 cm when traversing such areas on foot.

The impact of flooding on the trafficability of the more inland sites, in particular Sites 6 through 10, was notably different. Before flooding, one might leave footprints on these sediments to a depth of less than 0.5 cm. During or immediately after flooding, and for a period of several days thereafter, one would sink approximately 6 cm into the mud before encountering a subsurface layer capable of supporting

TABLE 6: SABKHA GROUNDWATER

Site	Mean Water Level Above Jubail Port Datum, cm: Cased Hole	Mean Water Level Above Jubail Port Datum, cm: Open Pit	Groundwater Chemistry, parts per thousand: Salinity °/oo	Groundwater Chemistry, parts per thousand: Sulfate °/oo
1	192	179	145.6	11.25
2	179	174	112.8	-
3	182	181	142.3	-
4	188	178	126.8	-
5	238	-	94.7	-
6	189	178	206.4	-
7	183	170	178.5	-
8	194	167	222.3	-
9	195	183	195.8	-
10	200	194	144.3	-
11	188	-	129.7	-
12	207	-	83.6	-
13	221	-	150.7	-
14	220	-	113.5	-
15	223	-	126.3	-
16	220	-	124.4	-
17	220	-	208.4	-
18	220	-	280.3	-
Seawater, adjacent to Site 2			67.2	5.50
Borrow Pit			24.0 (2)	1.25
Water Hole			102.9	
Haul Road Sites				
Day 1: Dry Side			228.8	
Day 1: Wet Site			316.2	
Day 2: Dry Side			330.7	
Day 2: Wet Side			328.3	21.75

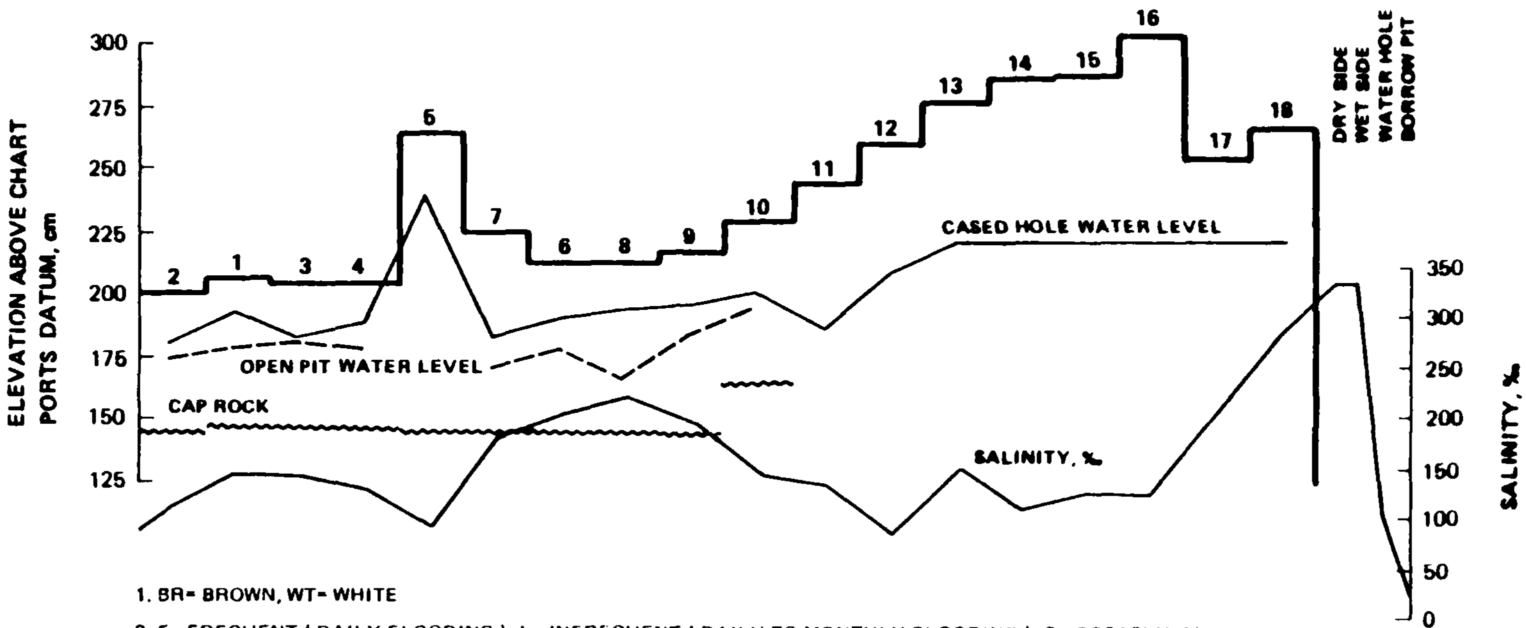
(1) Sulfate analyses performed by commercial laboratory in Jubail.

(2) Salinity determinations checked by commercial laboratory in Jubail using colorimetric techniques:
Tetra Tech Salinities = 24.028 °/oo
Commercial Lab Salinity = 24.037 °/oo

(3) Mean of two replicates, 228.82 and 228.74 °/oo.

(4) Mean of two replicates, 316.22 and 316.12 °/oo.

DESCRIPTORS																		
SURFACE COLOR[1]	BR	BR	BR	BR	WT	WT	BR	BR	BR	BR	BR	WT	BR	WT	BR	WT	BR	BR
FLOODING FREQUENCY[2]	F	F	F	F	I	O	I	O	O	O	I	R	R	R	R	R	R	R
% WATER — SURFACE	36	34	–	–	8	25	31	33	41	26	13	2	17	1	26	2	30	27
% WATER — -20 cm	56	55	–	–	14	38	57	41	29	34	30	17	16	14	29	6	33	14



1. BR= BROWN, WT= WHITE

2. F= FREQUENT (DAILY FLOODING), I = INFREQUENT (DAILY TO MONTHLY FLOODING), O= OCCASIONAL (MONTHLY OR LONGER FLOODING INTERVALS), R= RARE (FLOODING EVERY 4-5 YEARS)

WATER LEVELS: MEAN OF SEVEN OBSERVATIONS AT EACH CASED HOLE 31 MAY 1980, 0430 THROUGH 1701 HOURS
SALINITIES: SUBSURFACE SABKHA WATER USING ARGENTOMETRIC TITRATION

FIGURE 18 SUMMARY OF OBSERVATION DATA FOR ALL SAMPLE SITES the weight of a human body. In general, the flooding of sabkha liquifies the upper surface sediments to a depth of perhaps 6 cm. Such surface mud, when wet, is thixotropic. That is, when disturbed this sediment loses all cohesive bonding or shear strength and liquifies. If the underlying sediment layer is thixotropic and extends close to the surface, the net effect of flooding is to make the entire sediment column totally untrafficable. If, on the other hand, a hard layer--either sand or partially cemented sediments--is found near the surface, then only the fine sediment veneer is affected by flooding. This wet surficial mud, however, may rapidly clog all treads and drastically reduce vehicular traction.

To examine the amount of water which is absorbed by surface sediments following flooding a rather simple experiment was conducted. A 3.4 cm diameter core liner was cut into 6.0 cm sections and replicate samples taken of the surface sediments at Site 1 (covered by an algal mat) and at Site 6. Flooding occurred on 24 May when these samples were taken, but this flooding did not reach either of these sites. Neither site had, to the best of our knowledge, been flooded since 16 May. Ten replicate samples were taken at each location and both ends of the cores capped on-site. Thereafter, the samples were taken to the laboratory and five samples from each site were weighed, dried, and reweighed again to determine percent water content. The other five cores were filled with water after having their lower ends covered with several layers of 173 micron mesh cloth. The cloth retained the sediments while permitting excess water to drain out. The water content of those samples was then determined. Appendix Table A-6 presents these data. The blue-green algal mat was found to contain an average of 63.8 percent water. The sediments underlying this mat, on the other hand, contained 43.5 percent water. After saturation, these sediments contained 61.6 percent water. A similar experiment on samples taken adjacent to Site 6 (no algal mat covering) showed that the percent water content for natural sediments and artificially saturated sediments was 23.4 and 31.3 percent, respectively. In both instances, the water content of the surface sediment samples increased significantly, 42 percent by the sediments of Site 1 and 34 percent by the sediments of Site 6.

If surface sediment saturation through flooding effects sabkha trafficability, then rises in subsurface water elevations could have a similar effect. Measurement of the vertical excursions of sabkha groundwaters and their correlation to the forces which drive these fluctuations is critical to understanding the trafficability of sabkhas. Sediment porosity is the ratio of voids to solid material. Sediment permeability is the ease with which interstitial water may pass through these voids. Although finer grained sediments (silts and clays) may have the same porosity as a coarser sand or gravel, the influence of capillarity and molecular level attractions between the smaller grains and water is much higher and permeability is lower than in coarse grained sediments. In addition, the porosity of poorly sorted sediments, and thus its permeability, is lower than in well sorted sediments because of the efficient packing of voids in the poorly sorted sediments. Figure 16 shows sand or shell lenses which could act as horizontal water conduits sandwiched between silt or clay layers. Interspersed at unpredictable intervals between these sand layers are vertical "pipes" or diapirs of sand which would act as the vertical conduits of subsurface water moving up or down between the sand or shell lenses. Finally, the variability of water level fluctuations at coastal Sites 1-4 is considerably greater than that observed at Sites 17 and 18, the farthest inland.

The coefficient of variation of water levels in the cased hole at Site 4 was 7.57, while that at Site 18 was 0.87, almost a magnitude less. Thus, increasing distance from tidal bodies of water appears to act as a moderating influence on the variability of groundwater level and possible trafficability.

GROUNDWATER CHEMISTRY

Figure 18 above shows the salinities of groundwater at the sample sites. Except for a decrease below the sand berm at Site 5, there appears to be a gradual increase in groundwater salinity from the shore line inland to Site 8. Inland of Site 8, groundwater salinities gradually decrease towards the sand dunes between Sites 12 and 13 and then increase dramatically around Sites 17, 18 and uncontrolled sites Dry Side and Wet Side adjacent to the haul road. In fact, at these latter two sites, the sabkha water is essentially salt saturated.

Perhaps the most interesting aspect of these data is the locations at which the groundwater salinity is depressed with respect to the surrounding sites. Both Sites 5 and 12, for instance, represent surficial sand or shell sediments which could offer a ready conduit for the downward percolation of rain or sea water. The anomalously low salinity levels at these two sites, as well as their coarse sediment nature, was recognized at the time the samples were taken for analyses. For this reason water samples were taken at two additional uncontrolled sites. The water hole site, while being far inland, was situated adjacent to the base of a sand ridge approximately 2 m above the surrounding terrain, which was typical "brown" sabkha as found around Sites 17 and 18. The water hole site represents a shallow pit some 20 m on a side and 1-3 m deep from which tank trucks withdraw reflux groundwater for construction purposes. The water salinity at the water hole site was lower than that found at Sites 17 and 18, the two most inland sites sampled. After sampling the water hole site, we entertained the possibility that groundwater salinities may have peaked at Site 18 and were decreasing as one moved inland. To examine this hypothesis, the haul road sites were sampled and were found to be salt saturated. It did not, therefore, appear that groundwater salinities were necessarily decreasing with increasing distance inland. The final water sample was taken some 700 m from Site 18. This site would normally have been under some 4 m of sand. However, a borrow pit operation was in progress. A hole was dug into a coarse sand layer which, from visual observations, was at an elevation close to that of the surrounding sabkha. The water table here was about 0.5 m below the surface. The sample pit filled rapidly with water. This water, with a salinity of 24.0^{o}/oo, was the least saline encountered during this field work.

Based on these observations, it is hypothesized that coarse sand or shell deposits may promote the downward percolation of meteoric water or the upward percolation of low salinity groundwater. In addition, such vertical percolation, if localized at a spring or aquifer seep, might maintain the high porosity of the coarse sediments by preventing precipitation of salts and evaporitive minerals. An alternative hypothesis is that because of differential heating, evaporation rates in white sand or shell regions may be less than in darker colored areas. White sabkha areas are characteristically drier than surrounding dark areas. The data in Figure 18 shows that the white sabkha areas around Sites 12, 14 and 16 and the sand berm at Site 5 have water contents at the surface of less than 3 percent, while the surface water contents sampled at the brown sabkha sites were in excess of 27 percent. This pattern continues to 20 cm, where the water content of the white sabkha is 13 percent while for brown sabkhas it is about 36 percent. High water content plus dark coloration would be expected to produce higher surface temperatures through increased absorption and retention of solar radiation.

SEDIMENT RESPONSE TO ENVIRONMENTAL FACTORS

Figures 19 through 22 present the results of synoptic measurements of air and sediment temperatures at the study sites. These data are grouped by sabkha type and location. Also presented in Figure 22 are air temperatures, wind speed and direction, and relative air humidity values obtained from meteorological station 7 at Jubail during 31 May 1980. During the sediment response survey, air temperatures measured at + 10 m at Station 7 peaked (35.9°C) at 0900 hours and decreased during the afternoon. This variation from the normal pattern of temperature maxima in the early afternoon may be correlated to a shift in the wind direction from 330° (off the desert) to 14° (off the Arabian Gulf). Note also on Figure 22, that the relative air humidity at Station 7 doubled after this wind shift. Figures 19-22 show that this decrease in air temperature had no noticeable effect on air temperatures 0.1 cm above the air/sediment interface or on sediment temperatures at the sabkha surface.

Figures 19, 20 and 21 present information on brown sabkha. Of general interest here is that all of the surface air temperatures are considerably lower than the sabkha temperatures during the heat of the day. This differential can be as great as 4°C. Further, as one moves progressively inland, all of the soil temperatures increase, regardless at what depth they were monitored. This is also true for temperature measurements made at or near the water table (-50 cm). The subsurface water temperature at the coastal sites (1 through 4 as well as 5, although this is not shown on Figure 18) was 26.2°C while at the most inland sites (17, 18) it was 32.2°C. These higher temperatures, which occur throughout the sediment column, parallel the increase in salinities noted in the groundwater. The evaporative water loss from sabkhas appears to increase

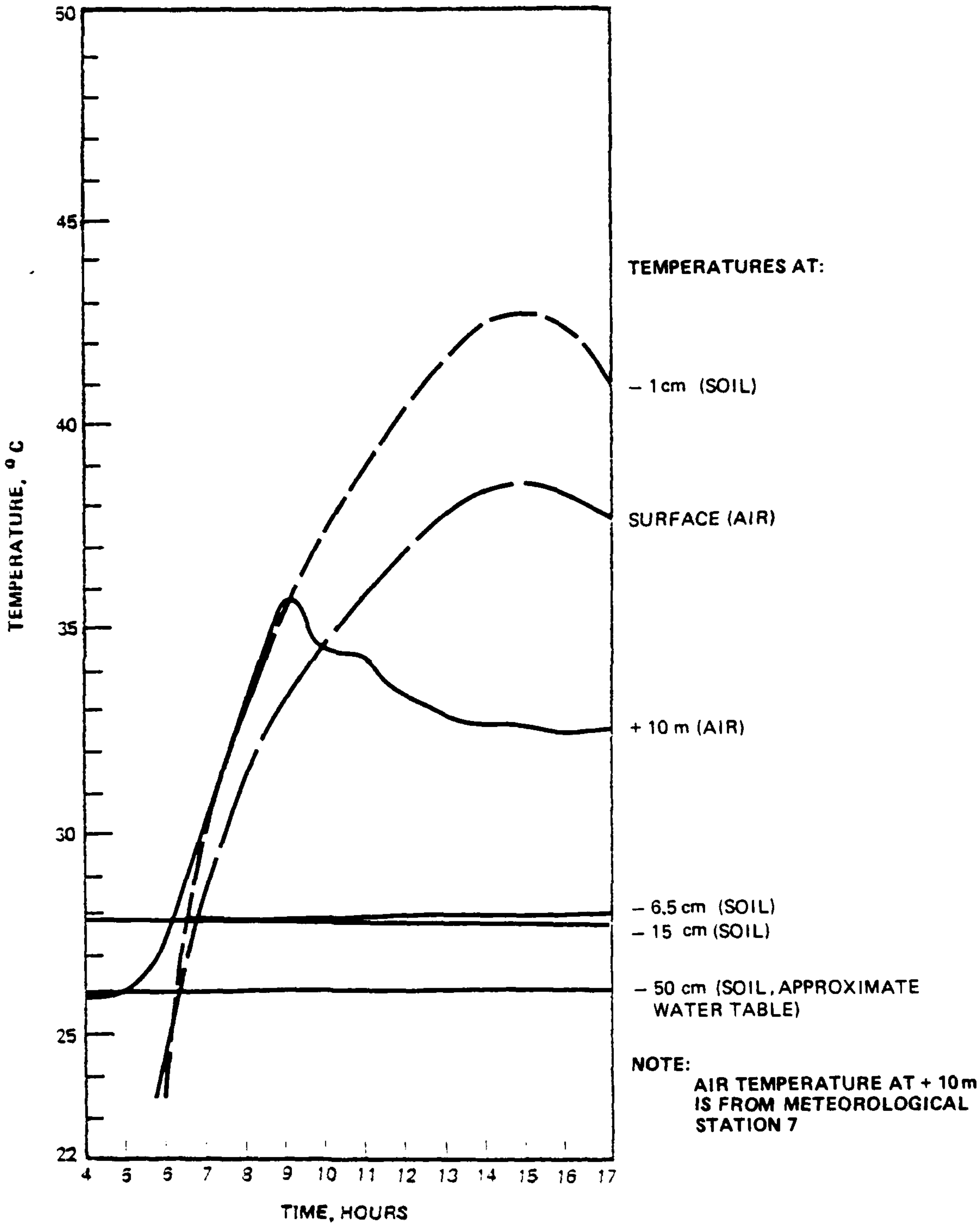


FIGURE 19 TEMPERATURE CHARACTERISTICS OF SITES 1, 2, 3 AND 4
31 MAY 1980 – ALGAL MAT

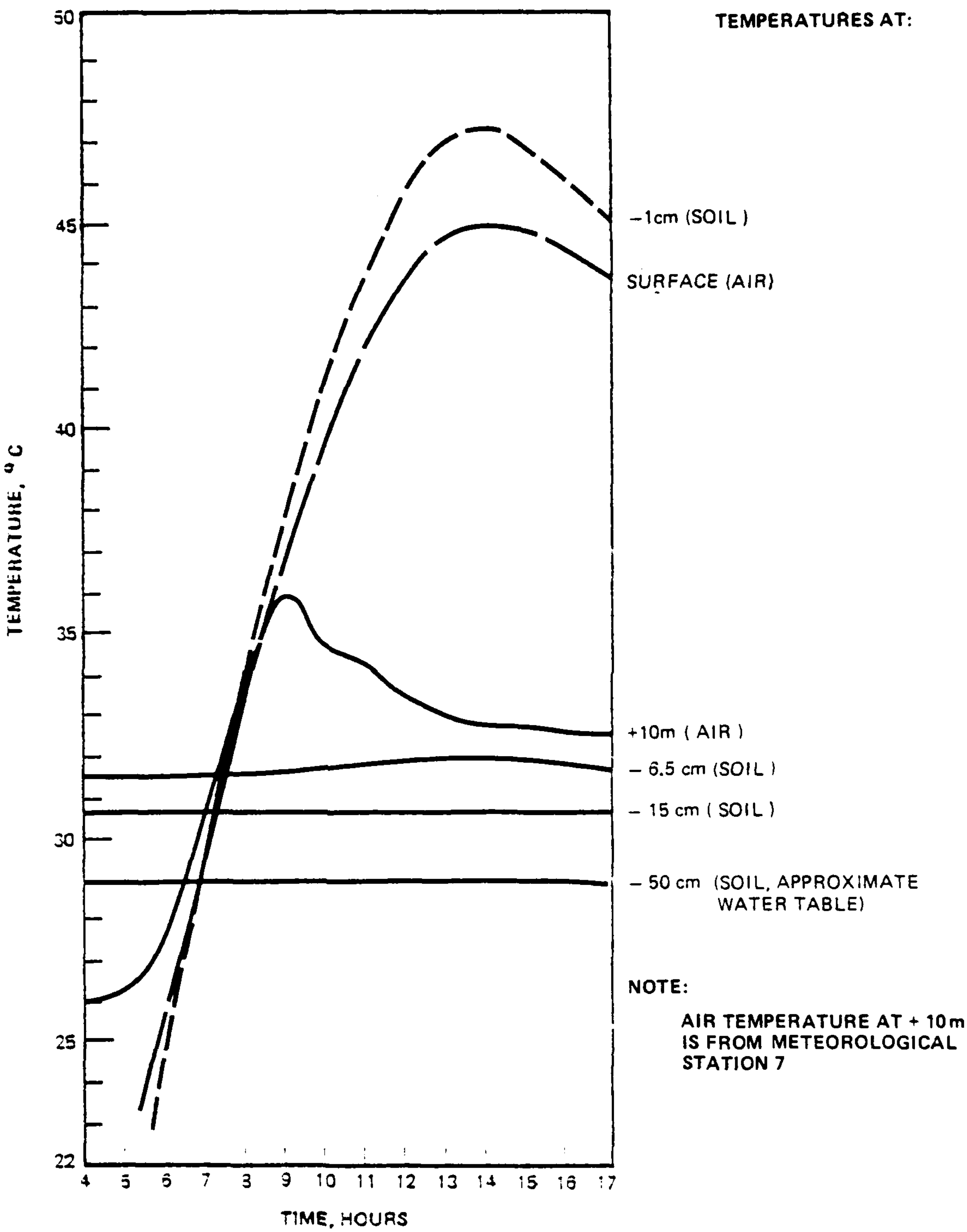


FIGURE 20 TEMPERATURE CHARACTERISTICS OF SITES 6, 8, 9 AND 10
31 MAY 1980 – BROWN SABKHA

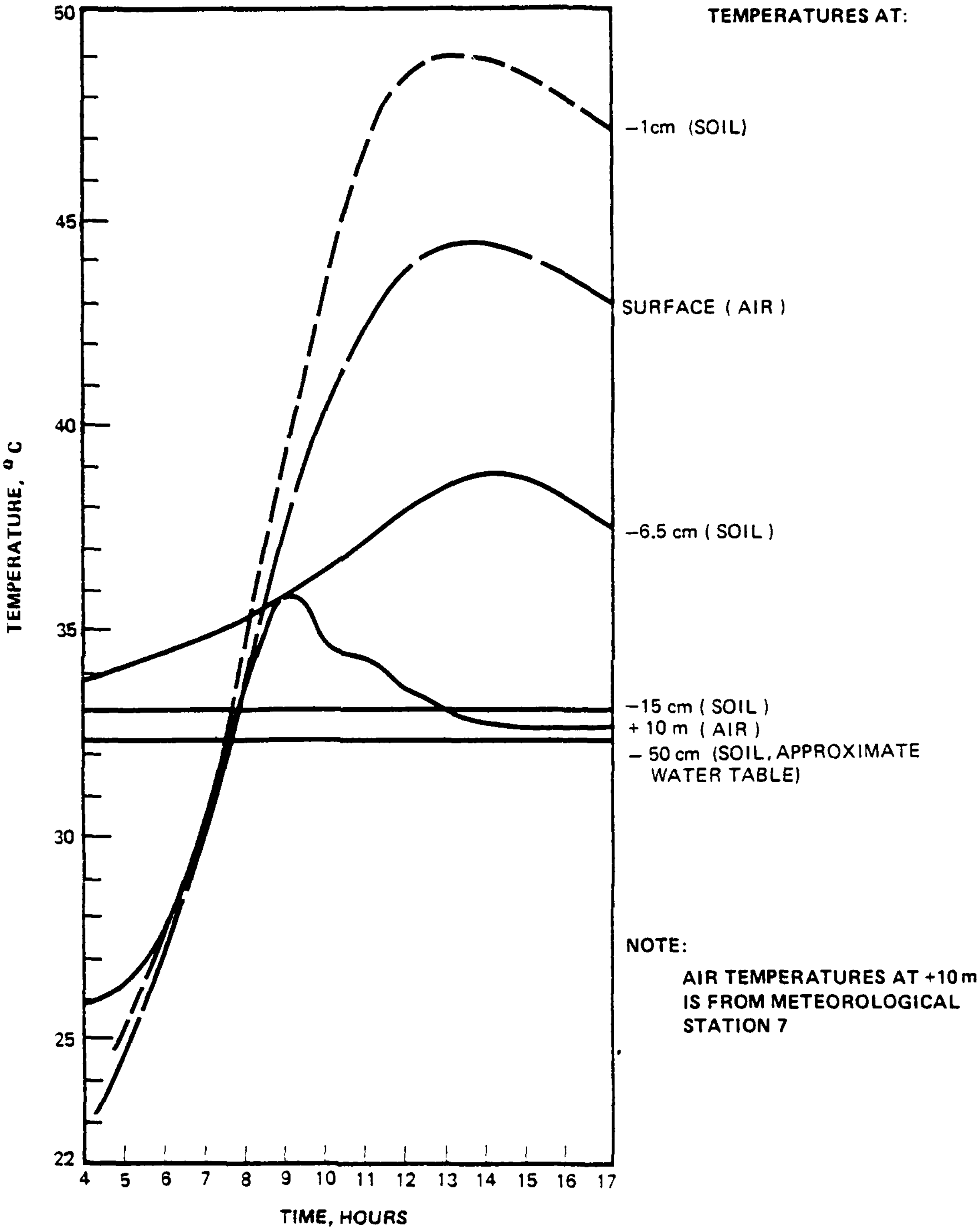


FIGURE 21 TEMPERATURE CHARACTERISTICS OF SITES 17 AND 18
31 MAY 1980 – BROWN SABKHA

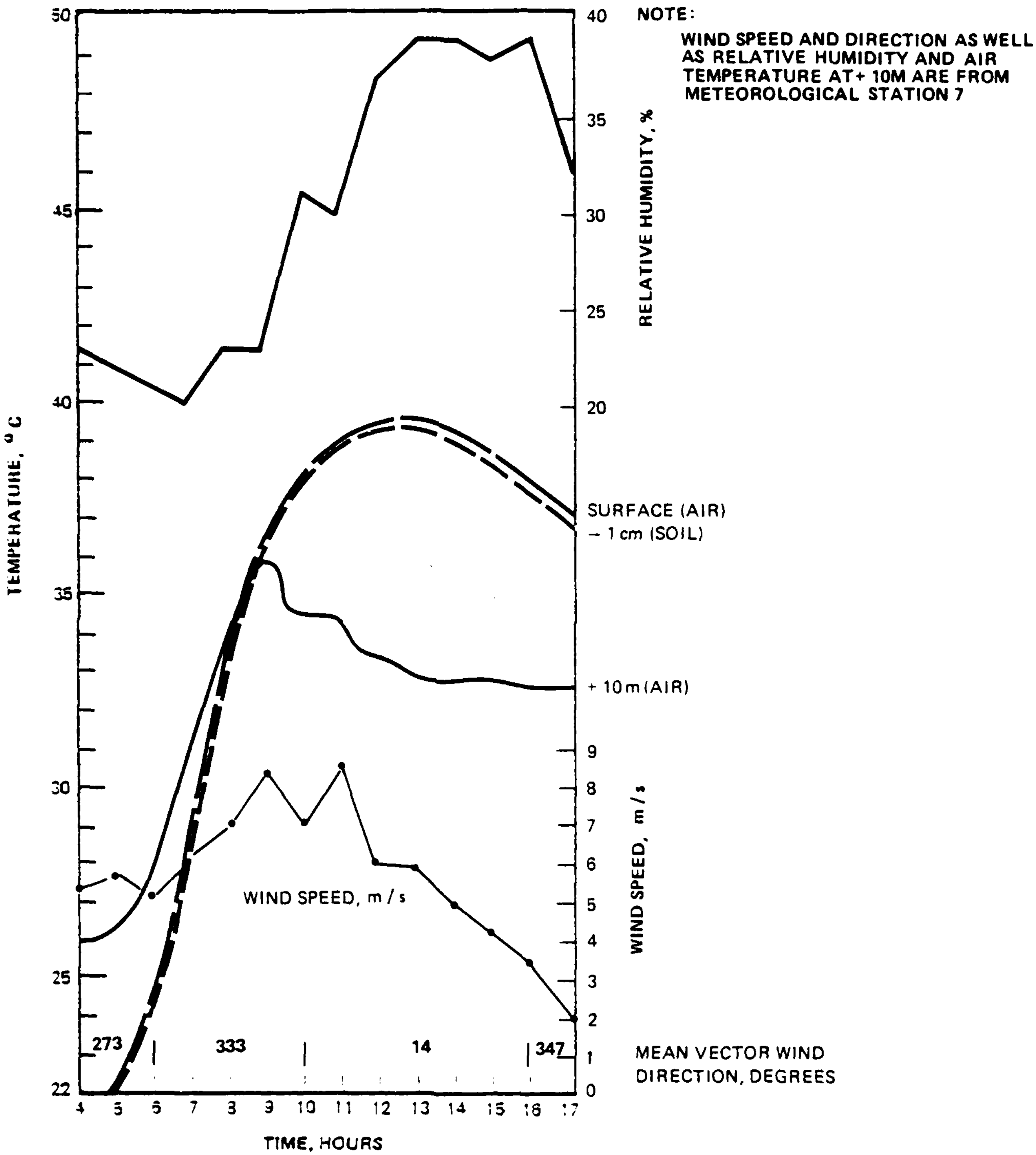


FIGURE 22 TEMPERATURE CHARACTERISTICS OF SITES 5, 12, 14, AND 15
31 MAY 1980 –WHITE SABKHA

the salinity of the underlying water. Conversely, the lower evaporative rates presumed to be associated with white and dry sabkha areas or sand dunes would result, with sufficient time, in lower salinities being associated with such areas.

Figure 23 shows meteorological parameters measured at Jubail meteorological Station 1 on 31 May 1980. These parameters include relative air humidity, air temperature, solar radiation, and soil temperature at -5 cm and -2 m. Station 1 is located 15 km east of Station 7 and 10 km inland from the Gulf. The wind shift of 31 May did not appear to have a major impact on either air humidity or air temperature at Station 1. Regardless of the wind direction at Station 1, it is always blowing across desert. Based on the surface soil and + 10 m air temperature readings, the surface air temperatures and the upper soil temperatures measured at all sites (Figures 19-22) and at Site 1, appear to respond (with some delay) to solar radiation rather than to the + 10 m air temperature. The incidence of solar radiation during 31 May 1980 reached its peak (71 Langleys/hour) at 1100 hours.

SABKHA FLOODING AT JUBAIL

Based on observational evidence over the past two years, we were fortunate to observe perhaps the first flooding to occur in the region of sample Site 10 for many months, if not years. Flooding episodes were observed on five occasions during May 1980. The most extensive flood occurred on 16 May. Sites 1 through 4 and 6 through 10 were flooded at this time. The only other flood which approached this in magnitude occurred on 24 May when Sites 2, 3, 4, 6, 8 and 9 flooded. The other flooding episodes occurred on 21 May (Sites 2, 3, 4), 22 May (Site 2) and 23 May (Sites 2, 3 and 4). Site 1 was not flooded on 21 or 23 May. This site is located between Sites 3 and 4 which were flooded. Further, the difference in eleva-

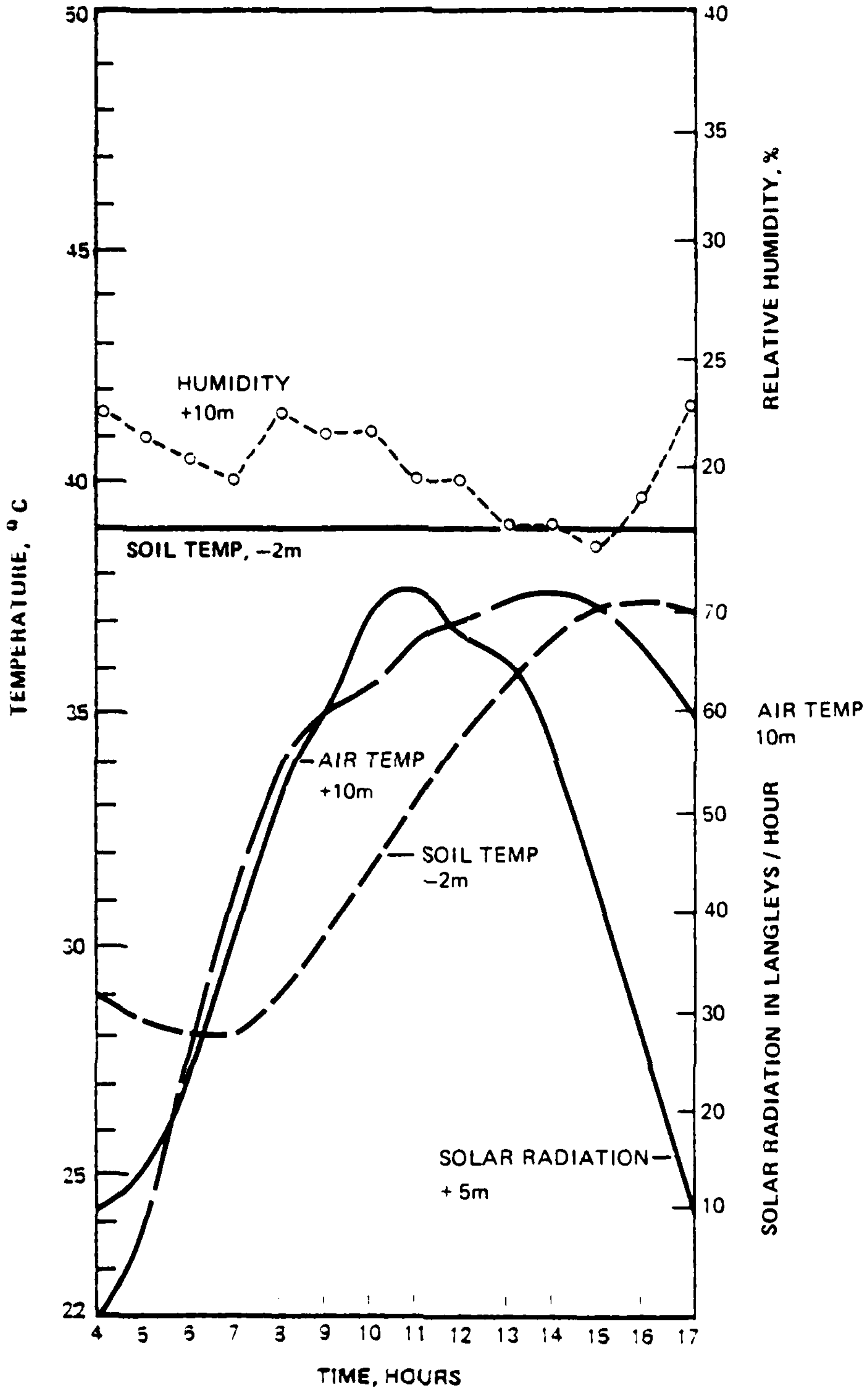
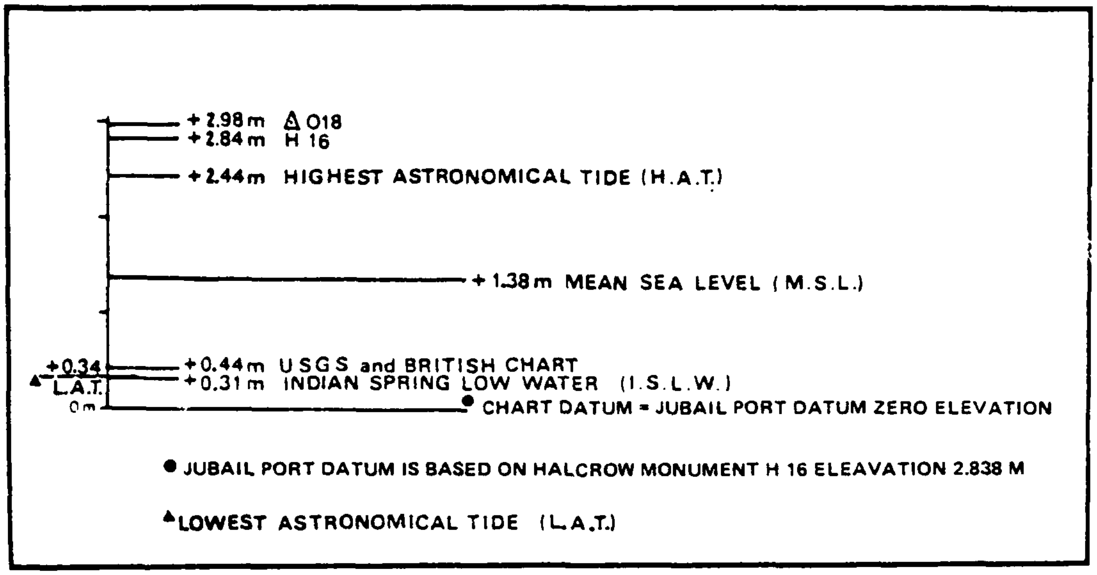


FIGURE 23 METEOROLOGICAL PARAMETERS AT METEOROLOGICAL STATION 1, 31 MAY 1980

tion between these sites is rather small. Site 1 is at an elevation of +2.08 m while the elevations of Sites 3 and 4 are 2.04 and 2.06 m, respectively. Thus, the difference in water levels required to flood one site and not another is measured in millimeters. Very minor changes in weather or tidal elevations may, then, be highly significant in determining flooding patterns.

To illustrate flooding patterns and the probably effect of modifying physical parameters in the flooding of the sites studied, we present data on flooding patterns recorded on 16, 17 and 24 May. It should be noted again that maximum flooding occurred on 16 May and 24 May. No flooding was observed on 17 May.

Figure 24 presents Jubail Port datum plane information required to convert Ras Tannura tides to the local datum plane. Ras Tannura is located 94 kilometers southeast of Jubail. Previous studies (Collins, 1972; Noda, 1973; and others) have noted that tides arrive at Jubail at approximately the same time as Ras Tannura. However, the high tides may be from 0.1 to 0.3 m lower than those predicted for Ras Tannura. Unfortunately the tidal elevations given in published U.S. Government tide tables for Ras Tannura (Appendix Table A-7) are not based on the same datum as used at Jubail Port. The Jubail Port zero datum plane is 0.44 m lower than that used by the U.S. Government or the British Admiralty. Therefore, 0.44 m must be added to all predicted tidal data to correct U.S. Government tidal datum to the Jubail Port tidal datum. The highest predicted tide is 2.3 m for 16 May 1980. Converted to the Jubail Port datum, this high tide corresponds to a tide of 2.7 m and should have, theoretically, inundated over half of our sample sites even under dead calm conditions. This did not occur. Therefore, these published tide tables are of assistance in obtaining relative tidal elevations, but are of limited use for absolute tidal elevations.



REF: FUGRO - CESCO, 1977

FIGURE 24 RELATIONSHIP OF JUBAIL PORT DATUM TO TIDE TABLE DATUM

Previous studies conducted by Tetra Tech at Jubail (Tetra Tech, 1979) have shown that both barometric pressure and wind can increase or decrease water levels over or under predicted values. To examine the effects of these factors the predicted tides were plotted against barometric pressure and compared to observed floodings. A high pressure ridge moving through the study area would lower water levels while decreased atmospheric pressure would cause them to rise. As will be observed in Figure 25, the predicted tidal elevations at the coastal sites on 16 and 17 May should have been sufficient to cause these sites to flood. Flooding did occur on the 16th, but not the 17th. This occurred under the opposite pressure regime which one would anticipate were atmospheric pressure a controlling factor in flooding. This is, flooding occurred under high atmospheric pressure and did not occur when the atmospheric pressure dropped.

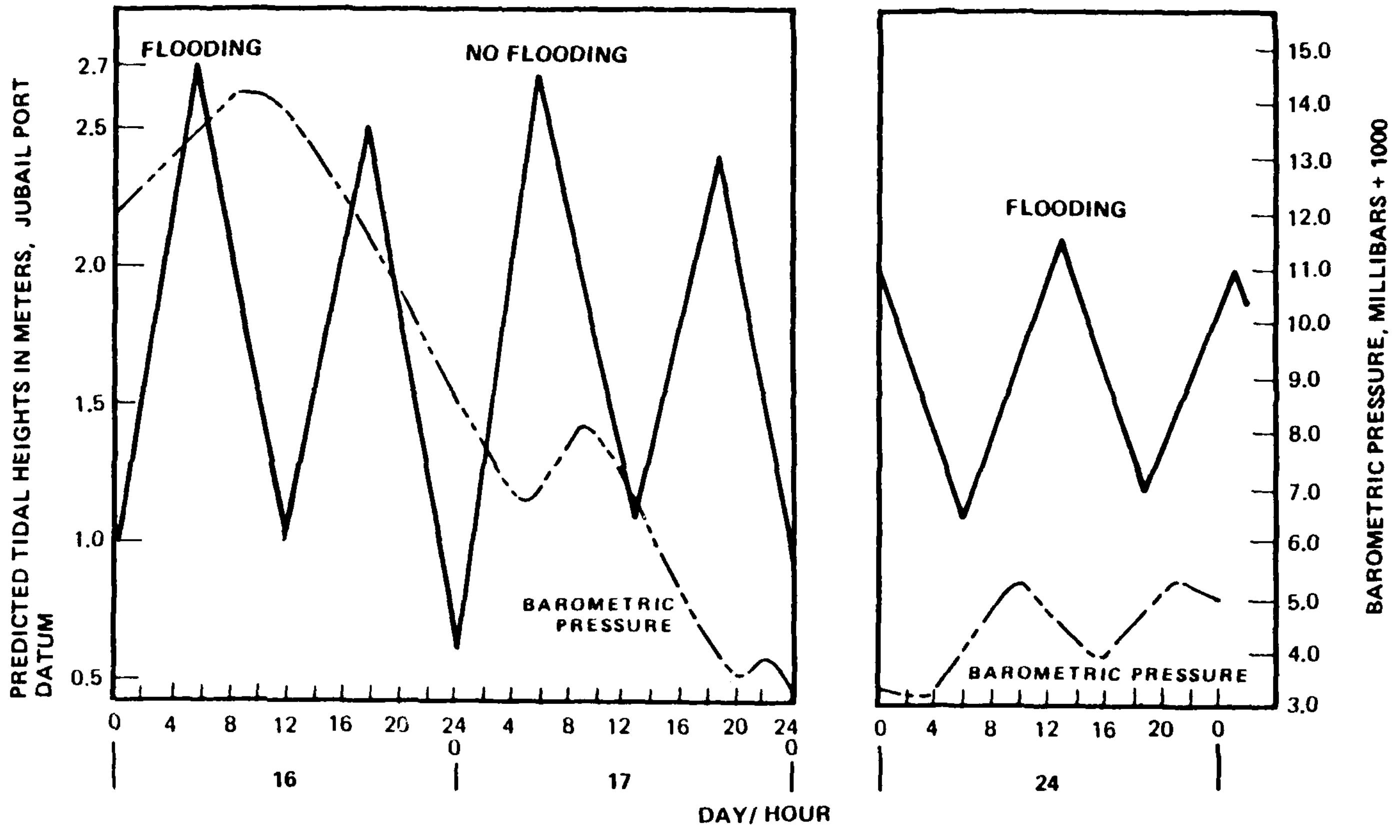


FIGURE 25 PREDICTED TIDES AND OBSERVED BAROMETRIC PRESSURE, 16, 17 AND 24 MAY 1980

Sabkha flooding also occurred on 24 August during a period of low barometric pressure and with a tidal height a full 0.6 m below that predicted for 17 May. It appears that while barometric pressure may play a role in flooding, it is not a dominant factor.

Figure 26 plots these same tidal data against both wind speed and direction. Comparing the data of 16 and 17 May shows that not only are the predicted tidal heights very similar, but so are the wind speeds and the period and duration of maximum wind speeds. One might assume that the sites should have flooded on 17 May particularly when it is noted that flooding did, in fact, occur on 24 May with a comparable wind speed regime, but a much lower predicted tide. The factors which successfully explain flooding in all these instances are the wind speed and direction. To simplify the graphic presentation, we reduced the wind direction data (presented in Appendix Table A-8) into wind sectors and present the mean wind directions in Figure 26. When a moderate wind is blowing (10-13 m/sec or 22 to 28 miles/hour), generally from the north-west, this results in set-up amenable to flooding as occurred on 16 and 24 May. Data from 17 May show a very high tide (the second highest of the entire year, exceeded only by that on 16 May) along with high winds and low and dropping barometric pressures. Yet no flooding occurred, apparently because the wind shifted 30 to 40 degrees towards the west. It was also noted on both 16 and 17 May that a considerable amount of foam was being blown by the wind. This foam contained a considerable amount of debris which was subsequently deposited at the foam line when the tide receded.

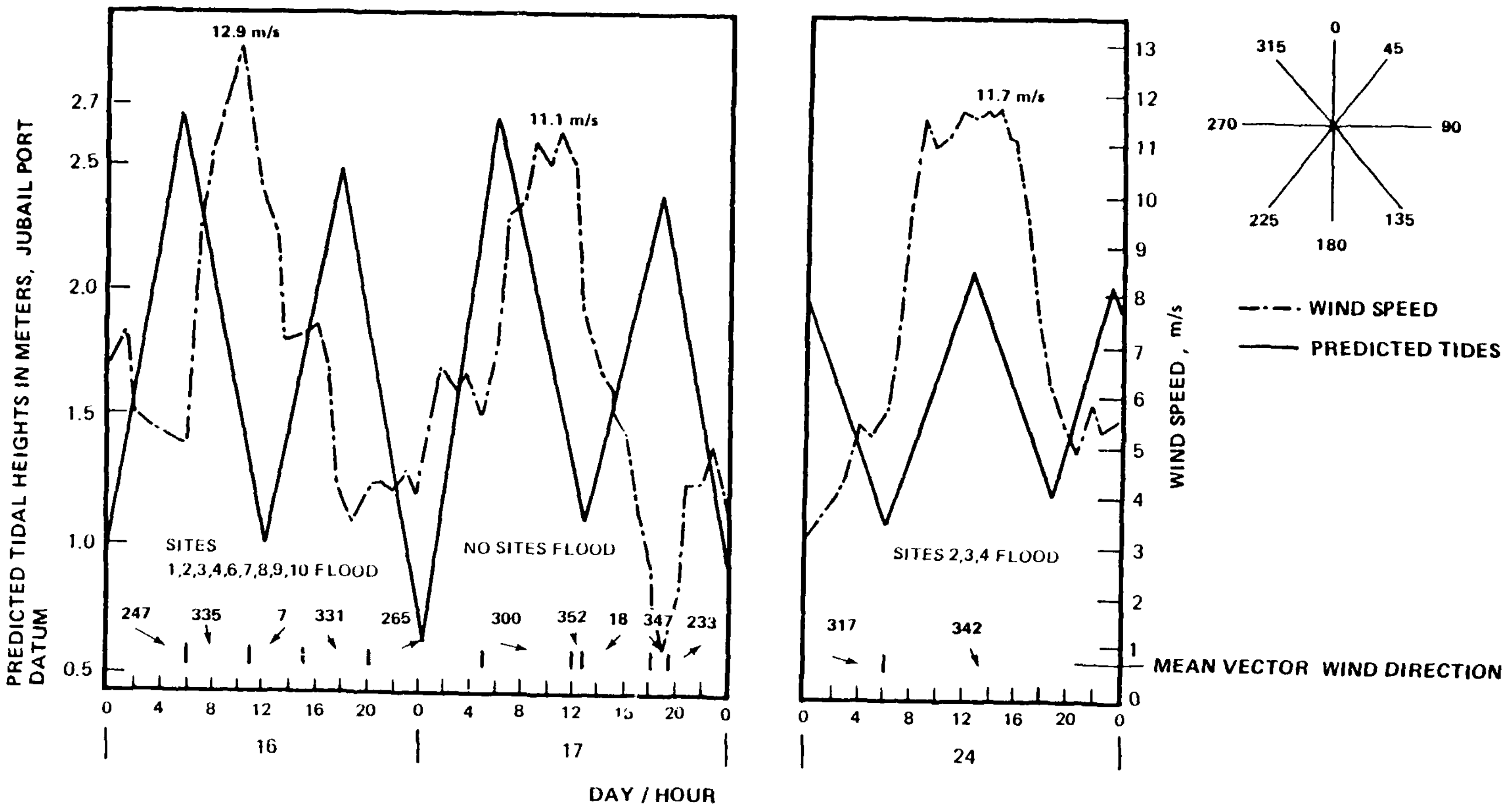


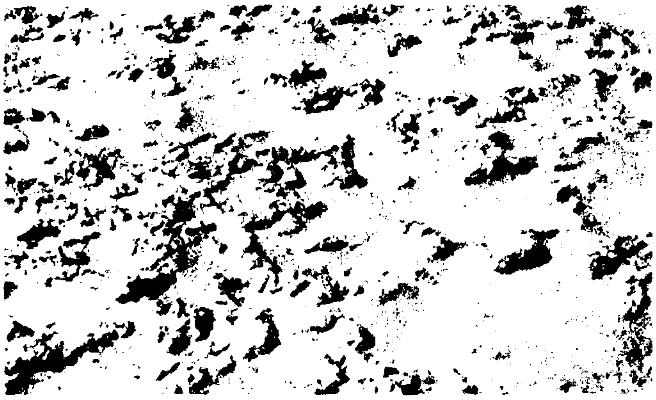
FIGURE 26 PREDICTED TIDES AND WIND SPEED AND DIRECTION 16,17 AND 24 MAY 1980

DISCUSSION

The objectives of this initial investigation were to determine if there were any properties of sabkhas directly or indirectly related to trafficability which could be detected by on-site inspection or by remote sensing or which could be predicted on the basis of forcing functions which could be monitored. The following discussions pertain directly to the sabkha studied, Sabkha al Fasl.

The areas studied which are covered with a blue-green algal mat are not trafficable with standard wheeled or tracked transport. The only exception to this would be where these areas are underlain by shallow cap rock. When relatively dry (no recent flooding) these blue-green algal mat areas are marginally trafficable on foot. During flooding and for a week or so thereafter, traversing these areas on foot is difficult. There are paths, however, crossing these blue-green algal mats, which are trafficable by foot even when the area is under water. These paths were presumably made by camels (although we saw none using them) since they wander aimlessly and are not associated with any human activity. The undisturbed blue-green algal mat has a blistered appearance as in Photo A in Figure 27. The paths themselves are flat and smooth in appearance and the algal mat is not blistered, Photo B in Figure 27. Similar paths are visible in areas which are periodically flooded. These paths are trafficable on foot regardless of whether the area is flooded or dry. The paths themselves are only depressed a few millimeters below the surrounding sabkha. Therefore, a small amount of packing appears to m e these types of sabkha trafficable on foot.

The white or cream colored sabkha is, from our observations, trafficable under all conditions. These regions are easily separated from brown sabkhas using color discrimination alone.



A

CLOSE UP OF BLUE–GREEN ALGAL MAT. NOTE BLISTERED SURFACE.

B

CAMEL PATHS CROSSING BLUE–GREEN ALGAL MAT. VIEW IS FROM NEAR SITE 5 AT AN ANGLE OF APPROXIMATELY 330°.

C

WELL TRAVELED ROAD ACROSS BROWN SABKHA. TRAFFICABILITY WAS CAUSING VEHICLE TO BREAK THROUGH SURFACE LAYER. NOTE SEVERAL OLD ABANDONED MAIN ROADS TO THE LEFT AND THE DEVELOPMENT OF A NEW MAIN ROAD TO THE RIGHT, AS THE NON-TRAFFICABLE PORTION OF THIS ROAD IS BYPASSED.

D

LOCATION WHERE A LARGE FRONT END LOADER ATTEMPTED TO LEAVE MAIN ROAD AND BECAME STUCK. NOTE THAT ONLY ONE WHEEL LEFT THE MAIN ROAD AND BROKE THROUGH THE SURFACE LAYER.

FIGURE 27 SURFICIAL CHARACTERISTICS

These white regions are characteristically dry with high shell and sand content.

Brown sabkhas are generally flat featureless plains. We observed numerous roads leading across these brown sabkha plains. Even when a road appeared to be well traveled by a variety of wheeled vehicles, however, there was no guarantee that local trafficability would not change drastically. Photo C in Figure 27 shows a well traveled road leading to the study sites. The original main dirt road ran close to the sand dunes to the left of the photo. As vehicles broke through the trafficable surface layer, pioneer roads were made further out onto the sabkha. Eventually, a large dump truck broke through the surface layer making this center road impassable. The lighter colored sand seen in the photo was placed around the wheels of the stuck truck to assist in its extraction.

Figure 27, Photo D, shows the location where a large front-end loader (large balloon tires, not a tracked vehicle) attempted to pioneer a new road across the sabkha to bypass a "dog leg". Only the right tires of this vehicle got off the main road before becoming bogged down. The contrast between the main road, where the passage of this or similar heavy equipment leave almost no visible tracks, and the adjacent large rut only a few feet away, is graphic evidence of the horizontal variability of sabkha trafficability.

The major difficulty in determining the trafficability of the brown sabkha is that, at least to the untrained or unaided eye, it all looks alike. A re-examination of Sites 6, 8, 9, 10 (Figure 11), 13 (Figure 12), 15 (Figure 13), 17, 18 (Figure 14) and Dry and Wet Side (Figure 15) shows that, in the unflooded state, there are essentially no surficial clues as to the underlying subsurface characteristics which determine trafficability. The sites which were the least trafficable (Sites 6, 8, 9, 10 and Wet Side) all flooded. Either the darker coloration of a saturated surface sediment layer, which persists for several days after flooding, or the thin halite crust, which seems to develop after several, closely spaced floodings, may be useful in determining trafficability. In the absence of such obvious and ephemeral clues, we found it difficult to define any parameters which could be quantified for easy transmittal to personnel, untrained or trained. One might use flooding and/or a halite crust as an identifier of trafficability, but flooding and the resulting formation of halite layers is a periodic phenomena which may not effect all trafficable or non-trafficable regions with consistency. There are also regions which may flood so infrequently that one could observe them for perhaps decades and never observe a flooding episode. Such may be the case for the periodically trafficable areas shown in Photos C and D in Figure 27.

The keys to determine the trafficability of brown sabkhas appears to be (1) the underlying sediment characteristics, (2) the water content of the sediments and, (3) the elevation of the area in question.

There appears to be no obvious method for determining the subsurface sediment characteristics of uniform brown sabkha based solely on visual clues. We have noted, as have other observers, that seasonal surface color changes do occur. These color changes occur in the absence of rain or flooding and, we presume, are in response to localized drying of sediments. Such changes might, thus, be a direct response to the rapidity with which groundwater was supplied to surface sediments. The rapidity with which groundwater moves toward the surface would, in turn, be based on both sediment type and the proximity of the groundwater table to the surface sediments. An instrument capable of spectral differentiation might yield information on the subsurface character. As mentioned in previous sections, the subsurface characteristics ` sabkhas can vary dramatically within a very few meters. Civilian satellite imagery, having a pixel resolution of about 6,000 m^2, does not appear to yield information of the required resolution or quality.

Elevation information, supplemented by high quality black and white or color photographs as well as multi-spectral analysis, could yield insight into sabkha trafficability. Differences of only a few centimeters in height may, in conjunction with surficial drying patterns, be sufficient to determine trafficability. For instance, Figure 28 shows a sequence of surface stages. The upper panorama shows the gradual transition of a "mixed" white-brown sabkha area (mostly coarse sand-shell) into a uniformly brown sabkha (moving right to left in this panorama). The mixed white-brown sabkha on the right was trafficable, while the pure brown sabkha on the left became increasingly untrafficable the further one progresses toward the left.

The bottom two photos in Figure 28 show the effect of extreme drying on brown sabkha. Near the sand dunes, tractors were scraping surficial sabkhas into mounds. The sabkha, once dry, was used for road beds. The close-up photograph on the right shows the effect of drying on a mound which is about 1 m high. The top is typical of white sabkha, the bottom typical of brown. It was impossible to determine just how far down such a mound would dry since once drying had reached the state shown, the entire mound was trucked away and used for road beds.

Areas with high shell and/or sand content appear trafficable while sediments with high fine contents are not. The geological processes which gave rise to these different sedimentologies may offer insights into how one might systematically discern trafficability patterns. The only other near surface study of sabkhas in the Jubail region uncovered complex sedi-

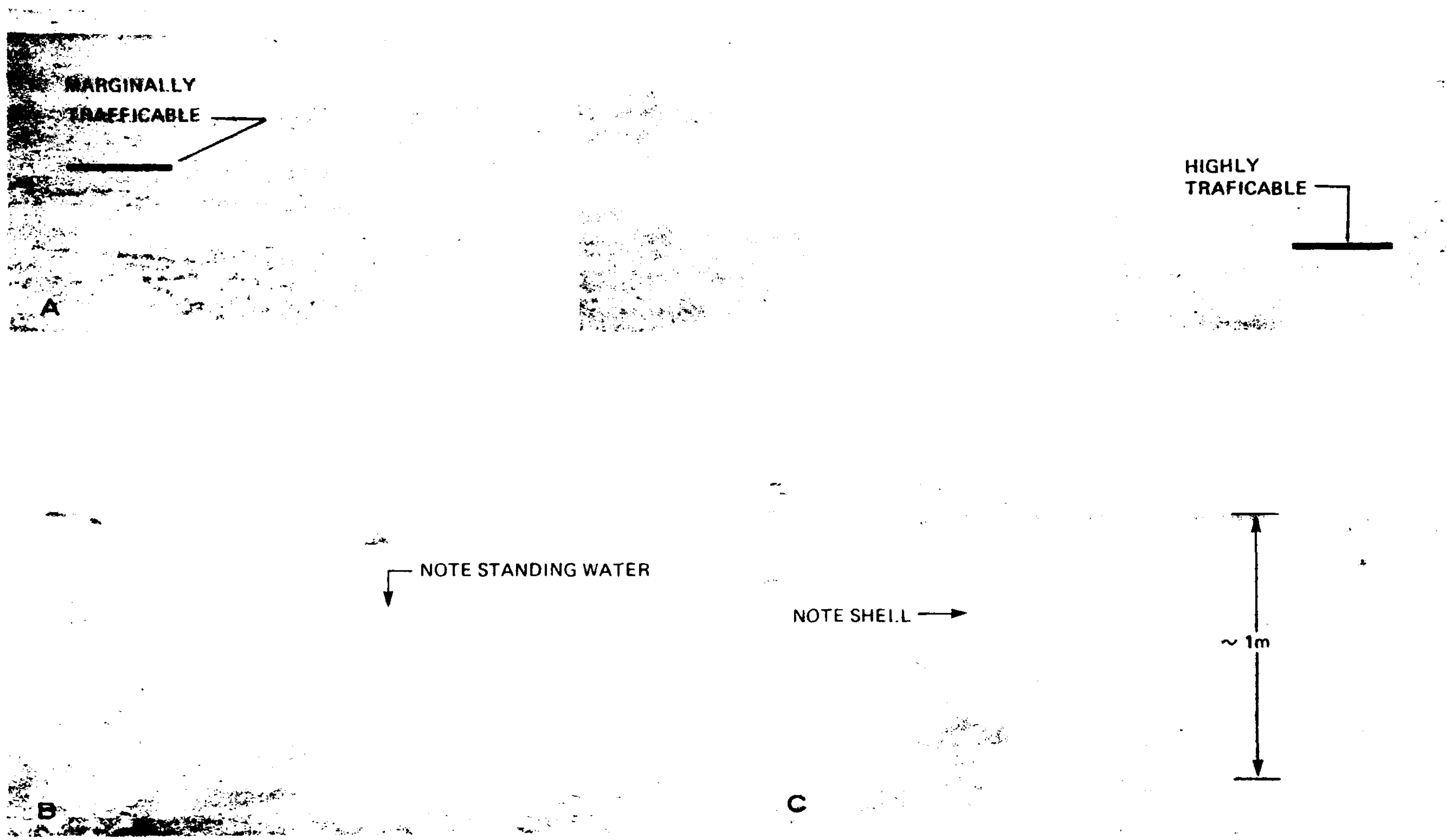


FIGURE 28 EFFECT OF DRYING ON SABKHA

mentation patterns. These studies were conducted by Johnson *et al* (1978) and covered the period 1973 to 1976. Johnson and his associates studied the Sabkha Ar Riyas which comes within 12 km south of Jubail. By digging holes to about 2 m with a shovel, they were able to determine the following:

> "The sediments were distinctly layered ... in many places below the crust there are several alternating 5 to 10 centimeter layers of poorly sorted fine- to medium-grained sand and grey mud... The contents between the various sand layers are in some places gradational and elsewhere very sharp; the sizes range from fine-grained to very-coarse-grained, and the sorting from poor to fair. In some holes, there are a few 1 to 3 centimeter layers of brown to grey mud between the sand layers...in a number of places small streaks and spots of dark reddish brown material appear...."

These same authors also noted an abundance of shell in some locations, a very gradual slope to the sabkha surface (20 cm/km in this case) with a water table which varied from 30 to 75 cm below the sediment surface. A general subsidence in the water table of 10 to 15 cm was also noted over a three month period. In general, then, the sabkha studied in the present investigation and that studied by Johnson *et al* (1978) appear to be very similar. These authors were primarily interested in studying groundwater geochemistry and not geomorphology or sedimentation processes.

There are in the samples taken several repeated combinations of shell, sand and silts. The areal distribution and proportions of these fractions can be explained in terms of sea level advance and retreat, aeolian transport, water transport either by fresh or salt water and post-depositional chemistry. The proportions of mollusc species observed in shell fragments may also be of importance. These classes of sediments are discussed below.

SEDIMENT CLASSES

Poorly Sorted Sands; Low Shell, Low Fine Content

Sediments of this type were found as isolated lenses a few centimeters (Sites 1, 2, 6, 8, 11, 12) to tens of centimeters thick (Site 9, 12, 13). All of these sediments have a shell content ranging from 0 to 0.75 percent and a fines content of 0.01 to 2.67 percent. The shell and fines contents may be less than this. The sediments sampled which have such low proportions of shell and fines correlate to sand dunes, which contained no shell and about 1 percent fines.

On the surfaces of some of the present dunes, there exist very fine layers of reddish-brown sand grains. These grains often give dunes a distinctly reddish cast. The same distinct color was noted at many bedding discontinuities. The core sample in brown sabkha at Site 13 from 5.5 cm to the limit of sampling (87.5 cm) had all the character of a dune.

Well Sorted Sediments, High Shell, Low Fine Content

The sediments in this category were found as lenses at Sites 5, 11 and 12. For these sediments, the shell content runs from a low of 19.3 percent to a high of 34.6, while the fines constitute between 0.1 to 1.9 percent. The buried shell found at all sites are characteristically epifaunal gastropods. The lack of infaunal pelecypods suggests that these assemblages were derived from open coastal environments. Two modes of shell accumulation may be inferred from the data, the first being illustrated by the shell band found at Site 5. This shell band is only 3 cm in depth. If this is taken to be the maximum thickness, that is, if this sample is not the periphery of a much thicker deposit, then one probable mode of accumulation is as wind blown foam deposits. Figure 10 (Photo C) is a close-up photograph of such a foamline located several hundred meters from Site 5. Site 5 is at an offshore sand berm at which is accumulating a lense of shell debris. The discontinuity between this surficial shell layer and the silty layer below is distinct.

A different process may have accumulated the shell layers found at Site 11 and 12. Shell aggregations of a similar magnitude and fines content have been observed at several open coastal sites in the Jubail region. Here surf action creates a berm composed mostly of shell of the species composition typical of our samples. These deposits also have a characteristically low fines content. At both sites these shell layers are overlain by sediments which closely approximate that found in dunes with the exception of either slightly elevated shell or fines content. It is of interest to note that the coquina layer found 42.5 to 44.5 cm below the surface at Site 12 contains a small mussel shell which, to the best of our knowledge, is found primarily in the shallow subtidal of the open coast in the Jubail area. If Site 12 were, at one time submerged, then Site 11 must have also been submerged since it is located only 100 m seaward from Site 12 and is 0.5 m lower in elevation. Thus, we propose that thick shell rich but fine poor sediments have a coastal berm origin. Similar layers, but thinner, could result from the accumulation of shell being carried, and deposited by wind blown foam.

Well Sorted Silty Sands With Low Shell

This class of sediments is perhaps the easiest to explain since they may be correlated to the ongoing deposition of silty fine sand and aragonitic mud in a calm, back water area such as is characteristic of the study area. The presence of shell fractions up to around 5 percent is easily understood since present silty sediments contain an infaunal and epifaunal assemblage much as those encountered at depth. This sediment class usually has shell contents from 0 to 4.8 percent and fines contents varying from 24.3 to 65.2 percent. Such sediments were found at varying depths at Sites 1, 2, 5, 6, 7, 8, 9, 10, 14, 15, 17 and 18.

Poorly Sorted Silty Sands With High Shell

A high shell content argues for proximity to a high energy coastal environment. A high fines content, on the other hand, argues for a calm, protected aquatic (or aeolian) environment. High shell and high fines occurring in the same strata should, therefore, imply two different sedimentary origins. Yet, the 4 cm of strata found between 16.0-22.0 cm at Site 17 contains 39.1 percent shell and 50.4 percent fines. Reference to Figure 14 (Photo D) shows the distinctiveness of these layers.

In 1977, Tetra Tech conducted a survey of the geology, biology and oceanography of the study area. At several locations, a high shell layer was encountered by cores at a depth of about 10 cm below the sediment surface while sampling for infaunal organisms. In all instances, these shell layers were overlain by high fines sediments. Furthermore, all previous biological sampling was conducted in an intertidal region. It might, therefore, be possible for infrequent severe storms to sweep into a shallow back water area and stir up the sediments, causing the heavier shell fraction to sink. Since the tidal exchange in this region is very poor (See Figure 9 and cover), the suspended fines would not be swept out to sea, but would remain suspended and move back and forth with the tides. Once the agitation ceased the fines in the water column would settle resulting in sediments with high shell and high fines content. The absolute percentage of each component as well as the depth of the resulting layers would depend on the amount of shell present in the overlying sediments, the time between severe storms, and the ability for the enclosed area to retain sediments. Such a sequence of events could account for sediments with high proportions of shell and fines.

SURFACE SEDIMENTS

Many authors suggest that the present sabkha surface represents an equilibrium aeolian accretion-deflation surface the elevation of which is controlled by interstitial moisture. There are several lines of evidence which suggest that, at least for some localities, this hypothesis is valid. Massive gypsum crystals and "desert roses" are found just below and on the surface of several sabkhas in the Jubail region. They have not, however, been found in the study region. These gypsum crystals are only formed under sediments. The finer grained sediments would be winnowed by the wind, leaving lag deposits of shell, coarse sand and, if present, large gypsum crystals. Thus, the surficial sediments of present sabkhas probably do not represent their original depositional composition. The exceptions may be on the seaward edge of the sabkha where active sediment deposition may be causing the sabkha to prograde.

The surficial sediments in the nearshore zone, exclusive of the algal mat themselves, differ dramatically from the underlying horizon. At Sites 1 and 2, for instance, the uppermost sediment layer varies between 2.0 and 3.9 cm in thickness and is composed almost entirely of what appears to be dune materials with a fines content of less than 0.3 percent. The underlying sediments, on the other hand, are primarily silts or aragonitic muds with a fines content of around 50 percent. In contrast, the uppermost sediments on both brown and white sabkhas, which in most cases are 6.5 cm or less in thickness, have fines contents which appear to vary in an unpredictable manner. On occasion, the surface layer of brown sabkha has a much higher fines content than the underlying horizon as is the case at Sites 17 and 18, the two most remote sites sampled.

The formation of salt crusts (or salcrete) on the sabkha surface would retard deflation, if only temporarily. These salt crusts appear to be primarily halite, and may be formed by evaporation after tidal flooding (Phleger, 1969) or reflux percolation from saline groundwaters (Gavish, 1974). Such a salt crust was observed to form after two successive floodings at the near coastal sites (See Figure 12) which appeared to be pure halite. The salt crust at the inland sites, as shown in Figure 14, also appeared to be halite. The salt crust at the coastal sites is virtually pure white and less than a millimeter in depth, while that at the inland sites is darker in color (perhaps due to silt) and may be several millimeters thick. The nearshore salt crust seems, thus, to be an ephemeral surficial feature (since it did not exist at the beginning of the field work) while that at the inland sites is probably more persistent. Further, these salt crusts were observed only on brown sabkhas. White sabkhas, as mentioned, have a surface of coarse sediments which are apparently neither conducive to the vertical transport of sabkha water nor capable of sustaining a pool of water at the surface.

Pye (1980) observed the formation of salcretes on beaches in North Queensland, Australia. Here salcretes of up to 2 cm were observed--with crusts of up to 1.5 cm being formed over a single day. These salt crusts can persist for many months, until dissolved by water (rain or reflooding) or destroyed by saltating sand grains from areas where no crust is present (Svasek and Terwindt, 1974). Pye (1980) observed that wind gusts of up to 12 m/s failed to move sand in crusted areas. We can add that we, too, observed no sand movement nor breakup of the salcrete in winds which averaged greater than 12 m/s. We did, though, note that sand from uncemented regions adjacent to crusted areas blows across the salcrete but, as far as we could determine, did not have an appreciable impact on it. Thus, the salcrete, be it pure salt or contaminated by silt, seems to persist for an undetermined period of time even in the face of persistent winds and fairly constant blowing sand. This is in slight contrast to observations of Kinsman (1969) and Bush (1973) who reported that the halite layer is an ephemeral crust which is destroyed by flooding. The halite we observed was produced by several successive floodings rather than destroyed by flooding.

FORMATION OF JUBAIL SABKHAS AND TRAFFICABILITY

We concur with previous authors who believe that the coastal sabkhas of Arabia represent the remnants of dunes and relict shore lines which have been submerged and reworked by the last Holocene transgression. We further concur that the present coastal sabkha surface at Jubail represents an equilibrium aeolian accretion-deflation surface whose elevation is controlled by the elevation of subsurface groundwater. It remains, however, to determine how one can rapidly and efficiently determine trafficability.

The key to determining easily trafficable areas seems to lie in being able to differentiate relict dune cores and beaches, areas we view as trafficable, from recently deposited aragonitic mud, which we view as definitely non-trafficable.

Aragonitic muds may be post-depositional products or may accumulate in calm water areas with elevated salinities. In the latter case, such depositional sites are commonly covered with a persistent algal mat. Locating algal mats should, by inference, define non-trafficable areas. Within the Jubail region, wide algal mats are visible on both black and white and color aerial photographs. The algal mat covering sample Sites 1 through 4 can, for instance, be identified in the aerial photograph presented as Figure 9. This same algal mat, however, is not readily visible on the black and white LANDSAT imagery, but more extensive coastal algal mats are (See Figure 5 and this report's cover). There also exist muddy or silty areas which are likewise non-trafficable but which are not covered by an algal mat. Based on our observations, these non-trafficable areas occur intertidally but were not examined in detail for this project--our studies being restricted to supratidal areas.

Relict beaches may be identifiable from both satellite imagery and aerial photography, although the latter again offers better definition. For instance, in Figure 9, what has been identified as relict beaches (based on high shell and sediment samples such as at Sites 12 and 14) clearly stand out as lighter than the surrounding dark sabkha. The active sand berm, typified by Site 5, is also clearly discernible. Satellite imagery, on the other hand, picks up these same features, but lacks useful definition. Reference to Charts 1-3 suggests that the relict beach can be inferred from changes in topographic relief, as occurs between Sites 10 and 11. The relief change, here the 2.5 m contour line, separates sabkha of marginal trafficability (Sites 1 through 4 and 6 through 10) from sites which we found to be easily trafficable (Sites 11 through 16). Site 13, and by inference the isolated brown sabkha region which it represents, appears to be a relict core of a deflated dune. The brown sabkha represented by sample Site 15 appears to be located between what may have been relict beaches. The basic configuration (elongated) suggests that this zone may not have been a dune area since isolated dunes at present are elliptical and not elongated. The sample from Site 15 appears to be accumulated aeolian sediments rather than marine detrital sediments. The 13 cm thick layer of shell 37 cm below the surface may have resulted from storms which overtopped the outermost shell berm, depositing the shell and coarse skeletal sand found mixed with fines.

Sites 17 and 18 represent complex depositional zones which cannot easily be classed as either wholly beach, berm or dune. The differences between these two sites are marked. It was mentioned previously that sediments having high fines and

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high shell contents, such as those at Site 17, could have been deposited during severe storms in a nearshore environment. Intertidal areas sampled during previous surveys in this area have a dense shell layer at -10 cm which are now being overlain by silts. These deposits are also being reworked by severe storms to produce a similar sedimentary composition.

Site 18 is of interest for several reasons. First, the absence of shell is indicative of a sand dune--a supratidal aeolian formation. The presence of an elevated proportion of fines suggests a low energy marine or aeolian depositional environment. For the present, we suggest that this sample was taken on the leaward side of a bachan dune.

The two haul road sites (Dry Side and Wet Side) are located seaward of the 2.5 m contour. The sediments found here were most certainly deposited inter- or subtidally, since they both lack significant sand sized fractions. These findings are consistent with the hypothesis that the 2.5 m contour most probably represents the elevation above which relict beaches and trafficable areas will be found in the Jubail region.

Further reference to Figure 9 shows a light colored area, which we believe to be surface halite, which covers a portion of the sabkha seaward of the 2.5 m contour. This salt crust appears to cover a non-trafficable or at least marginally trafficable portion of the sabkha. The relationship of salt crust to trafficability needs verification.

Kinsman (1966) observed that sabkha water levels essentially parallel mean sea level for the outer two-thirds of coastal sabkhas. Although our period of observation was abbreviated, we suggest that sabkha groundwater levels closely approximate the mean high tide level rather than mean sea level.

The source and mode of travel of sabkha groundwater while of interest, has not been studied in sufficient detail to provide definitive evidence relating to trafficability. Groundwater source and flux through sabkhas should relate directly to cohesiveness, chemogenic constituents, thixotropy and other geotechnical properties of sabkha.

The frequency of sabkha flooding, as well as the apparent depth of flooding, does not appear to be sufficient to maintain the water contents observed in surface sabkha sediments. Each successive flooding appears to supply enough seawater to saturate only the upper few centimeters of the sediment column. Within a week or so of flooding the surface sediments reach a water equilibrium with the underlying sediments such that the the surface elements (at least those of the brown sabkhas) maintain a water content within relatively narrow limits. Rain, for a similar reason, could not supply sufficient water to maintain sabkha dampness particularly since net evaporation seems to exceed net precipitation by roughly an order of magnitude. Sabkha groundwaters must, therefore, be supplied by either continental aquifers or lateral intrusion of seawater at the sabkha-sea interface.

The Alat aquifer underlies the Jubail region. According to James F. MacLaren, Ltd. (1979), this is a confined aquifer with a static head some six feet above sea level. A rupture in this aquifer underlying sabkha could provide a source of water. We assume the Al Ghumisa submarine spring is an offshore manifestation of this aquifer. Overlying the Alat aquifer is an aquifer of significantly higher salinities (10‰ - 20‰) of Quaternary or Recent age. This is a likely source of sabkha groundwaters and may well be responsible for the pocket of low salinity groundwater (24‰) encountered at the Borrow Pit.

Previous investigators have suggested that seawater is the principal source of sabkha water in the Trucial States (Butler, 1969) and Gulf of Suez (Gavish, 1974) while Johnson *et al* (1978) who studied the sabkha Ar Riyas, south of Jubail (Figure 5), thought that the waters of this sabkha might be continental in origin. Both sources of water are likely to contribute to sabkha subsurface waters in varying proportions at different locations.

Movement of water through sediments is roughly proportional to pore size. Well sorted coarse sediments offer a ready conduit for water, while well sorted fines do not. Further, poorly sorted sediments, containing both sands and silts or clays, are poor conduits since the smaller fines clog pore spaces between larger sand grains. On the other hand, the capillary forces operating between fines is considerably greater than that between sands which, in turn, suggest that for a constant level water table, the height of wetted sediments will be higher in fines than in sands.

Within our study region, we defined a trend of generally increasing salinities with increasing distance from seawater supplied by the Gulf. Two of the more remote sites sampled, Water Hole and Borrow Pit, had salinities less than that found in the surrounding sabkha. We hypothesized that this could result from (1) reduced evaporation, (2) increased downward percolation of rain water or, (3) groundwater supply from continental aquifers. We further hypothesized, based on the presence of low salinity pockets at Sites 5 and 12, that water movement in the upper sediment horizons (which are, incidentally, above mean high tide) is primarily vertical. If this is indeed the case, we might predict that a vertical salinity gradient may well exist within a given sediment column such that the uppermost sediment layers, which are subject to intense heating and evaporation, would have the highest salinities. The possibility of such vertical salinity gradients should be part of future studies of sabkhas at Jubail. Such salinity gradients were found by Butler (1969) in Trucial States coastal sabkhas. A partial confirmation of this hypothesis was made at the Dry

Side site. Here water samples were taken on successive days. The first sample was taken on 29 May from the apparent water table, which, at that time, stood at approximately -0.74 m below the surface. The salinity of this water was 228.8‰. The following date the site was again visited to examine *in situ* stratigraphy but, instead, the water level was found to have risen to about -0.25 m. A water sample was taken and found to have a salinity of 330.7‰. We hypothesize that the first water sample represented the salinity at the lowest horizon sampled (and the salinity of the upper groundwater in general) while the salinity on the second day represented near surface interstitial water which had entered the hole from the sides of the excavation. This is consistent with a vertical salinity gradient. This same explanation could also be used as one explanation for the reduced salinity found in the Water Hole site of 102.9‰. Here water is continually being withdrawn. If replacement were predominantly from the aquifer immediately beneath this excavation (vertical) rather than from the walls (horizontal) the salinity would be expected to be less than surrounding near surface waters. Whether this groundwater is continental or marine cannot be addressed without a detailed study of specific ionic species.

Our general hypothesis to explain water movement in the sabkha we studied is that seawater travels under the sabkha, probably at a depth of several meters, from the Gulf landward. Tidal hydraulic pressure maintains a groundwater level approximating that of the mean higher tide. This water is "pulled" under the sabkha to replace surface waters lost through a mechanism such as "evaporative pumping" suggested by Hsü and Siegenthaler (1969). We assume that this active pumping mechanism is operative rather than simple capillary action since groundwater levels at the inland, more highly saline and hotter sabkhas stands higher than those closer to shore.

To support the hypothesis for deep sea water recharge (i.e., greater than 2 m) rather than direct lateral recharge, we cite the following. First, the outermost sabkha sediments (to a depth of roughly 1 m) are dominated by fine grained silts and clay and would not be conducive to significant lateral water movement. A significant horizontal movement of seawater would then presuppose deeper, coarse sand sediments to serve as lateral water conduits. These sands do exist under the cap rock layer which we did sample below during this study. Fugro-Cesco (1977) performed a number of soil borings in the region and encountered extensive medium to coarse grain sand underlying offshore muds and cap rock. The boring location, as well as seismic refraction data for the sample closest to our study sites, are shown in Figure 6. Second, the cap rock layer under the sabkha must not preclude the vertical movement of water. As stated elsewhere, this cap rock appears to be highly porous and should permit vertical water movement. Third, the existence of pockets of low salinity water (Sites 5 and 12) strongly suggests vertical movement of low salinity groundwater to the upper sediment layers. If horizontal water movement occurs to any significant degree in the uppermost sediment layers one would expect these low salinity pockets to be dispersed. That they are not argues, we believe, for vertical water movement. Once this water flows under the fines and reaches relict dunes or beaches, lateral dispersal of this water could occur.

Vertical water movement in soils is certainly one of the potential factors which control sabkha trafficability. One of the last experiments attempted in Saudi Arabia was intended to address this problem but had to be abandoned due to time constraints. We dried and sieved a large quantity of sabkha sediments into 12 fractions using the sieves from 2.8 to 0.063 mm. We tightly packed these sieved sediments into core liners, placed one end in water to determine the maximum vertical excursion of water within these core liners due to capillary action alone. Our hypothesis was that water levels would be higher in fines than in coarse grain sediments and that an equilibrium would be reached quickly. The three coarsest ments (2.80, 2.00 and 1.40 mm) were packed first. The water levels in all three cores rose at a relatively constant rate. After four days the capillary water level in all three core liners stood at 22 cm and was still rising. But this experiment had to be abandoned at this point and we do not know how high the water levels would have reached under equilibrium conditions.

Finally, previous investigations (Kinsman, 1966) suggest that sabkha water levels approximate mean sea level for the outer two-thirds of coastal sabkhas. Previous Tetra Tech studies in Jubail established the tidal regime close to our study area (Table 7). Comparing these data to those presented in Table 6 strongly suggests that sabkha water levels closely approximate mean high tide rather than mean sea level.

TABLE 7: MEAN TIDAL LEVELS AT THE STUDY SITE, CENTIMETERS

Month and Year	High Tide	MEAN Sea Level	Low Tide
May--June 1979	175	133	091
July 1977	184	142	100
Aug 1977	180	136	093
Sept 1977	175	133	091

Datum: Port Authority

CONCLUSIONS

The sabkhas of the Jubail region of the Kingdom of Saudi Arabia represent a complex stratigraphic province which developed in response to the last Holocene transgression. During this transgression, aeolian deposits were isolated from their sand sources by the rising sea and were consequently deflated by persistent desert winds blowing primarily from the northwest. The highest sea level incursion probably occurred some 4,000 years B.P. and may have resulted in the formation of cap rock at the +3 to +4 m level, the formation of coastal beaches and berms several kilometers inland of the present shoreline, and the deposition of quantities of shell along these coastal berms.

A shoreline regression and relative lowering of sea level began some 3,750 years B.P. with at least one sea level standstill until the present mean sea level was reached about 1,000 years B.P. This most recent regression stranded old beaches, berms and the coastal dunes. With time, these features were deflated to an elevation which is now at, or slightly higher than +2.5 m above the Jubail Port Datum plane. Deflation ceased at this point due to the presence of subsurface waters which maintained the moisture in the sabkha surface sediments, retarding further aeolian erosion.

Seaward of these relict features, and in conjunction with the corresponding fall in sea level, a low energy lagoonal environment was formed. This intertidal zone received deposits of aragonitic muds and aeolian fines. Over the last thousand or so years the continual build-up of these fines, frequently stabilized by a blue-green algal mat at the sabkha-seawater interface, resulted in the progradation of the shoreline seaward. These sediments, deposited at an elevation of less than

-2.5 m, consist of fines below the sediment surface with a veneer of coarse, poorly sorted, reworked beaches and which now include shell and aeolian sand accumulations.

From a trafficability standpoint, the sediments lying above 2.5 m are generally trafficable while those lying below 2.5 m are generally not. This represents the apparent breakpoint between the Holocene shoreline of 1,000 years B.P. and the subsequent progradation of the beach and subtidal zone. Along the supratidal fringes of this prograding shoreline and in particular the regions covered by blue-green algal mats, the sediments deposited consisted predominantly of fines and are at present non-trafficable by standard wheeled or tracked vehicles.

The question of resolving trafficability of a given area thus seems to rely on differentiating between aeolian and marine depositional areas and surface sediment water content. In general, civilian satellite imagery resolution is too coarse for this purpose due to the size of individual pixels (80 x 80 m). High resolution aerial photography, particularly color or false color, offers significant advantages as would, possibily, military satellite imagery. If one could combine high resolution aerial photography, spectral imaging (for water content) and height information we feel relatively confident that sabkha trafficability can be determined remotely.

It is also apparent that there are vertical and horizontal variabilities in the surficial sediment water contents and in groundwater salinities of sabkhas and that groundwater elevations do vary both with time and with distance from the shoreline.

RECOMMENDATIONS

There are several logical additional lines of study which might be undertaken to refine sabkha trafficability assessments. To test the central hypothesis that trafficability depends on depositional and post-depositional history, it is suggested that trenches, rather than cores, be used to examine sediment stratigraphy. If this were done, the hypothesis on the development of sabkhas and the presence of trafficable regions along relict beaches and berms could be confirmed. It is, then, suggested that radial excavations from the existing Jubail sampling grid be performed to verify the depositional characteristics that were inferred from core samples.

Secondly, it is assumed that the + 2.5 m contour at the Jubail site follows a scarp which appears to be the trace of the relict beach. It is suggested that excavations be dug through this scarp at the 2.5 m contour in other sabkha locations to refine or disprove this hypothesis.

Third, there exist several large, algal covered, coastal flats fronting the open coast around Jubail. It is suggested that the subsurface sediment characteristics of these algal mats be examined to see whether they are underlain by silts and clays (non-trafficable sediments) or trafficable sands and whether this relationship may be extrapolated to other areas of algal mat cover.

Fourth, a remote method should be found which can rapidly determine the relative water content of surficial soils. Such a technique need not be highly precise. Monitoring the spectral band width for surface intertidal water contents or water vapors overlying sabkhas or using infrared film should be sufficient. The latter is based on the principal that the darker, wet, saline sediments absorb and hold considerably more heat than the surrounding drier sediments. Wetter sediments might, therefore, be expected to yield more radiant heat longer into the evening than would the drier sediments.

Fifth, water movement through sabkhas has an important impact on surface trafficability. We know of no one, however, who has specifically addressed this problem and decomposed movement mechanisms into vertical and horizontal components. This should be done. Injections of tracers into the sabkhas would be a suitable means of monitoring groundwater movement along with improved *in-situ* water level monitoring systems to look at fine scale fluctuations of groundwater over extended periods.

Sixth, and in conjunction with the above, the determination whether there exists fundamental differences in vertical transport of water through calcareous and siliceous sediments is needed. This would yield data which might allow information gained at Jubail to be transformed to other regions of the world where sediments are high in lithogenic rather than biogenic materials. Companion work should be conducted to examine two vertical transport mechanisms; simple capillary action and/or evaporative transport.

Seventh, coastal and continental sabkhas exist in many other parts of the world. It is proposed that additional reconnaissance surveys be conducted in representative areas to determine whether the trafficability of these sabkhas is determined by the same factors as those we studied in Arabia.

Eighth, standard instruments designed to measure trafficability, such as the U.S. Army Corps of Engineers soil penetrometer, proved inadequate in sabkhas. Development of a more quantitative yet easily transportable and usable means of accessing trafficability seems an important goal.

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GLOSSARY OF TERMS

ACCRETION: The accumulation of transported sediments.

AEOLIAN: Transported by the wind. Also spelled eolian.

ALAT MEMBER: Geological stratum in the Jubail region which is water bearing. Member of the Dammam Formation.

ALGAE(AL): Group of plants that have no true roots, stems or leaves. The term is used to refer to the blue-green algal mats in the Gulf region which are dominated by several species of filamentous and coccoid algae.

AQUIFER: Water bearing geologic stratum.

ARGENTOMETRIC TITRATION: Method by which the salt content of water is determined by titrating chloride ions with silver ions.

BARCHAN: Term (Turkestani) applied to cresentic dunes which occur both as isolated dunes or dune chains. Depth limited, these dunes are driven across the desert by wind.

BENCH MARK: Permanent or semi-permanent monument the location and elevation of which is known with a high degree of accuracy.

BERM: The highest portion of an upper beach face with a relief generally higher than the surrounding terrain.

CALCARENITE: A textural term used to describe an oölitic or foramiferal limestone of medium grain size.

CALCAREOUS: Containing an abundance of the element calcium often in the form of lime or limestone.

CAP ROCK: Highly indurated sedimentary rock, usually occurring in sheets over uncemented sediments in the Northwest Arabian Gulf.

CARBONATE: Containing the chemical species $CO_3^{=}$.

COEFFICIENT OF VARIATION: The standard deviation of a number of measurements divided by the mean of these same measurements.

COQUINA: Cemented shell.

DAMMAM FORMATION:	Extensive geologic formation in the Eastern Province of Saudi Arabia of Eocene Age. Named after the city of Dammam in Saudi Arabia.
DEFLATION:	Removal of surface sediment deposits by wind.
DEHYDRATION:	Removal of water. In the context used here, it refers to the dehydration of gypsum to anhydrite ($CaSO_4 \cdot 2H_2O \rightarrow CaSO_4 + 2H_2O$).
DETRITUS:	Particles of rock worn and carried away from a central mass.
DIAGENESIS:	Changes occurring in sediments between the time of deposition and complete lithification.
DIAPIR:	Movement of a fluidized, less dense sedimentary unit upwards through denser overlying strata.
DIKAKA:	Area dominated by dunes.
EOCENE:	Epic of the tertiary period.
EPIFAUNA:	Marine organisms which live on top of the sediment.
EUSTATIC:	Worldwide, usually in reference to sea level.
EVAPORITE (-ITIC, -S):	Minerals which are precipitated from sea water through evaporation.
EVAPORATIVE PUMPING:	Process of actively drawing up water into a sediment column to replace that lost through evaporation.
FAROUSH:	Arabic term for beach rock.
FINES:	All sediments which pass through a 0.063 millimeter square mesh screen.
FLANDRIAN:	Most recent rise in sea level.
GASTROPOD:	Member of the Phyllum Mollusca with a foot used for locomotion and a single shell (snails).
GEOMORPHOLOGY:	Branch of geology which deals with land forms and processes.
HOLOCENE:	Most recent epoch of the Quaternary Period.

HORIZON:	Bounded, easily recognizable layer in stratigraphic studies.
HYDRATE:	A mineral to which one or more water molecules are attached. Hydrated minerals are written as $X \cdot H_2O$ for the monohydrate, $X \cdot 2H_2O$ for the dihydrate, etc.
HYDROGEN SULFIDE:	Gas with the formula of H_2S and which has a rotten egg odor. Formed during the anaerobic decay of organic matter.
INDURATED:	Consolidated and partially cemented sediments.
INFAUNA:	Organisms which live in, rather than on, the sediment.
INTERSTITIAL:	The space between sediment grains.
INTERTIDAL:	Found or occurring between the high and low tide lines.
JEBEL:	Isolated hill in Arabic.
KHOBAR MEMBER:	One of the water bearing strata of the Dammam Formation dating from the Eocene. Named after the city of Al Khobar in Saudi Arabia.
LAG DEPOSIT:	Heavy sediments which remain following winnowing away of fines by the wind.
LAMALLAE:	Thin plates or membranes.
LANGLEY:	Unit of solar radiation equal to one gram calorie per square centimeter.
LITHIFY (-IED, -ICATION):	The process of turning unconsolidated sediments to rock.
MARL:	A lithified deposit of sand, silt or clay cemented by calcium carbonate.
MESOZOIC:	Geologic Era.
MIOCENE:	Geologic Epoch of the Tertiary Period.
MOLLUSC(K):	Invertebrate animal with a soft unsegmented body usually enclosed by a calcium carbonate shell (snails, clams, etc.).
MUD:	Sediment composed of particles falling in the size range of silts (<0.063 mm) and clays (<0.002 mm).

NEOGENE FORMATION: Uppermost Recent sediment deposits in the Eastern Province of Saudi Arabia.

OÖLITE: Rock consisting of small round grains usually of calcium carbonate (calcite or aragonite) in the Gulf.

PALEOZOIC: Epoch of the Tertiary Period.

PASCAL: Unit of pressure, Newton/m^2.

PELECYPOD: Member of the Phyllum Mollusca which have their body enclosed between two shells (clams).

PELLETAL: Small rounded or spherical body, pellet-like.

PISOLITIC: An aggregation of large, rounded pellets, usually calcite or aragonite in the Gulf.

PLEISTOCENE: Epoch of the Quaternary Period.

PLIOCENE: Epoch of the Tertiary Period.

PRECIPITATE: Solid chemical compound which forms in an aqueous solution.

PROGRADE: The seaward movement of a shoreline either by a decrease in sea level or sedimentary accretion in the shorezone.

QUARTZOSE: Having a composition dominated by quartz.

QUATERNARY: The most recent period of the Cenozoic era.

RECENT: Equivalent to the Holocene, or the present Epoch of the Quaternary.

REGRESSION: In the context used here, the seaward migration of the shoreline often through a relative fall in sea level.

RETROGRADE: The landward migration of the shoreline through a relative rise in sea level or erosion.

SABKHA: Supratidal salt flats underlain by clay, silt, sand and frequently by evaporites. These usually represent sedimentation--accretion equilibrium surfaces, the elevavation of which is controlled by groundwater. Two types of sabkhas, continental and coastal, exist. Only the latter is discussed in this paper.

SALCRETE:	A surficial covering of sand cemented by halite and other salts.
SALINITY:	In general usage, the quantity of salts, expressed in parts per thousand, contained per unit volume of water.
SALTATION:	The process during which sand grains bounce rather than roll along the sediment surface during transport.
SANDS:	Soil particles larger than 0.063 mm and smaller than 2.0 mm in size.
SEEPAGE REFLUX:	A process in which sea water which floods a coastal plain percolates downward into the surface sediments and is returned to the sea.
SILT:	Loose material greater than 0.002 mm but less than 0.063 mm in diameter.
SKELETAL SAND:	Sand which is formed from the skeletons of dead marine organisms rather than from the weathering of rocks.
STANDSTILL:	The point at which the sea level remained constant for a fairly long period of time as evidenced by some prominent geological features such as shorelines.
STROMATOLITE:	Fossil sedimentary laminations formed by the burial of a blue-green algal mat.
STRATIGRAPHY:	The geological discipline that deals with the origin, composition, distribution and succession of strata.
SUBAERIAL:	Processes which occur to sediments above the level of groundwater or the sea.
SUBTIDAL:	Areas below the low tide level.
SUPRATIDAL:	Areas above the high tide line.
TERTIARY:	A geologic Period within the Cenozoic Era.
THIXOTROPIC:	Fine grained sediments which lose electrovalent bonding strength (seen as a rapid loss of shear strength) when distrubed but regain this strain over time if undisturbed.

TRANSGRESSION:	Movement of the sea across a coastal area usually during a rise in sea level.
UNCONFORMITY:	Lack of continuity in deposition corresponding to a period of non-deposition and/or erosion between sedimentary cycles.
UNCONSOLIDATED:	Not lithified.
VADOSE:	Occurring in the soil above the groundwater table.
WÜRM GLACIATION:	Most recent European glaciation.

GLOSSARY OF MINERALS

Mineralogical Name	Chemical Name	Chemical Formulae	Comments
Anhydrite	Calcium sulfate	$CaSO_4$	Transformed to gypsum by hydration. Commonly associated with salt deposits as cap rock and in limestone rocks. Formed by evaporation and precipitation of brines at temperatures of 42°C or higher.
Aragonite	Calcium carbonate	$CaCO_3$	Chemically identical, but structurally different from calcite. Aragonite is the less stable of the two forms and is, thus, the lesser abundant form. Aragonite, secreted by molluscs for the production of shell, usually undergoes a natural transformation to calcite. In hot brine solutions, aragonite is usually the precipitate, whereas in cold brine solutions, calcite is usually precipitated.
Biotite	—	$K(Mg,Fe)_3(AlSi_3O_{10})(OH)_2$	Generic term applied to a class of chemicals in which K can be replaced in part by Na, Ca, Ba, Rb, or Cs. A closely related naturally occurring mineral is phlogopite, $KMg_3(AlSi_3O_{10})(OH)_2$. Usually found in igneous rocks. Another form of biotite is vermiculite, used as an insulator.
Calcite (Limestone)	Calcium carbonate	$CaCO_3$	The most common, naturally occurring, form of calcium carbonate. The lesser abundant form is aragonite. Calcite may be formed in igneous rocks as a decomposition product of lime silicates. In the Gulf region, however, calcite deposits are most likely the result of the deposition of animal skeletons. Calcite is an important cementing material in sedimentary rocks. Marls in the Gulf are calcite and are extensively used for road beds and as rip rap along causeways.
Carbonate	Carbonate	$CO_3^=$	Ionic species formed from the reaction of carbon dioxide and water ($CO_2 + H_2O + H_2^+ + CO_3^=$) to form carbonic acid. The free carbonate radical is then available to form carbonate minerals with positive ions, most notable calcium carbonate ($CaCO_3$) in the Gulf region of which calcite and aragonite are the primary isomers.
Celestite	Strontium sulfate	$SrSO_4$	Precipitated directly from brine solutions. Commonly found in limestone or sandstone deposits. Barium often substitutes for strontium resulting in barite, $BaSO_4$ (barium sulfate).
Dolomite	Calcium magnesium carbonate	$CaMg(CO_3)_2$	Dolomite is thought to be derived from calcite (limestone) by the replacement of calcium by magnesium. The distribution and occurrence of dolomite is similar to that of calcite.
Feldspar			
Orthoclase	Potassium aluminosilicate	$KAlSi_3O_8$	Feldspar is the generic term applied to the silicates of aluminum with potassium, sodium and calcium and rarely barium. The most abundant of the feldspars are listed. These are commonly associated with igneous rocks. The plagioclase feldspar series, however [(Ca,Na)(Al,Si)AlSi$_2$O$_8$], may also be found in metamorphic and sedimentary rocks.
Albite	Sodium aluminatrisilicate	$NaAlSi_3O_8$	
Anorthite	Calcium aluminosilicate	$CaAl_2Si_2O_8$	
Glauconite	—	$K(Fe,Mg,Al)_2Si_4O_{10}(OH)_2$	An authigenic mineral of marine sedimentary rocks. Can form from detrital biotite and directly from an aluminosilicate gel by crystallization.
Gypsum	Calcium sulfate dihydrate	$CaSO_4 \cdot 2H_2O$	Hydrated form of anhydrate, $CaSO_4$. Found in sedimentary deposits imbedded with limestone, shales, sandstones and rock salt. Normally formed by evaporation from brine solutions, usually being the first salt precipitated.
Halite	Sodium chloride	$NaCl$	Common table salt which is precipitated directly from sea water during evaporation. Forms a salcrete on the surface of sabkhas.

Minerological Name	Chemical Name	Chemical Formulae	Comments
Magnesite	Magnesium carbonate	$MgCO_3$	Magnesite is rarely found in sedimentary rocks. When it does occur in such deposits, its presence probably results from magnesium replacing calcium in calcite, forming magnesite.
Mica	—	—	Mica is a term used to refer to a group of minerals with similar physical properties. Biotite and phlogopite are micas and have previously been discussed. The next most important mica in the Gulf region is muscovite, discussed below.
Muscovite	—	$KAl_2(AlSi_3O_{10})(OH)_2$	Primarily found in igneous rocks and is highly resistant to weathering. It is, thus, not infrequently found in marine sediments. It may also form in marine sediments with clay micas (illite) often making a significant contribution.
Polyhalite	—	$K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$	Formed by the mutual precipitation of complex ionic species in saturated brine solutions. The last stable compound to be so precipitated.
Quartz	Silicon dioxide	SiO_2	Quartz is an important mineral in igneous rock with an excess of silica. Being highly resistant to chemical or mechanical attack, quartz grains accumulate as sand in riverbeds and along the seashore. It is also the chief mineral in sandstones.

TABLE A-1: LOCATION AND ELEVATIONS OF SAMPLE SITES AND REFERENCE BENCH MARKS, IN METERS

LOCATION	HEIGHT, M	INDUSTRIAL SITE GRID COORDINATES NORTHINGS, M	EASTINGS, M
SITE: 1[1]	2.08	61702.86	59666.22
2	1.97	61744.43	59726.39
3	2.04	61759.37	59618.22
4	2.06	61630.30	59715.30
5	2.64	61662.55	59623.57
6	2.15	61625.31	59552.00
7	2.25	61654.48	59600.94
8	2.16	61709.73	59535.76
9	2.17	61541.80	59584.05
10	2.30	61514.60	59416.63
11	2.51	61455.01	59373.45
12	3.02	61429.72	59270.98
13	2.77	61476.78	59079.62
14	2.87	60656.43	59250.63
15	2.90	60655.84	59266.15
16	3.06	60713.97	59113.15
17	2.57	59126.66	59558.91
18	2.73	57458.11	59322.23
BENCH MARKS			
RCT 91	4.706	57432.87	59422.77
RCT 98	4.046	61396.31	59135.21
SEAWATER SAMPLE[2]	Surface	61750	59800
BORROW PIT[2]	3.3	57096	58621
WATER HOLE[2]	<5	766325[3]	200875
UPPER COMMUNITY HARBOR			
Dry[2]	<3	768200[3]	199725
Wet[2]		768250[3]	199550
ROAD CUT[2]	<20	766250[3]	202950

(1) Locations and elevations surveyed by professional commercial surveying company personnel.

(2) Locations approximated from topographic maps using hand held compass and triangulation. Elevations listed are those given on topographic maps.

(3) Local UTM grid coordinate system.

APPENDIX

Table A—2 : Site 1 , Sieve Analysis Summary (Percent sieved dry weight)

Depth Strata, cm	0-1 cm	1-3 cm	3-37 cm	37-39 cm
Sieve Size				
4.0 mm	Blue-Green Algal Mat	0	0	.44
2.8 mm		0	0	.56
2.0 mm		0	.02	.30
1.4 mm		2.53	.38	.37
1.0 mm		5.39	.57	1.19
0.710 mm		13.20	.86	1.76
0.500 mm		13.30	1.25	1.95
0.355 mm		13.29	1.97	3.01
0.250 mm		36.64	3.43	4.71
0.180 mm		4.35	4.93	4.85
0.125 mm		4.77	11.73	12.34
0.090 mm		3.98	17.47	17.76
0.063 mm		1.17	6.24	5.31
Passing 0.063 mm		.28	51.15	44.35
Total, %		100	100	100
Sediment, %		100	100	96.76
Shell Debris, %		0	0	3.24
Total		100	100	100
Water, %	36.22	33.33	54.58	48.53

APPENDIX

Table A—2 : Site 2 , Sieve Analysis Summary (Percent sieved dry weight)

Depth Strata, cm	0 - .5	.5 - 4.5	4.5 - 16
Sieve Size			
4.0 mm	Blue-Green Algal Mat	0	0
2.8 mm		0	0
2.0 mm		0	0
1.4 mm		2.15	.25
1.0 mm		6.50	.63
0.710 mm		12.99	.95
0.500 mm		13.95	1.01
0.355 mm		13.69	2.06
0.250 mm		36.31	4.00
0.180 mm		4.01	4.54
0.125 mm		4.45	12.50
0.090 mm		4.63	16.73
0.063 mm		.99	7.50
Passing 0.063 mm		.33	49.83
Total, %		100	100
Sediment, %		100	100
Shell Debris, %		0	0
Total		100	100
Water, %	33.79	35.63	55.55

APPENDIX

Table A—2 : Site 5 , Sieve Analysis Summary (Percent sieved dry weight)

Depth Strata, cm	0 - 17	17 - 34.5	34.5 - 37.5	37.5 - 62.5
Sieve Size				
4.0 mm	0	0	0	.02
2.8 mm	0	.02	0	.46
2.0 mm	4.11	3.30	5.56	1.01
1.4 mm	5.10	3.37	11.84	.95
1.0 mm	5.46	6.59	10.01	1.03
0.710 mm	9.32	10.39	11.97	1.07
0.500 mm	13.92	13.44	10.37	2.07
0.355 mm	18.64	17.56	11.28	3.76
0.250 mm	20.21	18.21	11.97	6.75
0.180 mm	3.38	9.26	6.50	5.35
0.125 mm	7.28	5.33	3.35	14.09
0.090 mm	3.73	7.20	6.39	18.75
0.063 mm	2.52	3.38	3.35	8.37
Passing 0.063 mm	1.33	.35	1.91	35.82
Total, %	100	100	100	100
Sediment, %	96.17	96.41	75.95	97.49
Shell Debris, %	3.33	3.59	24.05	2.51
Total	100	100	100	100
Water, %	7.93	13.60	17.08	46.66

APPENDIX

Table A—2 : Site 6 , Sieve Analysis Summary (Percent sieved dry weight)

Depth Strata, cm	0-1.5	1.5-9.5	9.5-13.0	13.0-14.5	14.5-19.5	19.5-26.5	26.5-31.6	31.6-38.7
Sieve Size								
4.0 mm	0	0	0	0	0	0	0	0
2.8 mm	0	.49	0	0	0	0	0	0
2.0 mm	.21	1.33	0	.93	.77	1.08	0	1.13
1.4 mm	.66	4.19	1.48	5.70	1.73	2.09	.14	1.06
1.0 mm	2.34	9.38	3.31	12.27	4.09	4.30	.69	1.43
0.710 mm	5.37	12.45	5.34	16.63	5.90	6.64	2.11	1.00
0.500 mm	10.38	10.97	6.33	20.58	3.91	7.65	3.50	1.79
0.355 mm	13.37	12.78	3.52	19.53	10.71	9.57	6.33	4.06
0.250 mm	17.60	19.11	3.27	10.99	12.01	10.31	9.58	5.76
0.180 mm	13.17	10.50	3.42	6.40	9.33	4.41	4.33	4.39
0.125 mm	12.18	7.41	4.40	1.57	3.74	5.67	5.08	[illegible]
0.090 mm	16.78	10.33	5.64	3.84	10.38	6.09	6.14	16.33
0.063 mm	5.46	.94	3.66	1.22	1.66	4.79	5.94	5.76
Passing 0.063 mm	2.48	.12	48.03	0.34	24.27	36.90	55.66	45.02
Total, %	100	100	100	100	100	100	100	100
Sediment, %	100	100	100	91.73	98.34	100	100	99.45
Shell Debris, %	0	0	0	3.27	1.16	0	0	.55
Total	100	100	100	100	100	100	100	100
Water, %	30.73	38.10	36.39	19.30	42.32	57.40	38.50	31.31

APPENDIX

Table A—2: Site 7, Sieve Analysis Summary (Percent sieved dry weight)

Depth Strata, cm	0—10.5	10.5—44	44.0—55.5
Sieve Size			
4.0 mm	0	.27	
2.8 mm	2.07	.58	.05
2.0 mm	5.57	1.05	.95
1.4 mm	8.27	2.07	.39
1.0 mm	9.25	2.14	1.65
0.710 mm	10.49	2.65	1.10
0.500 mm	10.43	3.34	2.57
0.355 mm	11.59	4.54	7.55
0.250 mm	13.58	6.28	9.76
0.180 mm	10.33	5.03	5.56
0.125 mm	5.37	7.77	7.66
0.090 mm	9.55	9.47	12.45
0.063 mm	2.61	3.33	4.95
Passing 0.063 mm	.29	51.48	44.56
Total, %	100	100	100
Sediment, %	95.70	99.67	99.75
Shell Debris, %	4.30	.33	.25
Total	100	100	100
Water, %	24.93	37.32	61.19

APPENDIX

Table A—2: Site 3, Sieve Analysis Summary (Percent sieved dry weight)

Depth Strata, cm	0—5.0	5.0—21.5	21.5—36.0
Sieve Size			
4.0 mm	0	0	0
2.8 mm	0	.44	0
2.0 mm	.37	3.14	.56
1.4 mm	1.00	5.99	1.65
1.0 mm	3.05	10.23	1.73
0.710 mm	7.64	10.30	2.01
0.500 mm	9.41	11.98	2.49
0.355 mm	10.37	12.33	3.11
0.250 mm	12.63	12.38	4.22
0.180 mm	19.02	10.19	3.39
0.125 mm	14.25	9.68	7.42
0.090 mm	15.23	8.97	9.79
0.063 mm	4.51	2.55	2.50
Passing 0.063 mm	2.02	.72	60.43
Total, %	100	100	100
Sediment, %	99.76	99.31	98.35
Shell Debris, %	.24	.09	1.15
Total	100	100	100
Water, %	32.60	39.34	40.96

APPENDIX

Table A—2 : Site 9 , Sieve Analysis Summary (Percent sieved dry weight)

Depth Strata, cm	0—4.5	4.5—32.5	32.5—40.6	40.6—43.5
Sieve Size				
4.0 mm	0	0	0	0
2.8 mm	0	.43	0	0
2.0 mm	1.61	2.35	1.02	.40
1.4 mm	4.73	6.55	2.26	.39
1.0 mm	9.35	9.77	2.36	1.04
0.710 mm	11.73	9.06	2.70	1.20
0.500 mm	12.43	12.55	3.30	1.49
0.355 mm	9.05	12.75	4.07	1.36
0.250 mm	10.73	11.03	5.46	2.53
0.180 mm	16.55	9.51	5.05	2.03
0.125 mm	11.41	10.07	9.44	4.44
0.090 mm	9.15	9.01	12.59	3.36
0.063 mm	2.55	3.55	3.24	1.56
Passing 0.063 mm	.71	2.67	48.51	75.30
Total, %	100	100	100	100
Sediment, %	99.25	99.35	99.35	99.76
Shell Debris, %	.75	.15	.05	.24
Total	100	100	100	100
Water, %	40.61	40.75	39.29	29.60

APPENDIX

Table A— 2: Site 10 , Sieve Analysis Summary (Percent sieved dry weight)

Depth Strata, cm	0—5.0	5.0—33.0	33.0—37.0
Sieve Size			
4.0 mm	0	0	0
2.8 mm	.65	.34	0
2.0 mm	3.09	2.05	.73
1.4 mm	2.47	7.17	1.32
1.0 mm	4.38	3.63	1.91
0.710 mm	6.02	12.91	2.22
0.500 mm	5.35	10.06	2.75
0.355 mm	3.36	9.75	3.44
0.250 mm	18.05	14.89	4.66
0.180 mm	5.17	12.13	4.30
0.125 mm	5.53	7.33	3.20
0.090 mm	3.13	9.37	10.32
0.063 mm	3.74	15.28	2.39
Passing 0.063 mm	28.06	4.45	56.26
Total, %	100	100	100
Sediment, %	100	95.45	99.05
Shell Debris, %	0	4.55	0.95
Total	100	100	100
Water, %	26.25	32.57	33.34

APPENDIX

Table A— 2 : Site 11 , Sieve Analysis Summary (Percent sieved dry weight)

Depth Strata, cm	0—3.5	3.5—14.5	14.5—29.5	29.5—55.5	55.5—60.0
Sieve Size					
4.0 mm	0	0	0	.66	28.74
2.8 mm	0	0	0	2.85	3.76
2.0 mm	.16	.83	1.10	3.75	1.58
1.4 mm	1.28	1.74	4.33	2.90	1.86
1.0 mm	3.87	4.33	4.96	6.76	3.48
0.710 mm	6.13	9.24	8.89	4.50	4.32
0.500 mm	8.45	13.99	10.92	4.32	4.82
0.355 mm	11.80	18.39	16.86	9.73	6.71
0.250 mm	13.40	17.23	18.33	16.56	9.54
0.180 mm	7.47	8.33	5.57	8.30	10.16
0.125 mm	9.63	8.21	13.96	13.23	9.45
0.090 mm	10.78	12.41	6.95	12.61	12.36
0.063 mm	15.07	4.20	.97	9.51	2.11
Passing 0.063 mm	11.96	.60	5.56	3.32	.51
Total, %	100	100	100	100	100
Sediment, %	99.80	99.86	99.14	98.58	65.42
Shell Debris, %	0.20	.14	.86	1.42	34.58
Total	100	100	100	100	100
Water, %	18.24	18.25	17.65	30.28	29.99

APPENDIX

Table A— 2: Site 12 , Sieve Analysis Summary (Percent sieved dry weight)

Depth Strata, cm	0—11.5	11.5—22.0	22.0—41.0	41.0—42.5 *	44.5—56.0	56.0—72.0
Sieve Size						
4.0 mm	1.82	1.34	5.05	0	13.22	0
2.8 mm	1.34	4.45	3.04	0	9.79	.70
2.0 mm	4.29	4.33	2.55	0	6.09	1.21
1.4 mm	7.16	6.79	3.03	4.95	2.31	2.26
1.0 mm	5.98	9.31	4.35	4.08	5.74	5.91
0.710 mm	7.30	17.05	3.11	5.77	4.42	11.53
0.500 mm	11.30	24.73	5.60	9.32	5.86	25.30
0.355 mm	17.09	11.21	9.31	16.45	9.47	25.36
0.250 mm	17.34	5.88	13.49	23.46	13.20	15.50
0.180 mm	12.13	4.92	14.17	13.11	8.27	[illegible]
0.125 mm	5.75	5.03	18.38	11.79	10.93	2.36
0.090 mm	5.48	2.10	12.13	6.35	8.75	1.30
0.063 mm	.38	1.27	4.03	3.34	1.28	.51
Passing 0.063 mm	.14	.59	.76	1.38	.17	[illegible]
Total, %	100	100	100	100	100	100
Sediment, %	72.35	80.68	97.60	100	74.31	98.31
Shell Debris, %	25.65	19.32	2.40	0	25.19	[illegible]
Total	100	100	100	100	100	100
Water, %	2.07	3.31	17.14	15.59	13.44	[illegible]

(* Discontinuity because of rock)

APPENDIX

Table A—2 : Site 13, Sieve Analysis Summary (Percent sieved dry weight)

Depth Strata, cm	0—5.5	5.5—28.0	28.0—53.0	53.0—87.5
Sieve Size				
4.0 mm	0	0	0	0
2.8 mm	0	0	0	0
2.0 mm	0	0	0	0
1.4 mm	1.52	1.33	1.65	.49
1.0 mm	4.11	2.60	2.07	6.57
0.710 mm	3.63	3.47	3.75	3.44
0.500 mm	6.92	9.76	8.66	40.16
0.355 mm	14.36	17.10	18.37	10.36
0.250 mm	19.47	26.79	25.76	15.69
0.180 mm	13.38	14.64	15.05	10.34
0.125 mm	12.45	14.11	13.51	3.23
0.090 mm	3.70	7.88	6.06	3.27
0.063 mm	7.96	1.17	4.77	.94
Passing 0.063 mm	7.30	.65	.35	.01
Total, %	100	100	100	100
Sediment, %	100	100	100	100
Shell Debris, %	0	0	0	0
Total	100	100	100	100
Water, %	16.39	12.40	16.08	19.11

APPENDIX

Table A—2 : Site 14, Sieve Analysis Summary (Percent sieved dry weight)

Depth Strata, cm	0—2.0	2.0—7.0	7.0—9.0	9.0—40.0	40.0—65.0	65.0—121.0
Sieve Size						
4.0 mm	0	0	0	0	0	0
2.8 mm	0	0	0	0	0	0
2.0 mm	0	0	0	0	0	0
1.4 mm	2.5	9.9	0	7.5	0	1.2
1.0 mm	4.3	3.7	3.4	9.7	4.3	1.2
0.710 mm	10.2	13.0	7.1	12.3	9.7	3.2
0.500 mm	15.0	18.5	7.9	20.2	13.9	6.5
0.355 mm	7.7	14.1	2.3	6.2	15.2	7.4
0.250 mm	14.4	10.6	4.3	16.2	17.2	13.2
0.180 mm	3.3	3.6	2.5	5.6	11.5	13.7
0.125 mm	4.0	2.3	4.3	4.4	10.4	26.9
0.090 mm	0.9	0.1	1.1	0.2	1.4	3.3
0.063 mm	1.5	1.2	1.4	1.5	1.7	2.9
Passing 0.063 mm	35.2	12.9	65.2	15.7	14.2	19.9
Total, %	100	100	100	100	100	100
Sediment, %	95.5	82.3	97.6	58.5	70.3	94.0
Shell Debris, %	4.5	17.2	2.4	41.5	29.7	6.0
Total	100	100	100	100	100	100
Water, %	1.0	2.7	5.3	14.5	30.0	37.3

APPENDIX

Table A—2 : Site 15, Sieve Analysis Summary (Percent sieved dry weight)

Depth Strata, cm	0—6.0	6.0—37.0	37.0—50.0	50.0—66.0	66.0—121.0
Sieve Size					
4.0 mm	0	0	0	0	0
2.8 mm	0	0	0	0	0
2.0 mm	0	0	0	0	0
1.4 mm	0.3	0.7	0	0.1	0
1.0 mm	1.4	2.2	2.2	0.6	0.1
0.710 mm	3.1	5.8	15.0	4.4	4.9
0.500 mm	5.9	10.9	18.8	7.3	11.3
0.355 mm	2.3	5.2	14.3	7.0	7.7
0.250 mm	2.1	5.4	14.3	11.2	11.1
0.180 mm	1.2	2.1	6.8	10.3	3.9
0.125 mm	1.0	2.7	7.0	20.6	17.8
0.090 mm	0.3	0.8	1.5	6.7	4.2
0.063 mm	1.4	2.3	2.1	7.0	4.2
Passing 0.063 mm	31.0	61.9	18.0	25.3	29.3
Total, %	100	100	100	100	100
Sediment, %	99.4	99.1	82.6	96.4	95.2
Shell Debris, %	0.6	0.9	17.4	3.6	4.8
Total	100	100	100	100	100
Water, %	25.9	33.9	29.4	36.7	37.0

APPENDIX

Table A—2 : Site 16, Sieve Analysis Summary (Percent sieved dry weight)

Depth Strata, cm	0—33.0	33.0—88.0	88.0—122.0
Sieve Size			
4.0 mm	0	0	0
2.8 mm	0	0	0
2.0 mm	0	2.4	0
1.4 mm	5.3	4.2	5.6
1.0 mm	14.4	12.0	10.7
0.710 mm	23.1	23.1	18.7
0.500 mm	15.6	22.2	17.3
0.355 mm	8.3	7.3	8.5
0.250 mm	6.4	7.5	7.7
0.180 mm	4.4	2.9	5.2
0.125 mm	3.9	2.8	15.0
0.090 mm	0	0	3.3
0.063 mm	0	0	1.2
Passing 0.063 mm	19.1	15.6	6.8
Total, %	100	100	100
Sediment, %	82.6	97.1	84.4
Shell Debris, %	17.4	2.9	15.6
Total	100	100	100
Water, %	1.9	5.9	19.4

APPENDIX

Table A—2 : Site 17, Sieve Analysis Summary (Percent sieved dry weight)

Depth Strata, cm	0—6.5	6.5—16.0	16.0—22.0	22.0—37.5	37.5—12.2
Sieve Size					
4.0 mm	0	3.4	0	0	0
2.8 mm	0.9	1.2	3.9	0	0
2.0 mm	1.3	5.6	6.7	4.0	7.2
1.4 mm	0.6	3.2	5.4	3.3	5.3
1.0 mm	2.1	12.4	4.4	4.9	6.6
0.710 mm	2.3	17.9	5.7	7.2	3.4
0.500 mm	4.7	11.9	6.2	11.3	10.4
0.355 mm	2.3	2.0	3.0	7.6	5.3
0.250 mm	3.7	4.8	5.6	12.6	8.6
0.180 mm	1.4	1.9	3.1	6.1	0.7
0.125 mm	3.0	2.2	4.1	6.9	4.3
0.090 mm	1.1	0	0.2	0	1.3
0.063 mm	3.3	2.0	1.3	1.5	0.2
Passing 0.063 mm	73.3	25.7	50.4	34.1	37.2
Total, %	100	100	100	100	100
Sediment, %	100	95.2	60.9	81.6	65.1
Shell Debris, %	0	4.8	39.1	18.4	34.9
Total	100	100	100	100	100
Water, %	30.4	21.3	16.3	28.3	32.6

APPENDIX

Table A—2 : Site 18, Sieve Analysis Summary (Percent sieved dry weight)

Depth Strata, cm	0—6.5	6.5—13.5	13.5—52.0	52.0—122.0
Sieve Size				
4.0 mm	0	0	0	0
2.8 mm	0	0	0	0
2.0 mm	1.3	0	0	0
1.4 mm	1.9	0.9	0	0.7
1.0 mm	3.4	2.8	1.6	2.7
0.710 mm	7.0	3.9	8.6	3.3
0.500 mm	10.2	17.7	25.3	21.0
0.355 mm	3.6	7.9	12.3	9.3
0.250 mm	3.3	10.8	18.2	14.1
0.180 mm	1.4	5.3	11.0	8.3
0.125 mm	3.1	11.3	14.1	14.9
0.090 mm	1.1	1.2	1.3	1.5
0.063 mm	1.7	3.3	0.5	3.0
Passing 0.063 mm	61.5	29.4	6.6	15.2
Total, %	100	100	100	100
Sediment, %	100	100	100	100
Shell Debris, %	0	0	0	0
Total	100	100	100	100
Water, %	26.6	23.5	14.4	18.3

APPENDIX

Table A— 2: Sand Dune Sieve Analysis Summary (Percent sieved dry weight)

	A	B
Sieve Size		
4.0 mm	0	0
2.8 mm	0	0
2.0 mm	0	0
1.4 mm	.25	.14
1.0 mm	1.09	.99
0.710 mm	1.69	1.49
0.500 mm	2.50	2.96
0.355 mm	7.06	7.83
0.250 mm	19.66	22.32
0.180 mm	23.48	25.62
0.125 mm	23.71	21.36
0.090 mm	16.02	14.21
0.063 mm	3.25	2.07
Passing 0.063 mm	1.29	1.01
Total,%	100	100
Sediment, %	100	100
Shell Debris, %	0	0
Total	100	100
Water, %	1.00	2.05

A—Poorly cemented sand from top of road cut B—Uncemented sand taken immediately below above sample

APPENDIX

TABLE A-3: PENETROMETER READINGS IN POUNDS PER SQUARE INCH

SITE 1

Depth, Inches 6	12	18	300 PSI At
45	40	55	
35	35	45	
40	45	60	
40	40	55	
45	40	45	
45	35	60	
40	40	50	
40	40	50	
30	40	55	
35	35	40	
X 39.5	39.0	51.5	
S 5.0	3.2	6.7	

SITE 2

Depth, Inches 6	12	18	300 PSI At
25	35	30	
25	20	20	
20	35	20	
15	35	20	
15	40	20	
10	30	20	
20	20	20	
15	30	20	
10	20	20	
25	25	30	
X 18.0	29.0	22.0	
S 5.9	7.4	4.2	

SITE 3

Depth, Inches 6	12	18	300 PSI At
25	50	30	
65	80	50	
45	40	45	
40	70	40	
35	45	40	
35	40	55	
55	50	50	
50	40	40	
25	40	55	
50	90	40	
X 42.5	54.5	44.5	
S 13.0	18.6	8.0	

SITE 4

Depth, Inches 6	12	18	300 PSI At
55	75	45	
90	70	45	
45	70	45	
40	50	45	
60	50	50	
45	50	45	
50	55	50	
60	40	60	
45	35	50	
45	45	60	
X 53.5	54.0	49.5	
S 14.5	13.5	6.0	

SITE 5

Depth, Inches 6	12	18	300 PSI At
185	115	110	
245			7"
300			6"
			3"
			4"
			5"
			5"
300			6"
280			9"
240			9"
X			
S			

SITE 6

Depth, Inches 6	12	18	300 PSI At
60	30	50	
45	30	30	
70	50	35	
60	30	25	
60	30	40	
55	50	30	
75	35	30	
60	40	25	
85	35	30	
60	35	30	
X 63.0	36.5	32.5	
S 11.1	7.8	7.6	

APPENDIX

TABLE A-3: PENETROMETER READINGS IN POUNDS PER SQUARE INCH

SITE 7

Depth, Inches 6	12	18	300 PSI At
150	140	20	
70	125	35	
160			7"
110	80	35	
80	85	35	
225	65	40	
200			7"
150			7"
165			8"
115			7"
X 142.5			
S 49.5			

SITE 8

Depth, Inches 6	12	18	300 PSI At
150	45	35	
140	80	95	
130	40	20	
180	50	40	
115	45	50	
150	60	60	
150	35	60	
160	50	40	
160	70	50	
140			7"
X 147.5			
S 17.8			

SITE 9

Depth, Inches 6	12	18	300 PSI At
70	45	40	
80	40	45	
80	45	45	
50	25	35	
60	65	35	
55	30	35	
70	35	30	
40	30	30	
40	35	25	
80	35	30	
X 62.5	38.5	35.0	
S 15.9	11.3	6.7	

SITE 10

Depth, Inches 6	12	18	300 PSI At
			4"
300			6"
			5"
			5"
			5"
300			6"
300			6"
			5"
			4"
			3"

SITE 11

Depth, Inches 6	12	18	300 PSI At
120	140	300	
170	180	260	
290	140		17"
260	250	300	
215	235	300	
200	120		17"
220	160	160	
190	80	70	
130	100	50	
170	130	180	
X 196.5	153.5		
S 53.1	54.8		

SITE 12

Depth, Inches 6	12	18	300 PSI At
			5"
			1"
			S
			.25
			S
			1"
			S
			2"
280			7"
			S

S Surface

APPENDIX

TABLE A-3: PENETROMETER READINGS IN POUNDS PER SQUARE INCH

SITE 13

Depth, Inches 6	12	18	300 PSI At
			S
			S
			S
			S
			S
			S
			S
			S
			S
			S
X			
S			

SITE 14

Depth, Inches 6	12	18	300 PSI At
			2"
			3"
			3"
			2"
			2"
			2"
			2"
			2"
			3"
			1"
X			
S			

SITE 15

Depth, Inches 6	12	18	300 PSI At
180	110	120	
180	50	170	
200	55	175	
120	80	170	
140	90		4", 14"
200	145		14"
195	55	150	2"
140	95	260	2"
160	60		14"
165	60	230	
X 168.0	80.0		
S 27.9	30.6		

SITE 16

Depth, Inches 6	12	18	300 PSI At
			1"
			3"
			S
			3"
			4"
			3"
			3"
			4"
			4"
			3"
X			
S			

SITE 17

Depth, Inches 6	12	18	300 PSI At
			2"
			2"
			2"
			2"
			2"
			3"
			3"
			2"
			2"
			2"
X			
S			

SITE 18

Depth, Inches 6	12	18	300 PSI At
			2" 2"
			2" 2"
			3" 3"
			3" 3"
			3" 3"
			3" 3"
			3" 3"
			3" 3"
			3" 3"
			3" 3"
X			
S			

S = Surface

APPENDIX

TABLE A-4: SHEAR VANE READINGS IN KILO PASCALS

SITE 1

	Depth, Cm		
	6	22	52
	12.5	15.5	11.0
	11.5	13.0	15.5
	11.0	14.0	12.0
	8.5	12.5	13.5
	18.0	12.5	14.5
$\bar{X}$	12.3	13.5	13.3
S	3.5	1.3	1.8

SITE 2

	Depth, Cm		
	6	22	52
	10.0	8.0	9.0
	7.0	8.0	3.0
	6.0	6.0	6.5
	7.0	8.0	6.0
	5.0	9.5	6.5
$\bar{X}$	7.0	7.9	6.2
S	1.9	1.2	2.1

SITE 3

	Depth, Cm		
	6	22	52
	13.5	10.5	8.5
	15.0	11.5	8.5
	6.0	12.0	7.5
	18.5	14.5	7.5
	15.0	11.0	7.0
$\bar{X}$	13.6	11.9	7.8
S	4.6	1.6	0.7

SITE 4

	Depth, Cm		
	6	22	52
	21.0	24.5	7.0
	13.0	23.0	7.0
	7.0	21.5	8.5
	12.5	20.5	9.0
	17.0	22.0	9.5
$\bar{X}$	14.1	22.3	8.2
S	5.2	1.5	1.2

SITE 5

	Depth, Cm		
	6	22	52
	-----COARSE SAND --------		
$\bar{X}$			
S			

SITE 6

	Depth, Cm		
	6	22	52
	21.0	24.0	13.5
	18.0	17.0	15.0
	30.0	29.0	15.0
	29.5	13.5	15.0
	28.0	27.5	14.5
$\bar{X}$	25.3	22.2	14.6
S	5.4	6.7	0.7

APPENDIX

TABLE A-4: SHEAR VANE READINGS IN KILO PASCALS

SITE 7

	Depth, Cm		
	6	22	52
	17.0		
	21.0	No further	
	20.5	penetration	
	20.0	possible	
	24.0		
X̄	20.5		
S	2.5		

SITE 8

	Depth, Cm		
	6	22	52
	25.5	35.0	10.0
	17.0	21.0	10.0
	11.5	11.0	9.0
	8.0	37.0	10.0
	11.0	22.0	14.0
X̄	14.6	25.2	10.6
S	6.9	10.8	1.9

SITE 9

	Depth, Cm		
	6	22	52
	8.0	28.0	9.0
	18.0	29.0	8.0
	23.5	25.0	11.5
	26.5	22.5	9.0
	24.5	18.0	11.0
X̄	20.1	24.5	9.7
S	7.5	4.4	1.5

SITE 10

Depth, Cm		
6	22	52
8.5	55.0	7.0
9.0	68.0	17.0
13.0	57.0	17.0
9.5	79.0	12.0
11.0	74.0	18.0
10.2	66.6	14.2
1.8	10.5	4.7

SITE 11

	6	22	52
	22.0	20.0	20.0
	20.0	28.0	16.0
	22.0	20.0	22.0
	15.0	14.0	18.0
	34.0	22.0	18.0
X̄	22.6	20.8	18.8
S	7.0	5.0	2.3

SITES 12 THRU 18

-----COARSE SAND-----------------

X̄

S

TABLE A-5
APPENDIX

WATER HEIGHTS IN CENTIMETERS
BELOW SABKHA SURFACE IN OPEN PITS AND CASED HOLES[1]

SITE 1			SITE 2			SITE 3			SITE 4		
Time	Open Pit	Stand Pipe	Time	Open Pit	Stand Pipe	Time	Open Pit	Stand Pipe	Time	Open Pit	Stand Pipe
0555	30.0	14.9	0559	25.0	15.5	0610	24.0	19.8	0607	30.5	16.5
0840	29.8	15.5	0846	24.0	17.0	0835	24.0	20.0	0857	28.5	16.5
1003	28.0	16.0	1005	23.0	17.0	1000	23.0	20.0	1010	27.5	18.5
1105	28.1	16.3	1106	22.7	18.0	1101	22.5	20.5	1111	27.3	18.2
1316	28.2	16.5	1325	22.5	19.0	1312	22.4	21.5	1301	27.1	18.0
1542	28.4	16.2	1545	22.5	19.0	1529	22.4	24.6	1550	27.5	19.7
1651	28.3	16.3	1700	22.5	19.0	1647	22.6	24.5	1636	27.5	20.0

SITE 6			SITE 7			SITE 8			SITE 9		
Time	Open Pit	Stand Pipe	Time	Open Pit	Stand Pipe	Time	Open Pit	Stand Pipe	Time	Open Pit	Stand Pipe
0527	37.2	23.0	0535	55.4	42.1	0531	50.1	20.5	0522	34.3	21.8
0807	37.1	23.5	0820	54.6	41.0	0812	50.0	21.5	0803	34.5	20.0
0957	36.8	25.0	0959	55.0	41.9	0958	49.5	22.0	0940	34.5	21.0
1059	36.9	25.3	1103	54.8	41.7	1058	49.2	22.0	1041	34.5	22.0
1306	37.0	25.5	1325	54.5	41.5	1309	49.0	22.1	1304	34.5	22.5
1520	36.5	28.4	1555	53.9	41.9	1526	48.6	23.1	1513	34.1	22.6
1641	36.7	28.5	1705	54.0	41.9	1644	48.8	23.2	1639	34.2	22.7

SITE 10		
Time	Open Pit	Stand Pipe
0515	36.3	27.5
0755	36.7	29.5
0945	36.6	29.5
1046	36.6	29.5
1258	36.6	32.4
1512	36.1	31.5
1633	36.2	31.7

(1) Data gathered 31 May 1980

TABLE A-5

APPENDIX

WATER HEIGHTS IN CENTIMETERS
BELOW SABKHA SURFACE IN CASED HOLES[1]

SITE 5		SITE 11		SITE 12		SITE 13		SITE 14	
Time	Stand Pipe	Time	Stand Pipe	Time	Stand Pipe	Time	Stand Pipe	Time	Stand Pipe
0545	25.5	0501	62.7	0508	94.5	0504	57.0	0450	66.0
0827	24.5	0750	63.0	0745	94.9	0740	56.9	0730	66.8
1012	23.5	0943	63.0	0932	94.5	0930	56.0	0925	66.5
1114	23.6	1042	63.5	1031	94.5	1032	55.5	1023	66.7
1343	24.0	1255	63.6	1252	94.5	1249	55.7	1244	67.0
1552	29.8	1510	63.7	1508	94.8	1506	55.2	1500	66.7
1701	29.6	1630	63.4	1628	94.8	1626	55.0	1620	66.7

SITE 15		SITE 16		SITE 17		SITE 18	
Time	Stand Pipe	Time	Stand Pipe	Time	Stand Pipe	Time	Stand Pipe
0455	63.2	0500	87.0	0440	37.3	0430	53.5
0725	67.2	0732	86.2	0707	37.4	0655	52.5
0926	67.0	0927	86.0	0920	37.5	0915	52.0
1020	67.2	1023	86.1	1019	37.5	1014	52.4
1245	67.4	1247	86.3	1235	37.4	1225	52.6
1501	67.0	1503	86.5	1455	37.0	1440	52.4
1621	67.2	1622	86.4	1614	37.2	1611	52.7

(1) Data gathered 31 May 1980

APPENDIX

TABLE A-6 PERCENT WATER CONTENT OF SELECTED SURFICIAL SABKHA AREAS

Samples Taken 24 May 1980 Adjacent to Site 1

	0-6 cm[2]	
Algal Mat[1]	Unsaturated	Saturated
66.68	42.74	70.53
63.47	41.62	55.23
61.98	42.83	54.91
61.72	45.42	62.69
65.20	44.98	64.66
$\bar{X}$ 63.81	43.52	61.60
S 2.12	1.62	6.63

Samples Taken 24 May 1980 Adjacent to Site 6

0-6 cm	
Unsaturated	Saturated
22.14	35.27
23.18	26.93
23.84	33.88
23.01	33.25
24.61	26.97
$\bar{X}$ 23.36	31.26
S 0.93	4.00

(1) Sediments adhering to upper and lower surfaces of algal mat carefully removed before drying. "Unsaturated" and "saturated" samples taken directly underneath the algal mat which was removed.

(2) Taken with a modified plastic core liner taking a sample of 3.4 cm diameter x 6.0 cm long.

TABLE A-7

U.S. GOVERNMENT TIDE TABLES

RAS AT TANNURAH, PERSIAN GULF, SAUDI ARABIA, 1980

TIMES AND HEIGHTS OF HIGH AND LOW WATERS

APRIL

DAY	TIME h.m.	HEIGHT ft.	HEIGHT m.	DAY	TIME h.m.	HEIGHT ft.	HEIGHT m.
1	0524	6.2	1.9	16	0524	7.3	2.2
TU	1133	1.2	0.4	W	1133	0.9	0.3
	1748	6.3	1.9		1745	7.2	2.2
	2357	1.3	0.4		2358	0.5	0.2
2	0555	6.3	1.9	17	0610	7.5	2.3
W	1201	1.2	0.4	TH	1218	1.1	0.3
	1814	6.3	1.9		1827	7.1	2.2
3	0022	1.2	0.4	18	0039	0.5	0.2
TH	0626	6.4	2.0	F	0658	7.4	2.3
	1227	1.4	0.4		1304	1.6	0.5
	1840	6.2	1.9		1909	6.8	2.1
4	0049	1.2	0.4	19	0122	0.7	0.2
F	0658	6.4	2.0	SA	0745	7.2	2.2
	1256	1.6	0.5		1353	2.0	0.6
	1908	6.1	1.9		1953	6.5	2.0
5	0115	1.2	0.4	20	0207	0.9	0.3
SA	0733	6.3	1.9	SU	0834	6.8	2.1
	1325	1.9	0.6		1447	2.5	0.8
	1938	6.0	1.8		2039	6.0	1.8
6	0146	1.3	0.4	21	0258	1.3	0.4
SU	0810	6.2	1.9	M	0929	6.4	2.0
	1359	2.3	0.7		1551	2.9	0.9
	2013	5.8	1.8		2132	5.6	1.7
7	0221	1.4	0.4	22	0353	1.7	0.5
M	0852	6.0	1.8	TU	1035	5.9	1.8
	1439	2.6	0.8		1710	3.2	1.0
	2055	5.5	1.7		2235	5.2	1.6
8	0308	1.6	0.5	23	0502	2.0	0.6
TU	0948	5.8	1.8	W	1151	5.7	1.7
	1537	2.9	0.9		1833	3.2	1.0
	2148	5.3	1.6		2354	5.0	1.5
9	0409	1.8	0.5	24	0616	2.2	0.7
W	1054	5.6	1.7	TH	1310	5.6	1.7
	1705	3.2	1.0		1943	2.9	0.9
	2259	5.1	1.6				
10	0526	1.8	0.5	25	0112	5.1	1.6
TH	1213	5.6	1.7	F	0729	2.1	0.6
	1849	3.1	0.9		1415	5.7	1.7
					2037	2.6	0.8
11	0023	5.1	1.6	26	0215	5.3	1.6
F	0646	1.7	0.5	SA	0827	2.0	0.6
	1334	5.8	1.8		1502	5.8	1.8
	2007	2.7	0.8		2117	2.3	0.7
12	0144	5.5	1.7	27	0304	5.5	1.7
SA	0800	1.4	0.4	SU	0915	1.9	0.6
	1437	6.2	1.9		1541	5.9	1.8
	2104	2.1	0.6		2154	2.0	0.6
13	0248	6.0	1.8	28	0349	5.8	1.8
SU	0901	1.1	0.3	M	0957	1.8	0.5
	1533	6.6	2.0		1615	6.0	1.8
	2152	1.6	0.5		2226	1.7	0.5
14	0344	6.5	2.0	29	0426	6.1	1.9
M	0957	0.9	0.3	TU	1034	1.7	0.5
	1618	6.9	2.1		1645	6.1	1.9
	2235	1.1	0.3		2255	1.5	0.5
15	0435	7.0	2.1	30	0500	6.3	1.9
TU	1047	0.8	0.2	W	1106	1.8	0.5
	1703	7.1	2.2		1714	6.2	1.9
	2316	0.7	0.2		2324	1.3	0.4

MAY

DAY	TIME h.m.	HEIGHT ft.	HEIGHT m.	DAY	TIME h.m.	HEIGHT ft.	HEIGHT m.
1	0533	6.5	2.0	16	0557	7.6	2.3
TH	1137	1.9	0.6	F	1207	2.0	0.6
	1742	6.2	1.9		1804	6.9	2.1
	2351	1.3	0.4				
2	0605	6.6	2.0	17	0018	0.7	0.2
F	1209	2.0	0.6	SA	0644	7.5	2.3
	1811	6.2	1.9		1256	2.3	0.7
					1849	6.7	2.0
3	0020	1.2	0.4	18	0100	0.9	0.3
SA	0640	6.7	2.0	SU	0733	7.3	2.2
	1241	2.2	0.7		1345	2.6	0.8
	1842	6.1	1.9		1932	6.5	2.0
4	0050	1.3	0.4	19	0145	1.1	0.3
SU	0716	6.7	2.0	M	0818	7.0	2.1
	1314	2.5	0.8		1436	2.8	0.9
	1917	6.1	1.9		2018	6.2	1.9
5	0122	1.3	0.4	20	0231	1.5	0.5
M	0757	6.6	2.0	TU	0908	6.7	2.0
	1351	2.7	0.8		1533	3.0	0.9
	1956	5.9	1.8		2108	5.8	1.8
6	0202	1.4	0.4	21	0321	1.8	0.5
TU	0842	6.5	2.0	W	1003	6.3	1.9
	1439	2.9	0.9		1633	3.1	0.9
	2042	5.8	1.8		2201	5.5	1.7
7	0250	1.6	0.5	22	0420	2.1	0.6
W	0935	6.3	1.9	TH	1101	6.0	1.8
	1543	3.1	0.9		1741	3.1	0.9
	2137	5.6	1.7		2307	5.3	1.6
8	0351	1.7	0.5	23	0522	2.3	0.7
TH	1037	6.1	1.9	F	1206	5.8	1.8
	1702	3.1	0.9		1842	2.9	0.9
	2246	5.4	1.6				
9	0502	1.8	0.5	24	0017	5.2	1.6
F	1147	6.1	1.9	SA	0628	2.4	0.7
	1824	2.8	0.9		1310	5.7	1.7
					1934	2.7	0.8
10	0002	5.5	1.7	25	0124	5.3	1.6
SA	0618	1.8	0.5	SU	0731	2.5	0.8
	1259	6.2	1.9		1406	5.7	1.7
	1932	2.4	0.7		2024	2.4	0.7
11	0119	5.8	1.8	26	0224	5.5	1.7
SU	0730	1.8	0.5	M	0827	2.4	0.7
	1403	6.4	2.0		1448	5.8	1.8
	2029	2.0	0.6		2106	2.1	0.6
12	0227	6.2	1.9	27	0312	5.8	1.8
M	0837	1.7	0.5	TU	0917	2.4	0.7
	1459	6.6	2.0		1530	5.9	1.8
	2120	1.5	0.5		2142	1.8	0.5
13	0325	6.7	2.0	28	0354	6.1	1.9
TU	0936	1.6	0.5	W	1002	2.4	0.7
	1549	6.8	2.1		1607	6.0	1.8
	2207	1.1	0.3		2217	1.6	0.5
14	0419	7.1	2.2	29	0434	6.4	2.0
W	1029	1.6	0.5	TH	1042	2.5	0.8
	1637	7.0	2.1		1639	6.1	1.9
	2252	0.8	0.2		2252	1.5	0.5
15	0509	7.4	2.3	30	0511	6.6	2.0
TH	1119	1.8	0.5	F	1121	2.5	0.8
	1721	7.0	2.1		1714	6.2	1.9
	2335	0.6	0.2		2325	1.4	0.4
				31	0549	6.8	2.1
				SA	1159	2.6	0.8
					1748	6.3	1.9
					2357	1.3	0.4

JUNE

DAY	TIME h.m.	HEIGHT ft.	HEIGHT m.	DAY	TIME h.m.	HEIGHT ft.	HEIGHT m.
1	0625	7.0	2.1	16	0042	1.1	0.3
SU	1235	2.7	0.8	M	0717	7.4	2.3
	1823	6.3	1.9		1335	2.9	0.9
					1912	6.6	2.0
2	0032	1.3	0.4	17	0124	1.3	0.4
M	0704	7.0	2.1	TU	0759	7.2	2.2
	1312	2.8	0.9		1417	2.9	0.9
	1902	6.3	1.9		1954	6.4	2.0
3	0111	1.3	0.4	18	0205	1.6	0.5
TU	0746	7.0	2.1	W	0841	6.9	2.1
	1354	2.9	0.9		1503	3.0	0.9
	1945	6.2	1.9		2039	6.1	1.9
4	0153	1.4	0.4	19	0247	1.8	0.5
W	0831	7.0	2.1	TH	0926	6.6	2.0
	1444	2.9	0.9		1548	3.0	0.9
	2033	6.1	1.9		2126	5.9	1.8
5	0239	1.5	0.5	20	0335	2.1	0.6
TH	0923	6.8	2.1	F	1011	6.3	1.9
	1542	2.9	0.9		1638	3.0	0.9
	2127	6.0	1.8		2217	5.6	1.7
6	0335	1.7	0.5	21	0425	2.4	0.7
F	1017	6.6	2.0	SA	1059	6.0	1.8
	1648	2.8	0.9		1734	2.9	0.9
	2230	5.9	1.8		2315	5.5	1.7
7	0438	1.9	0.6	22	0522	2.7	0.8
SA	1121	6.5	2.0	SU	1154	5.8	1.8
	1754	2.6	0.8		1829	2.7	0.8
	2342	5.9	1.8				
8	0549	2.1	0.6	23	0022	5.4	1.6
SU	1225	6.4	2.0	M	0625	2.9	0.9
	1900	2.3	0.7		1253	5.7	1.7
					1923	2.5	0.8
9	0056	6.0	1.8	24	0129	5.5	1.7
M	0705	2.3	0.7	TU	0731	3.0	0.9
	1331	6.4	2.0		1350	5.7	1.7
	2000	1.9	0.6		2014	2.3	0.7
10	0208	6.3	1.9	25	0229	5.8	1.8
TU	0814	2.4	0.7	W	0835	3.1	0.9
	1429	6.5	2.0		1440	5.8	1.8
	2054	1.5	0.5		2101	2.1	0.6
11	0312	6.7	2.0	26	0325	6.1	1.9
W	0922	2.4	0.7	TH	0931	3.1	0.9
	1525	6.6	2.0		1525	5.9	1.8
	2146	1.2	0.4		2144	1.9	0.6
12	0407	7.1	2.2	27	0410	6.4	2.0
TH	1021	2.5	0.8	F	1023	3.0	0.9
	1615	6.8	2.1		1607	6.1	1.9
	2232	1.0	0.3		2223	1.7	0.5
13	0500	7.4	2.3	28	0452	5.8	2.1
F	1116	2.6	0.8	SA	1108	3.0	0.9
	1703	6.8	2.1		1647	6.3	1.9
	2319	1.0	0.3		2303	1.5	0.5
14	0549	7.5	2.3	29	0533	7.1	2.2
SA	1204	2.6	0.8	SU	1148	3.0	0.9
	1747	6.8	2.1		1727	6.5	2.0
					2340	1.3	0.4
15	0001	1.0	0.3	30	0613	7.3	2.2
SU	0634	7.6	2.3	M	1228	2.9	0.9
	1250	2.8	0.9		1808	6.6	2.0
	1830	6.7	2.0				

Ref: U.S. Department of Commerce, 1980.

TIME MERIDIAN 45° E. 0000 IS MIDNIGHT. 1200 IS NOON.
HEIGHTS ARE REFERRED TO THE CHART DATUM OF SOUNDINGS.

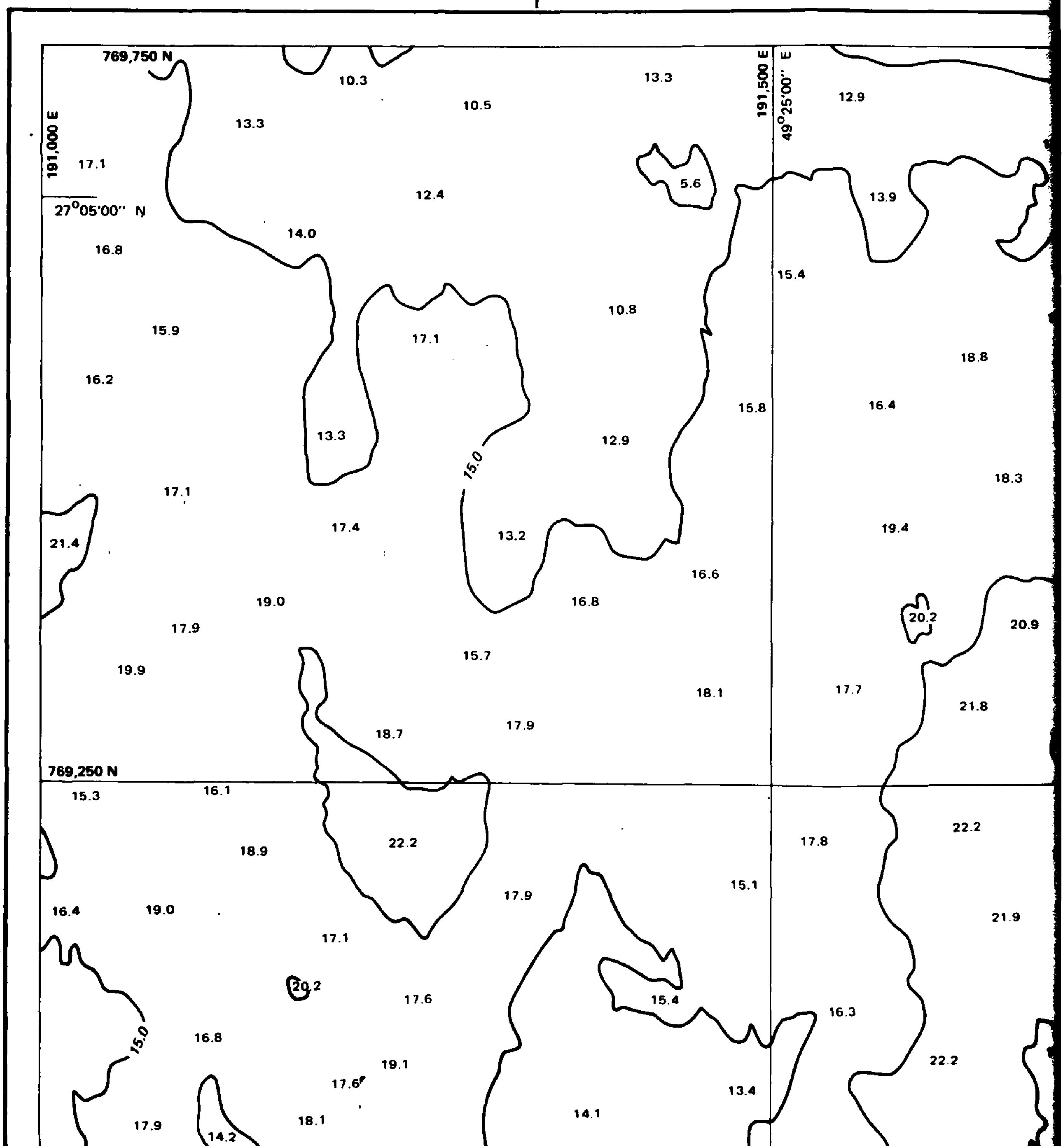
TABLE A-8

METEOROLOGICAL DATA, METEOROLOGICAL STATION 7

YEAR	(D A T E)	HOUR	FWD SECT	MWS MPS	VWD DEG	VMS MPS	TEMP DEGC	DP DEGC	RH %
1980	MAY 16	0	NNW	6.5	331	6.5	24.1	15.4	58
1980	MAY 16	1	NW	7.1	308	7.0	23.1	15.3	61
1980	MAY 16	2	WNW	5.5	296	5.4	22.5	14.2	60
1980	MAY 16	3	WNW	5.0	283	5.0	22.0	13.2	57
1980	MAY 16	4	WNW	5.2	295	5.2	21.7	12.7	56
1980	MAY 16	5	WNW	5.5	297	5.5	21.4	11.4	52
1980	MAY 16	6	WNW	4.9	300	4.8	22.7	12.2	52
1980	MAY 16	7	NNW	9.1	343	9.0	25.5	15.5	53
1980	MAY 16	8	NNW	10.6	334	10.5	26.8	14.5	47
1980	MAY 16	9	NNW	12.7	331	12.7	27.6	11.8	37
1980	MAY 16	10	NNW	12.9	338	12.8	28.0	10.6	33
1980	MAY 16	11	NNW	11.4	331	10.3	28.2	11.0	34
1980	MAY 16	12	N	10.1	2	10.1	27.8	12.7	39
1980	MAY 16	13	N	9.3	11	9.3	27.6	13.4	41
1980	MAY 16	14	NNE	7.0	14	6.9	27.5	14.6	44
1980	MAY 16	15	N	7.1	0	7.0	28.2	14.8	44
1980	MAY 16	16	NNW	7.3	345	7.3	28.8	13.4	38
1980	MAY 16	17	NNW	6.5	340	6.5	28.5	13.7	40
1980	MAY 16	18	NW	3.6	324	3.5	26.9	15.1	48
1980	MAY 16	19	NW	3.4	322	3.4	25.8	15.1	51
1980	MAY 16	20	NW	4.0	323	3.6	24.8	15.3	55
1980	MAY 16	21	NW	4.2	304	4.2	24.4	14.7	55
1980	MAY 16	22	WNW	4.0	284	3.9	24.4	14.4	53
1980	MAY 16	23	W	4.3	268	4.2	24.2	13.1	50

YEAR	(D A T E)	HOUR	FWD SECT	MWS MPS	VWD DEG	VMS MPS	TEMP DEGC	DP DEGC	RH %
1980	MAY 17	0	W	3.7	267	3.7	23.5	12.6	50
1980	MAY 17	1	W	5.3	262	5.3	23.6	11.0	45
1980	MAY 17	2	W	6.4	261	6.4	23.1	8.1	38
1980	MAY 17	3	W	6.0	269	6.0	22.8	5.1	31
1980	MAY 17	4	W	6.2	268	6.1	22.4	2.8	27
1980	MAY 17	5	W	5.4	264	5.4	22.3	2.5	27
1980	MAY 17	6	W	7.0	281	6.9	24.6	4.2	26
1980	MAY 17	7	WNW	9.4	297	9.3	27.0	6.0	26
1980	MAY 17	8	WNW	9.7	296	9.6	30.0	7.0	23
1980	MAY 17	9	WNW	11.0	298	10.9	31.8	6.9	21
1980	MAY 17	10	NW	10.5	305	10.4	33.2	6.8	19
1980	MAY 17	11	NW	11.1	312	10.9	34.4	6.7	18
1980	MAY 17	12	NW	10.5	312	10.3	35.3	6.7	17
1980	MAY 17	13	NNE	7.5	352	6.5	32.9	13.2	30
1980	MAY 17	14	NNE	6.6	24	6.6	30.7	16.5	43
1980	MAY 17	15	NNE	5.6	19	5.6	29.9	16.8	45
1980	MAY 17	16	NNE	5.1	19	5.1	29.3	17.0	47
1980	MAY 17	17	NNE	3.5	16	3.5	28.5	17.4	51
1980	MAY 17	18	NNE	1.7	31	1.7	28.5	17.0	50
1980	MAY 17	19	N	0.8	347	0.7	28.3	15.7	46
1980	MAY 17	20	SW	2.0	229	1.9	28.0	14.9	45
1980	MAY 17	21	SW	4.1	232	3.7	27.1	13.1	42
1980	MAY 17	22	SW	4.1	227	4.1	25.4	11.0	41
1980	MAY 17	23	WSW	5.0	244	4.9	24.6	9.3	38

YEAR	(D A T E)	HOUR	FWD SECT	MWS MPS	VWD DEG	VMS MPS	TEMP DEGC	DP DEGC	RH %
1980	MAY 24	0	WNW	3.1	300	3.1	27.1	18.4	59
1980	MAY 24	1	NW	3.6	314	3.6	26.7	18.3	60
1980	MAY 24	2	NNW	3.9	345	3.5	28.4	21.0	64
1980	MAY 24	3	NW	4.3	312	4.3	27.6	20.7	66
1980	MAY 24	4	NW	5.4	312	5.4	26.6	19.7	66
1980	MAY 24	5	NW	5.2	327	5.0	27.0	19.5	63
1980	MAY 24	6	NW	5.7	314	5.6	28.5	19.3	58
1980	MAY 24	7	NNW	7.1	340	7.1	30.7	18.7	49
1980	MAY 24	8	NNW	9.6	345	9.5	31.7	18.7	46
1980	MAY 24	9	NNW	11.3	337	11.3	32.9	18.0	42
1980	MAY 24	10	NNW	11.0	343	11.0	33.1	17.4	39
1980	MAY 24	11	NNW	11.2	346	11.1	33.0	17.4	40
1980	MAY 24	12	N	11.6	353	11.6	32.4	18.3	43
1980	MAY 24	13	N	11.5	2	11.4	31.3	19.5	49
1980	MAY 24	14	N	11.6	353	11.5	31.8	18.8	46
1980	MAY 24	15	NNW	11.7	347	11.6	32.0	18.1	43
1980	MAY 24	16	NNW	11.1	346	11.1	31.6	17.6	43
1980	MAY 24	17	NNW	9.6	345	9.6	31.1	17.5	44
1980	MAY 24	18	NNW	7.7	343	7.7	30.1	18.3	49
1980	MAY 24	19	NNW	6.3	339	6.3	29.6	18.0	49
1980	MAY 24	20	NNW	5.4	331	5.4	28.7	18.6	54
1980	MAY 24	21	NW	4.8	321	4.8	27.7	18.3	57
1980	MAY 24	22	NNW	5.8	326	5.2	27.4	17.6	55
1980	MAY 24	23	NNW	5.3	328	[illegible]	26.7	17.7	58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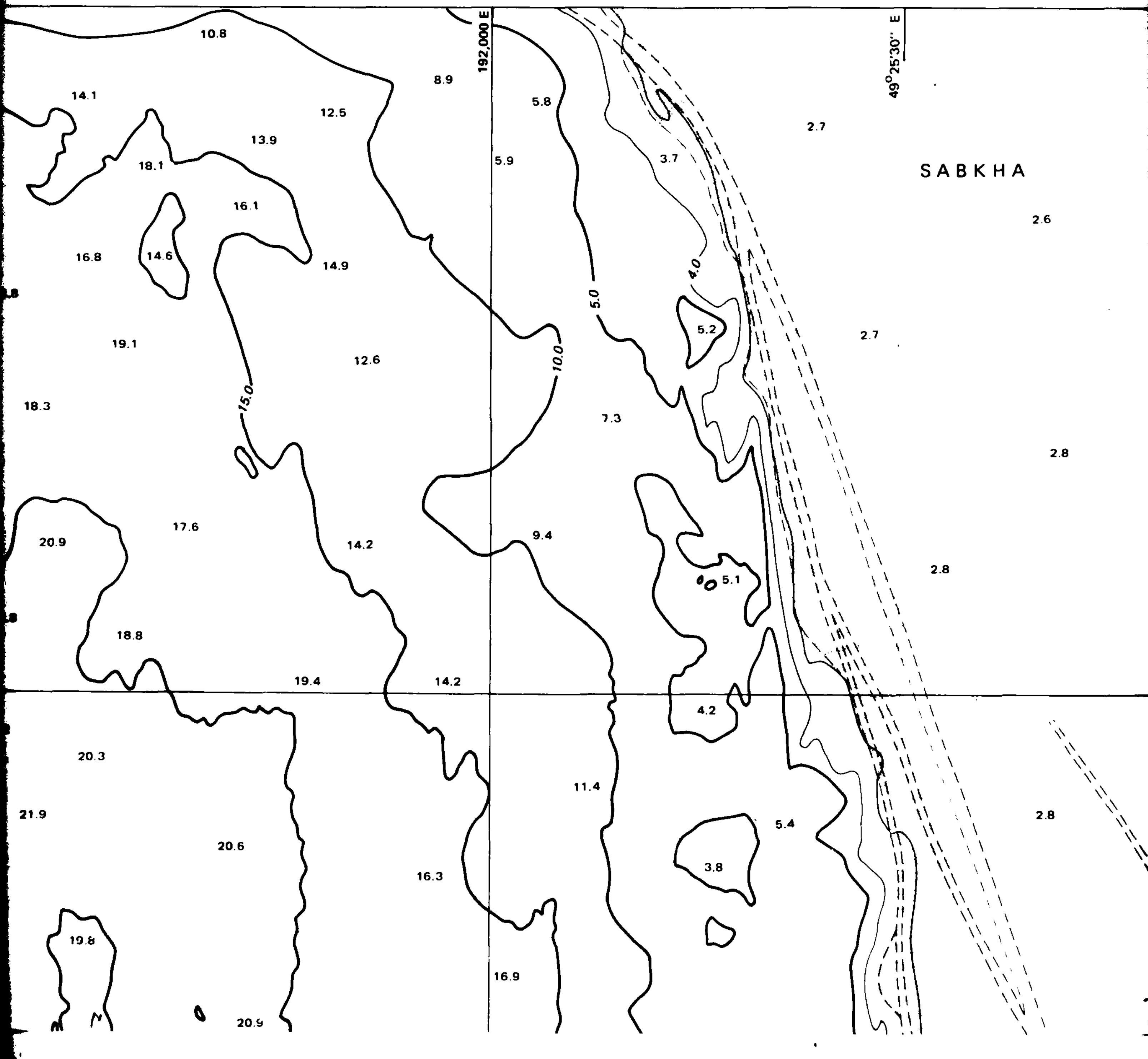
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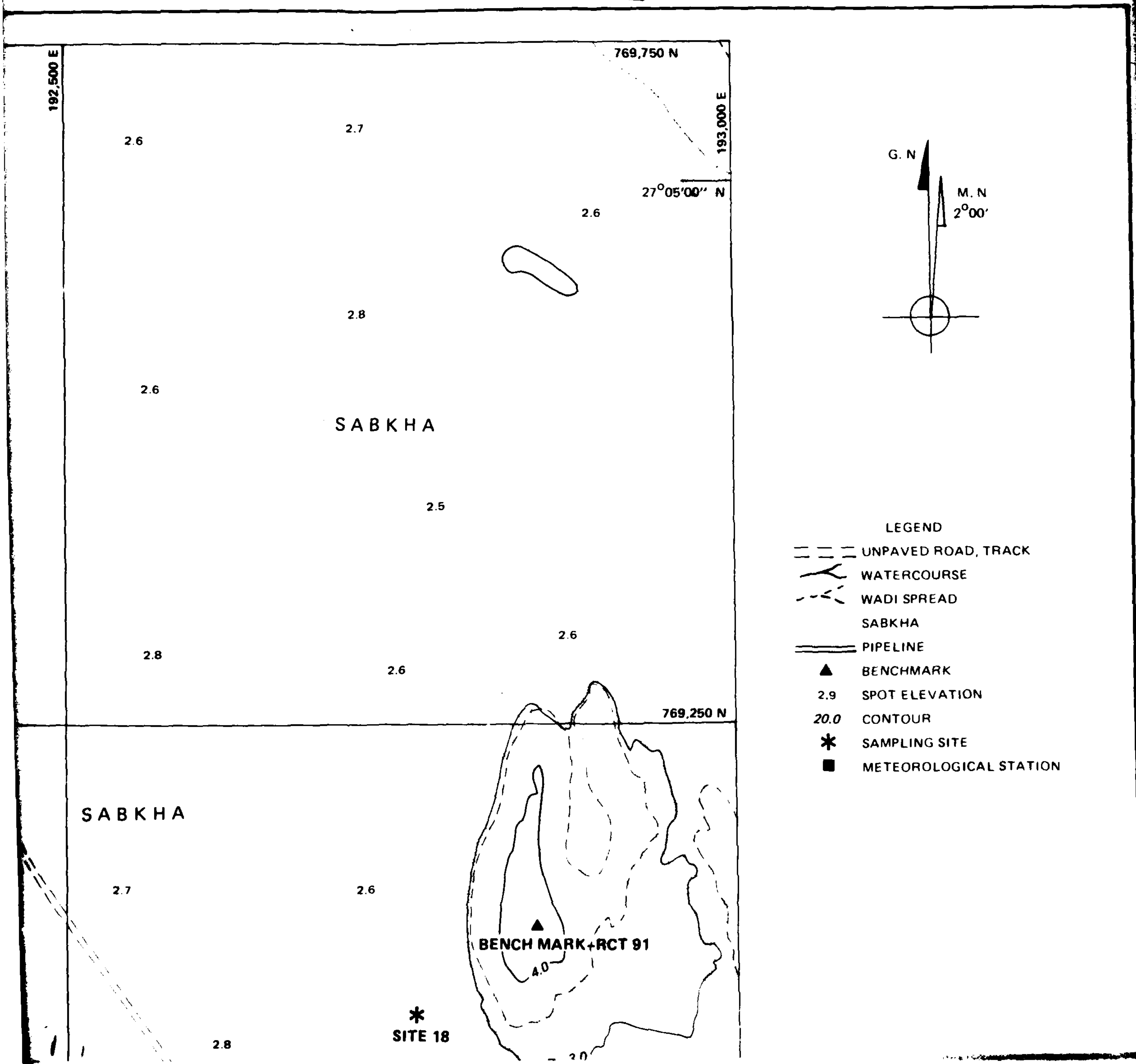
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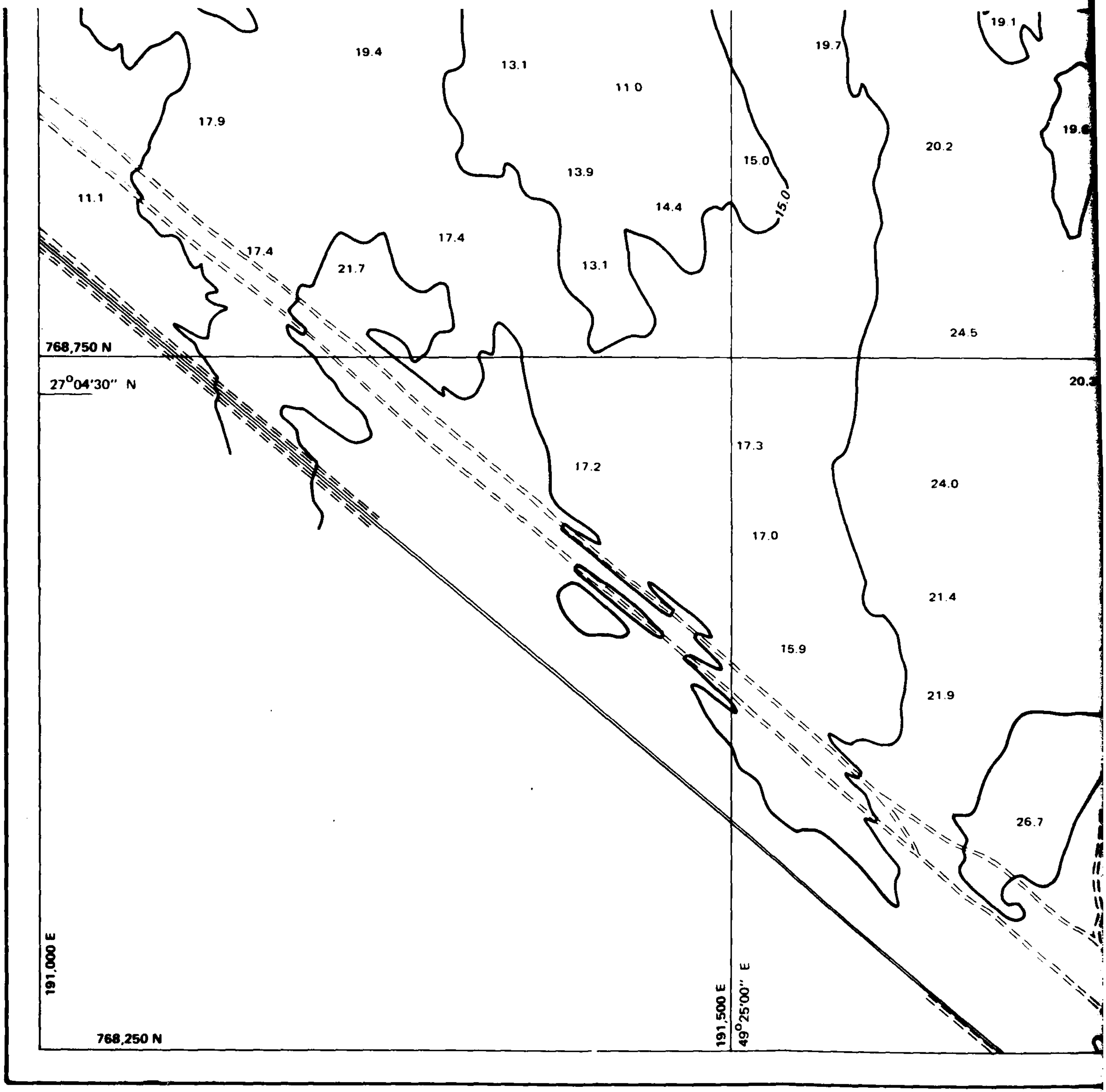
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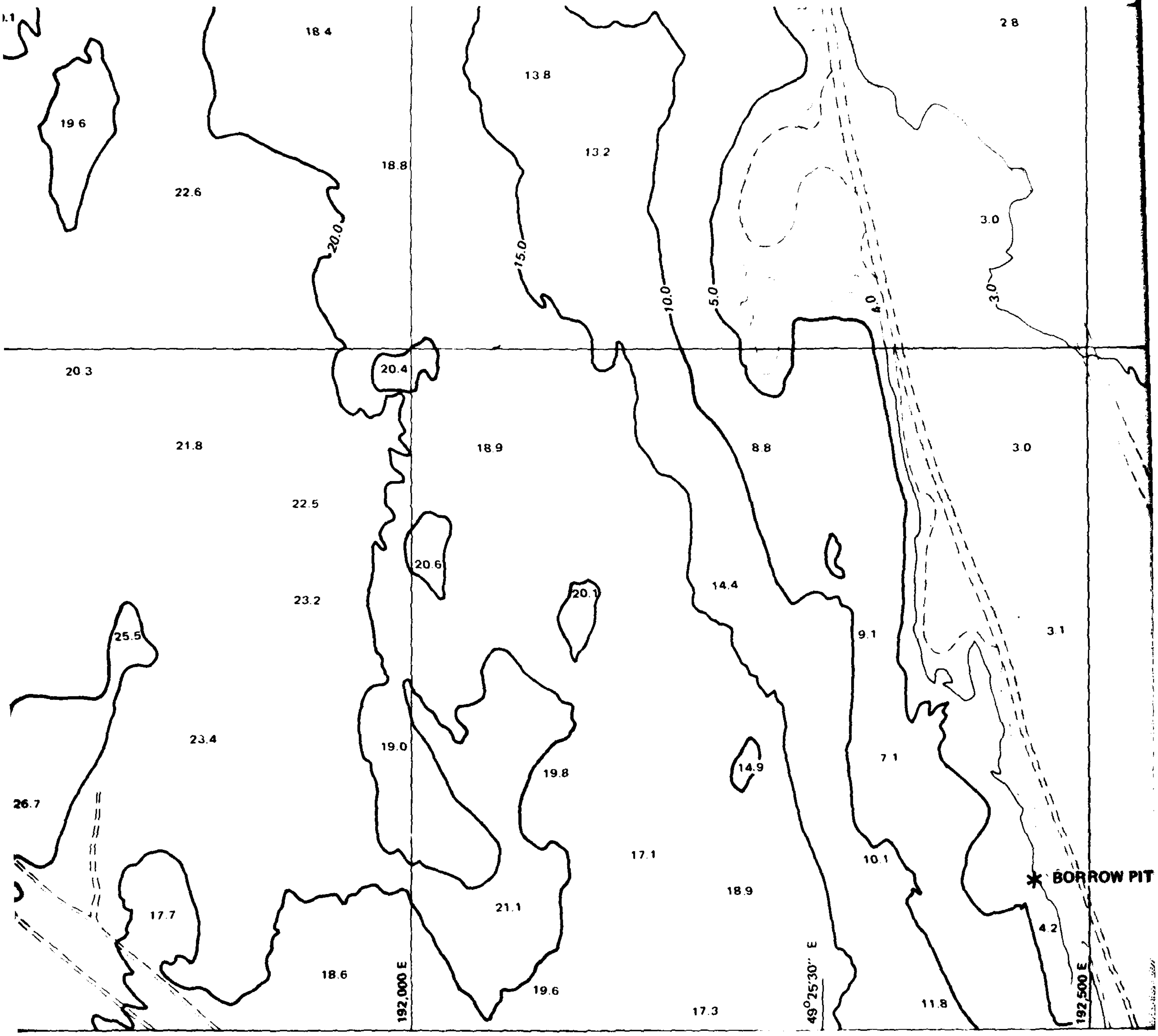
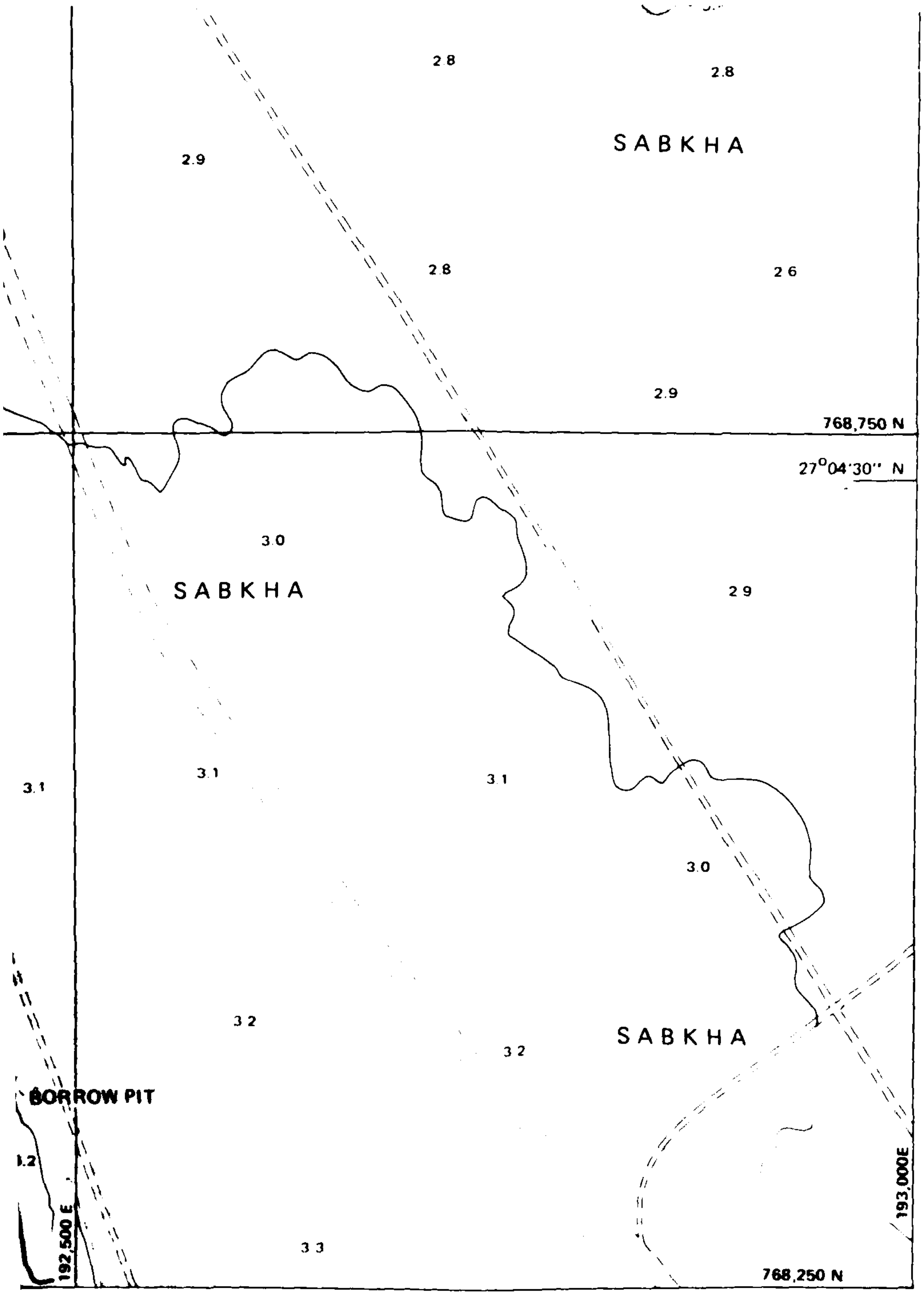
15.9
21.9
26.7
191,000 E
191,500 E
49°25'00" E
768,250 N

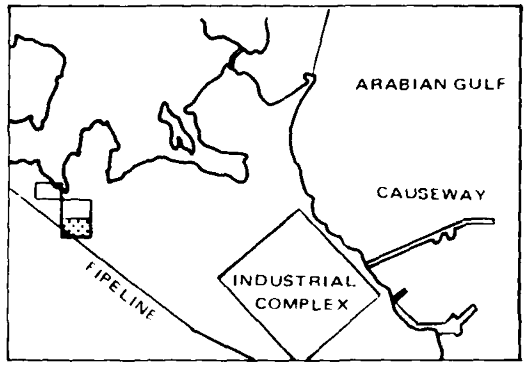

18.4
2.8
13.8
19.6
13.2
18.8
22.6
3.0
20.0
15.0
10.0
5.0
4.0
3.0
20.3
20.4
21.8
18.9
8.8
3.0
22.5
20.6
20.1
14.4
23.2
25.5
9.1
3.1
23.4
19.0
19.8
14.9
7.1
26.7
17.1
10.1
BORROW PIT
18.9
17.7
21.1
4.2
18.6
192,000 E
19.6
17.3
49°25'30" E
11.8
192,500 E

5



GENERAL NOTES

1) HEIGHTS IN METERS ARE REFERENCED TO JUBAIL PORT AUTHORITY DATUM
2) CONTOURS ARE: 1.9, 2.0, 2.5, 3.0, 4.0, 5.0, 10.0, 15.0, 20.0, 25.0 METERS
3) SHORELINE IS DEFINED AS THE 1.9m CONTOUR WHICH IS MEAN HIGH WATER



SCALE 1:3636

50 0 50 100

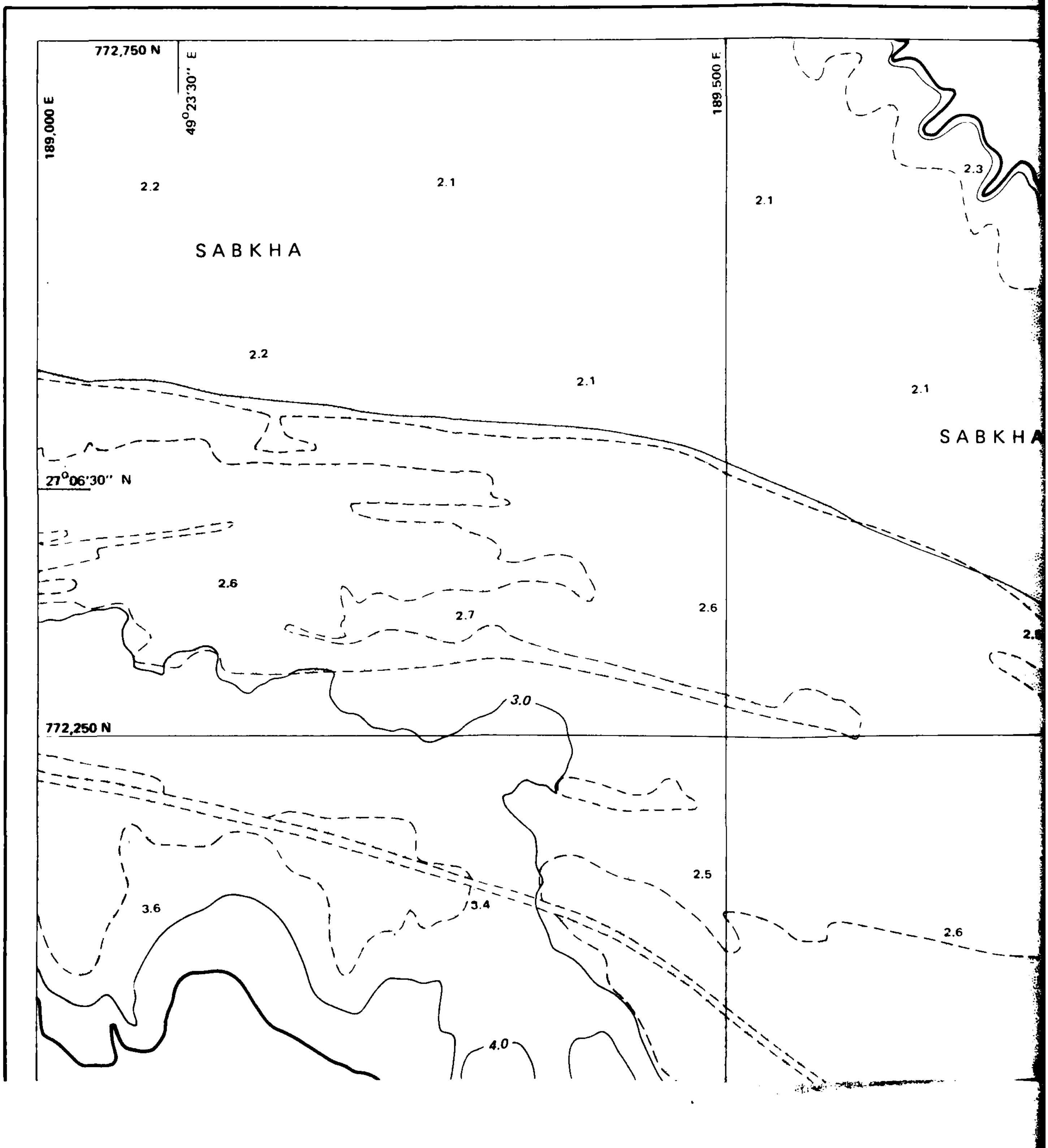
TETRA TECH, INC.

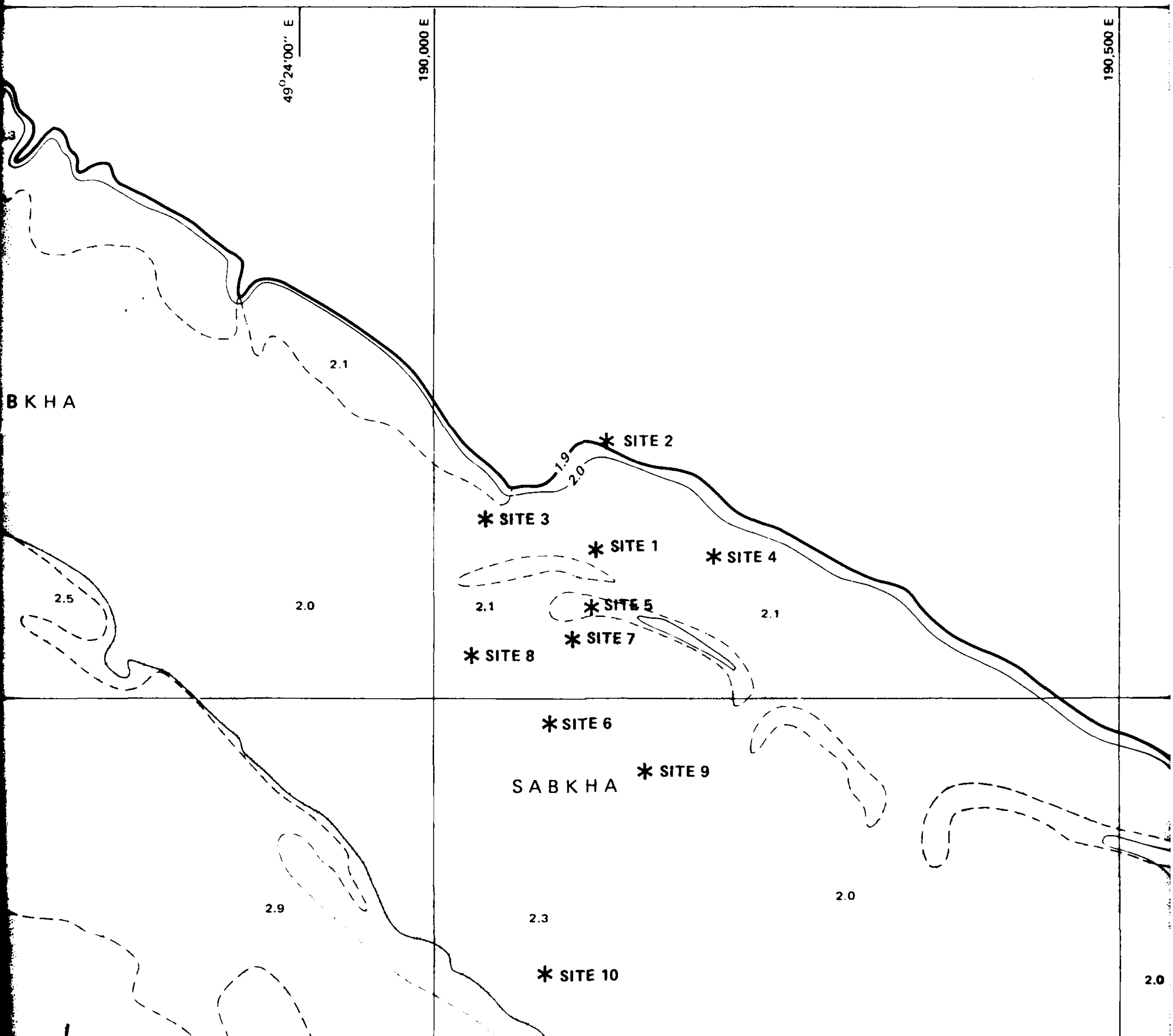
TOPOGRAPHIC MAPS PREPARED FOR OFFICE OF NAVAL RESEARCH

CONTRACT No. **N00014-80-C-0366**

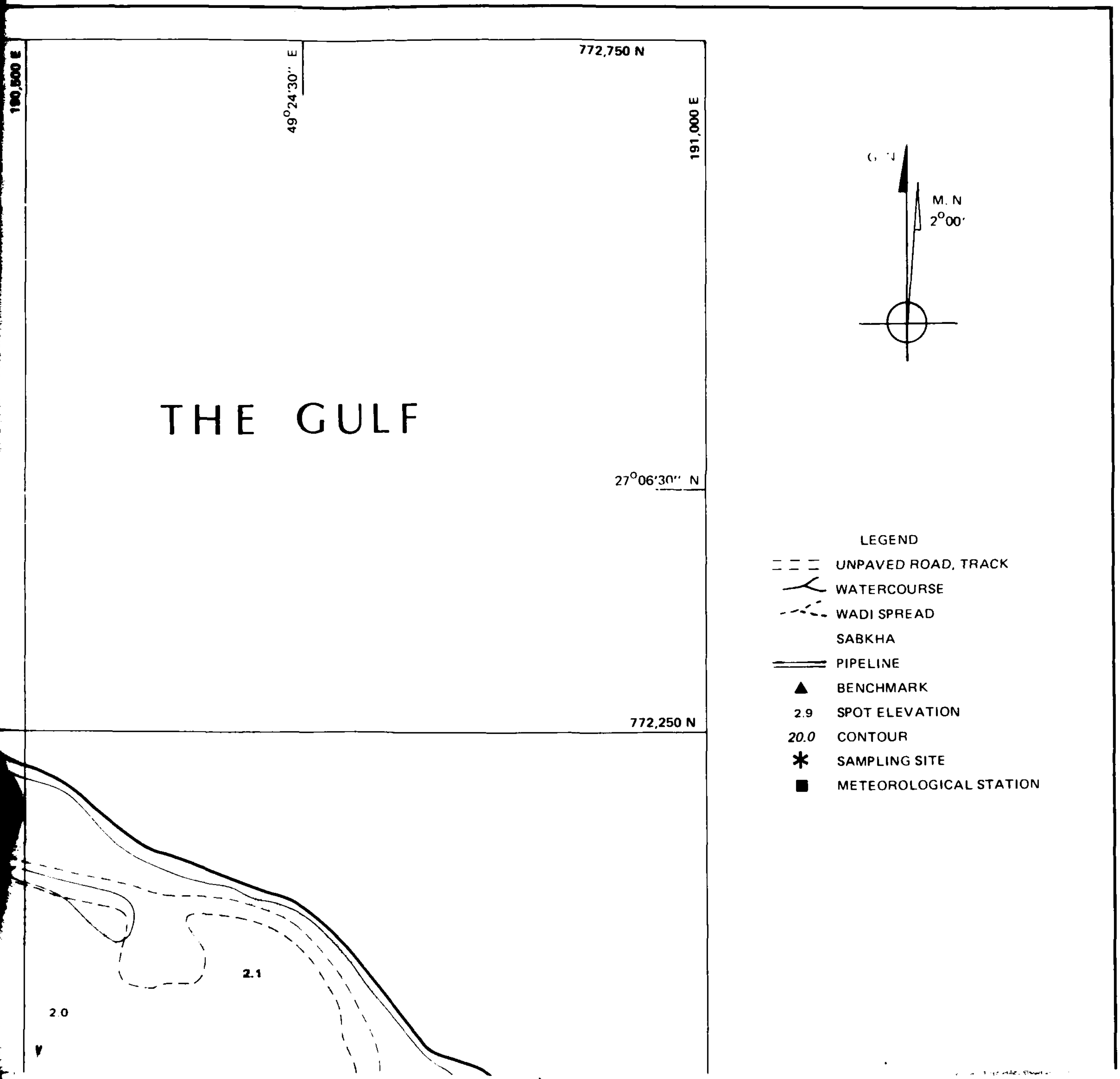
CHART 3 OF 3

SCALE **1:3636** 4 DECEMBER 1980

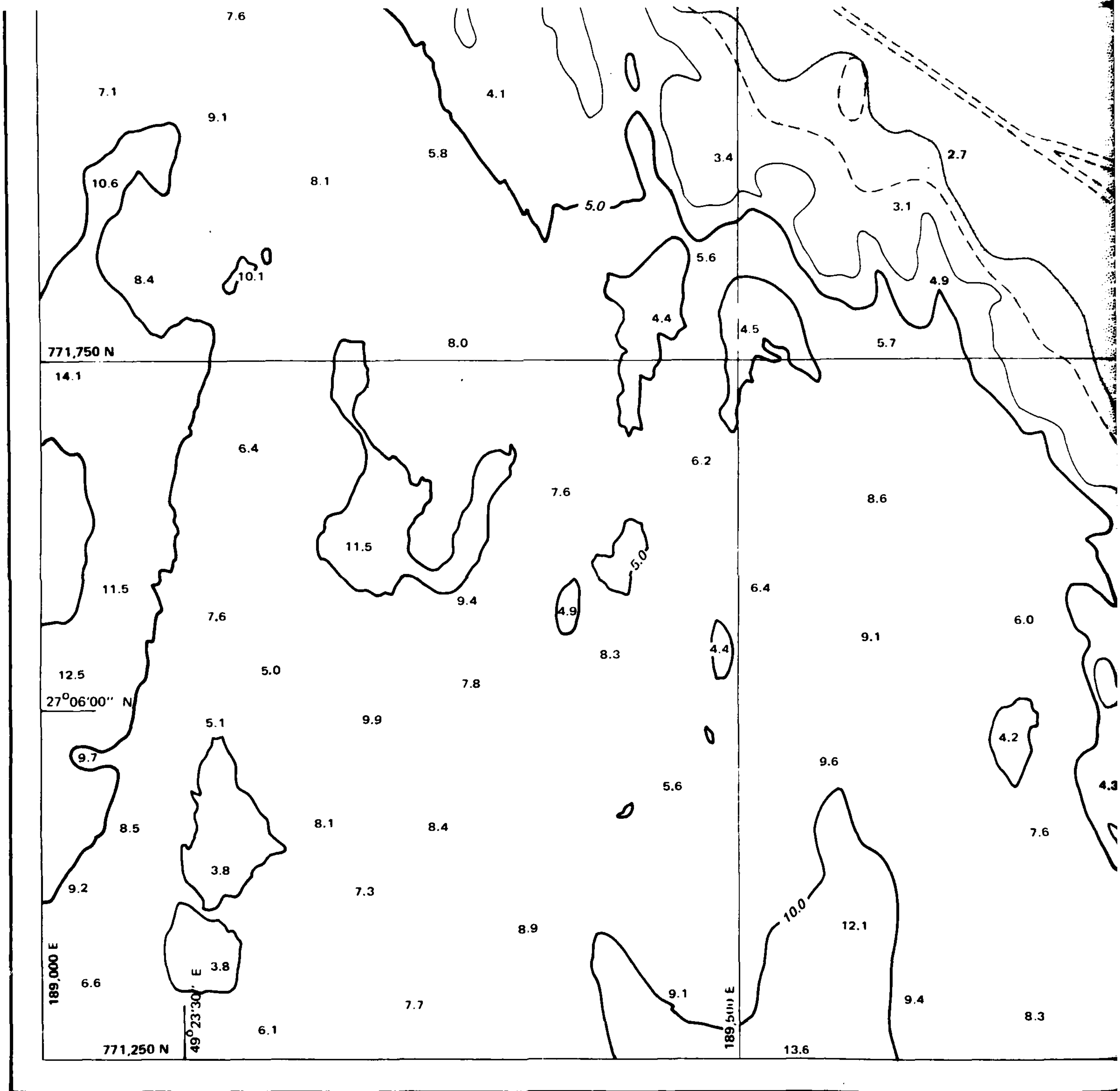

772,750 N
49°23'30'' E
189,000 E
189,500 E
2.2
2.1
2.1
2.3
SABKHA
2.2
2.1
2.1
SABKHA
27°06'30'' N
2.6
2.7
2.6
3.0
772,250 N
2.5
3.6
3.4
2.6
4.0


49°24'00" E
190,000 E
190,500 E
BKHA
2.1
SITE 2
1.9
2.0
SITE 3
SITE 1
SITE 4
2.5
2.0
2.1
SITE 5
2.1
SITE 7
SITE 8
SITE 6
SITE 9
SABKHA
2.9
2.3
2.0
SITE 10
2.0

3

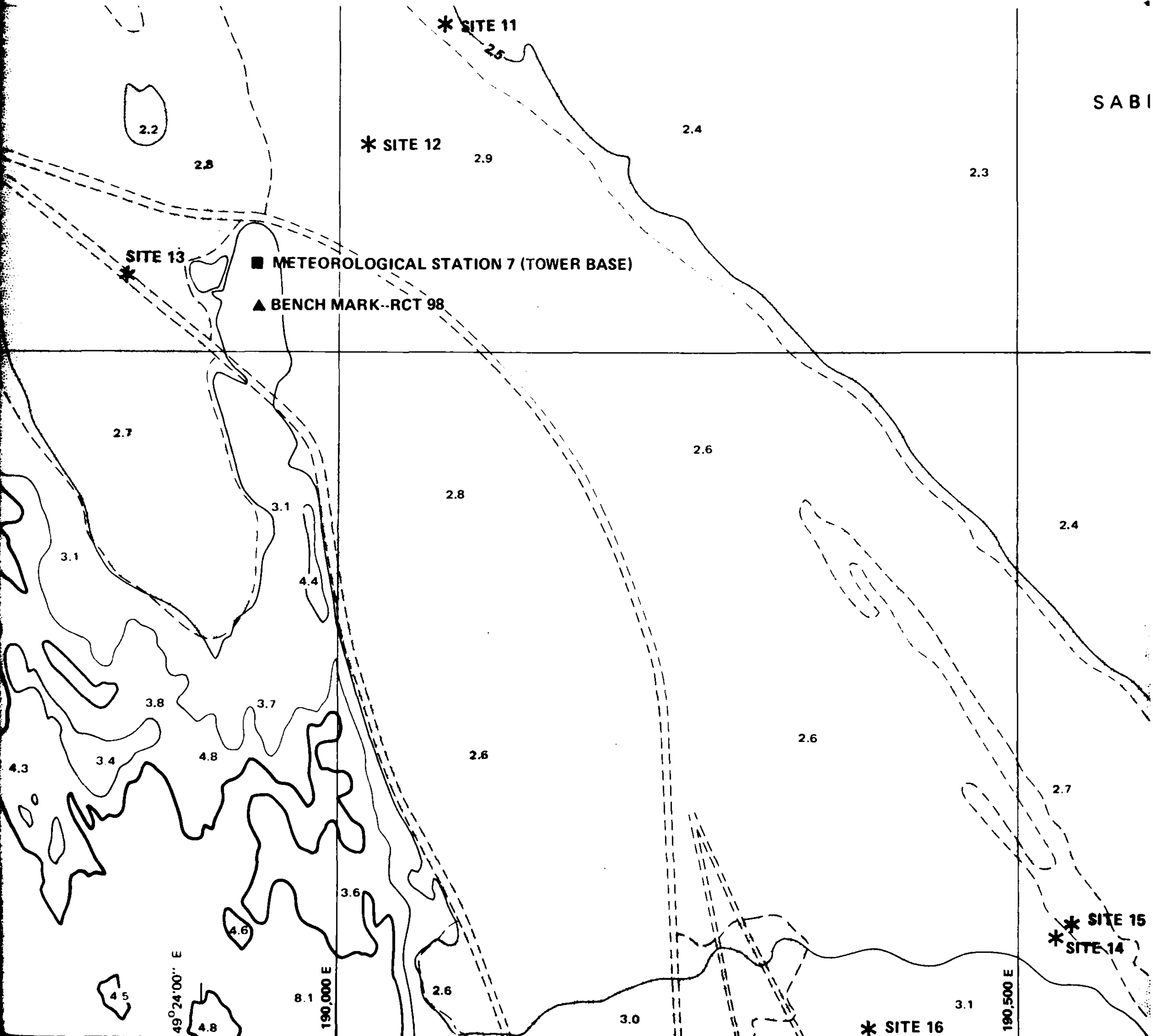


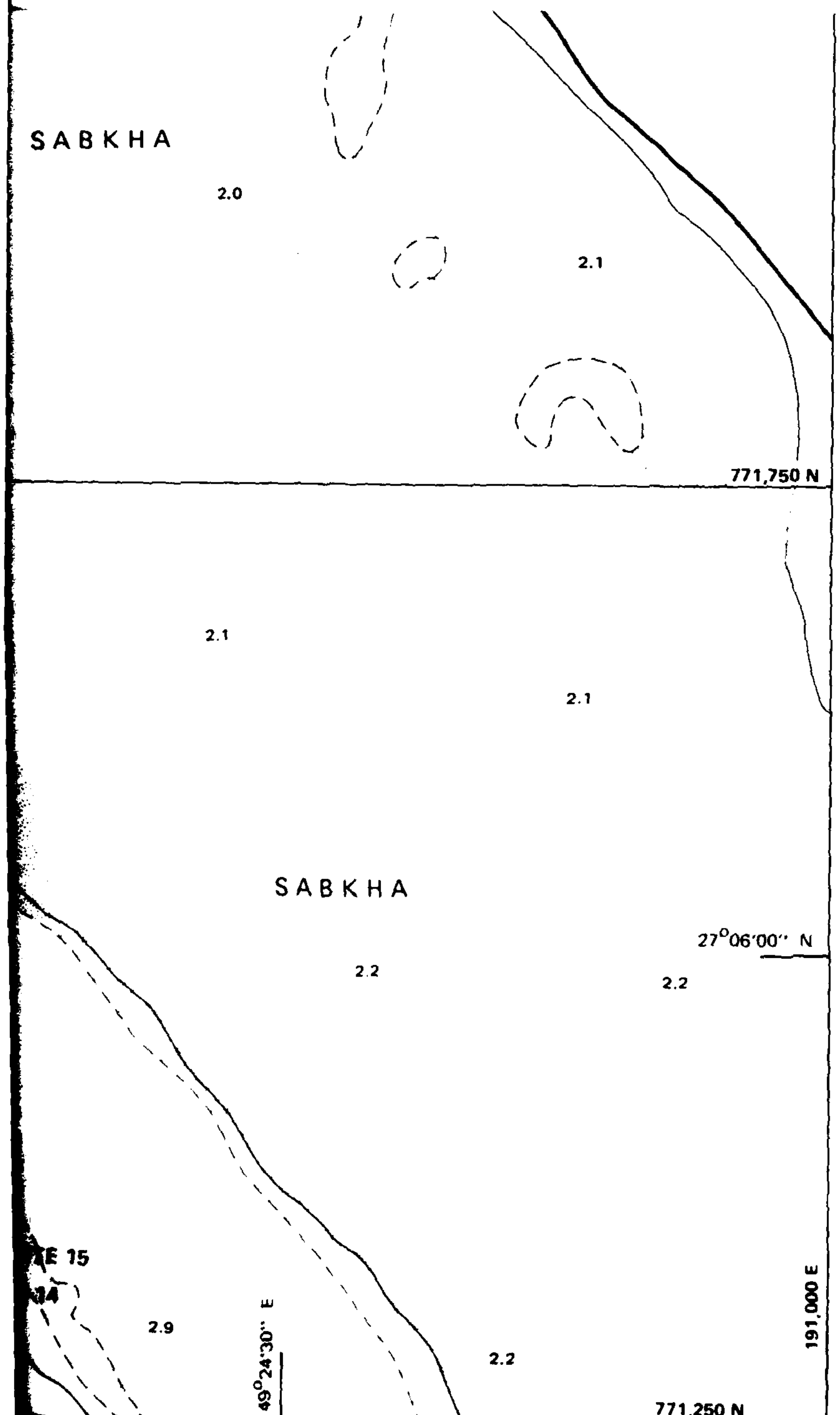
190,500 E
49°24'30'' E
772,750 N
191,000 E
M. N
2°00'
THE GULF
27°06'30'' N
772,250 N
2.1
2 0
LEGEND
UNPAVED ROAD, TRACK
WATERCOURSE
WADI SPREAD
SABKHA
PIPELINE
BENCHMARK
2.9 SPOT ELEVATION
20.0 CONTOUR
SAMPLING SITE
METEOROLOGICAL STATION



771,750 N
27°06'00" N
189,000 E
49°23'30" E
771,250 N
189,500 E
5.0
5.0
10.0
7.6
7.1
9.1
4.1
10.6
5.8
8.1
3.4
2.7
3.1
8.4
10.1
5.6
4.9
4.4
4.5
8.0
5.7
14.1
6.4
6.2
7.6
8.6
11.5
11.5
9.4
4.9
6.4
7.6
6.0
9.1
8.3
4.4
12.5
5.0
7.8
5.1
9.9
4.2
9.7
9.6
5.6
4.3
8.5
8.1
8.4
7.6
3.8
7.3
9.2
12.1
8.9
3.8
6.6
9.1
7.7
9.4
8.3
6.1
13.6

4


SITE 11
2.5
SABI
2.2
2.8
SITE 12
2.9
2.4
2.3
SITE 13
METEOROLOGICAL STATION 7 (TOWER BASE)
BENCH MARK--RCT 98
2.7
2.6
2.8
3.1
2.4
3.1
4.4
3.8
3.7
2.6
4.3
3.4
4.8
2.6
2.7
3.6
4.6
SITE 15
SITE 14
49°24'00" E
190,000 E
190,500 E
4.5
8.1
2.6
3.1
4.8
3.0
SITE 16



GENERAL NOTES

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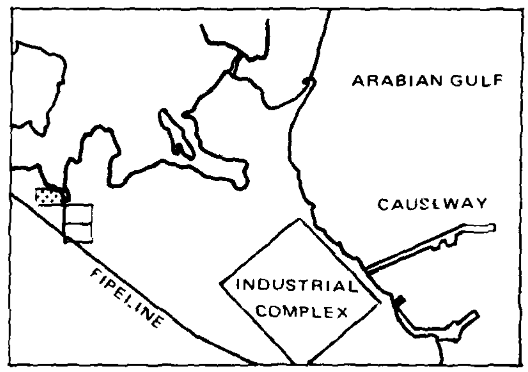

SCALE 1:3636

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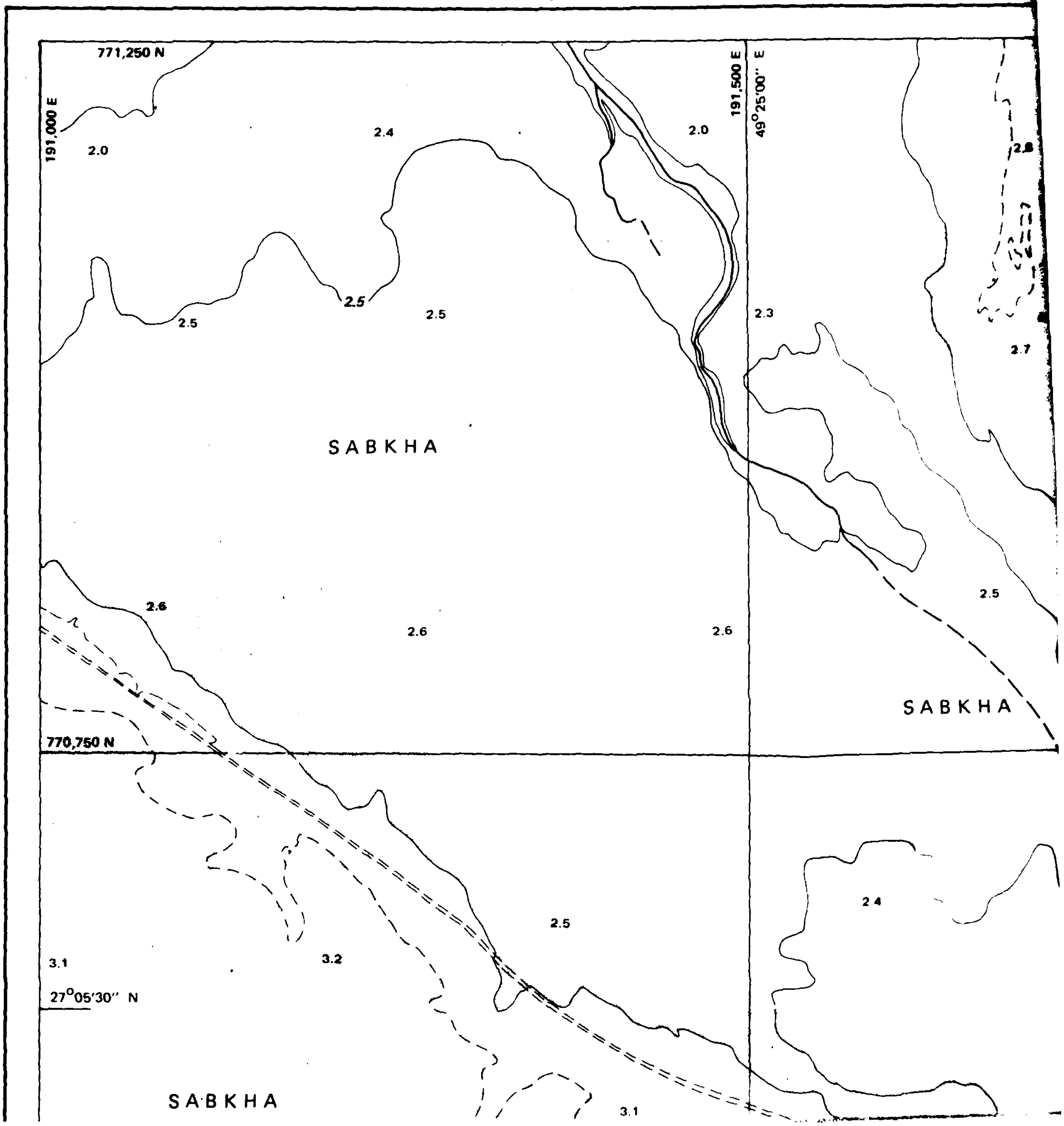
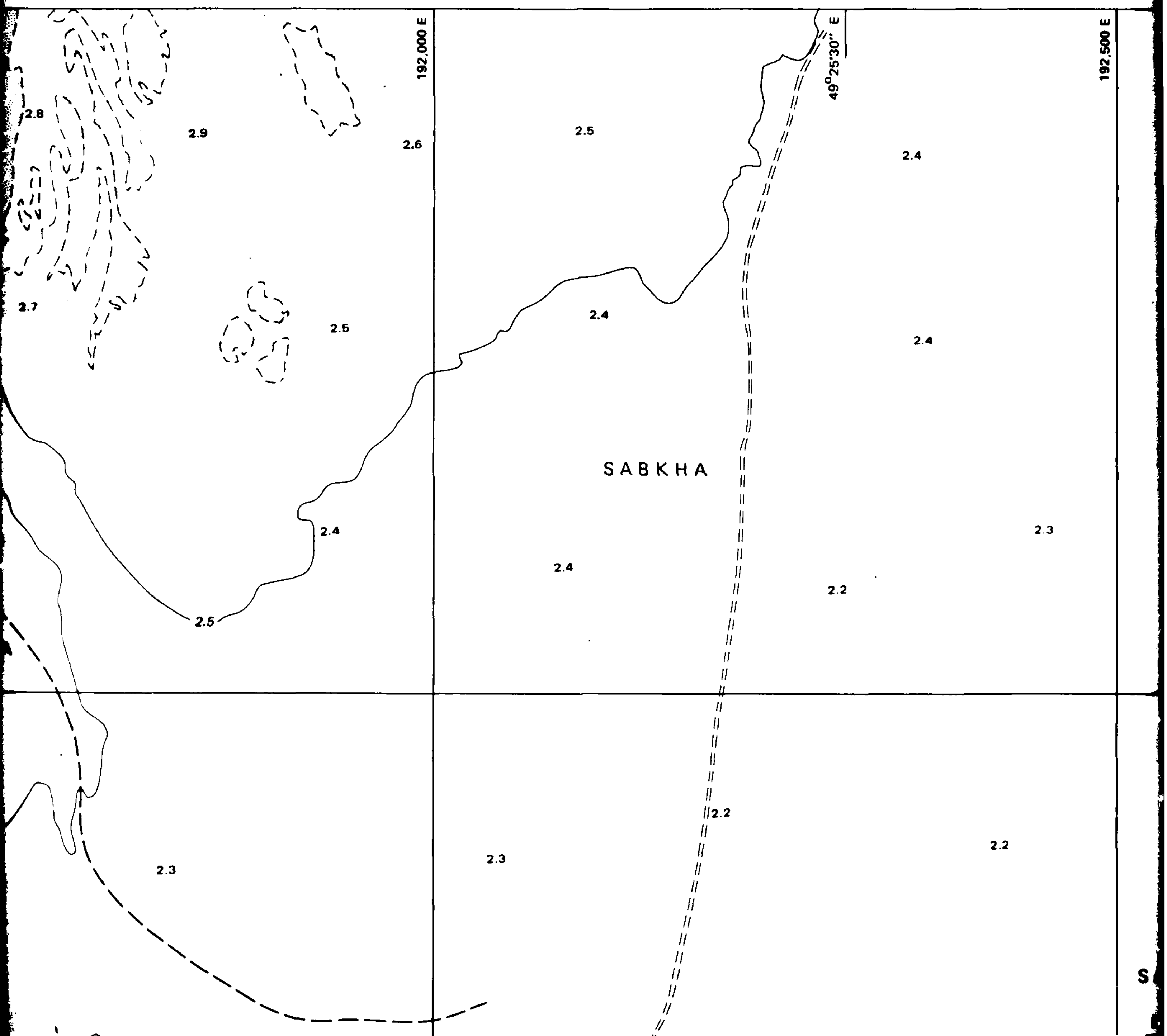
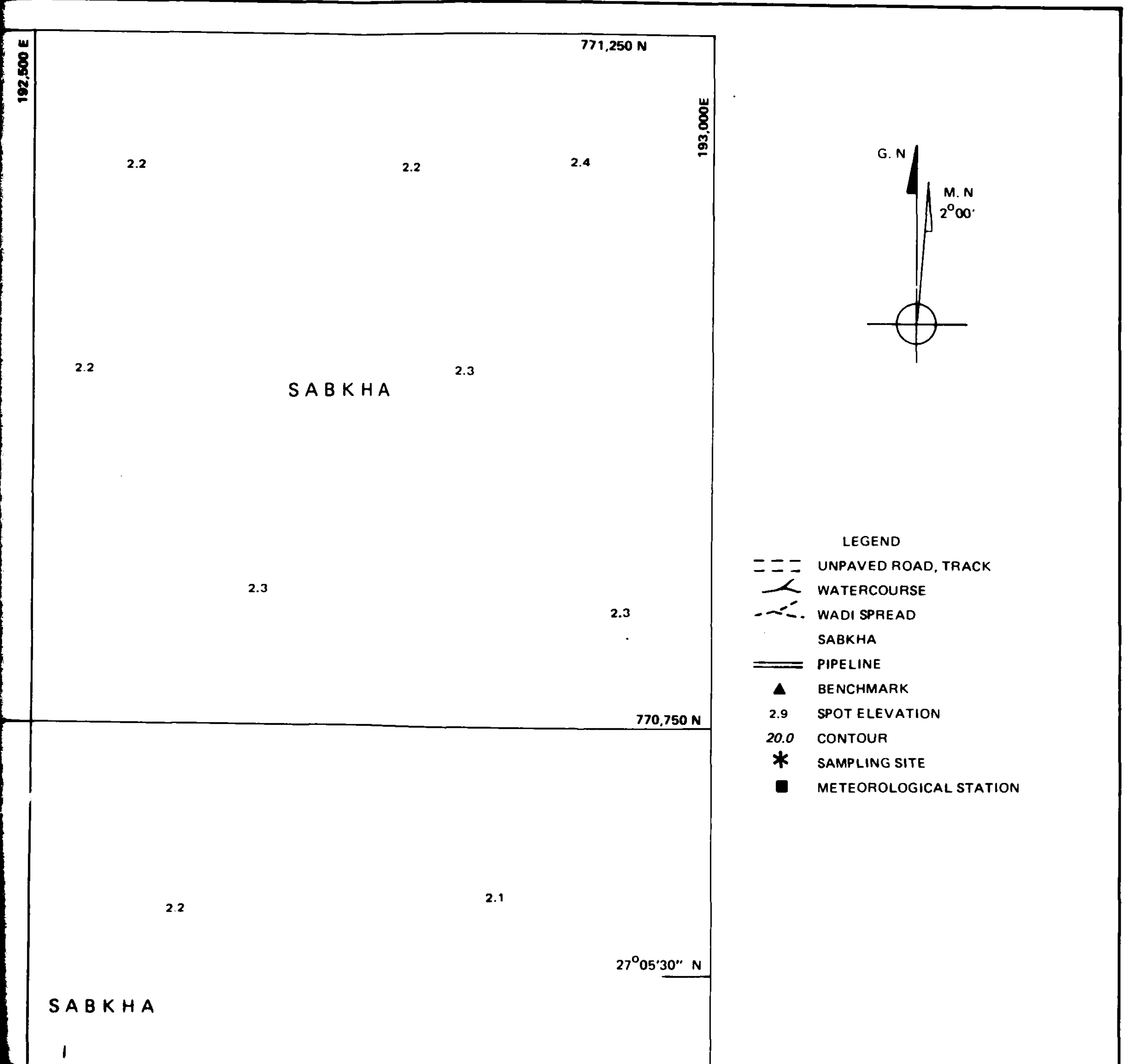
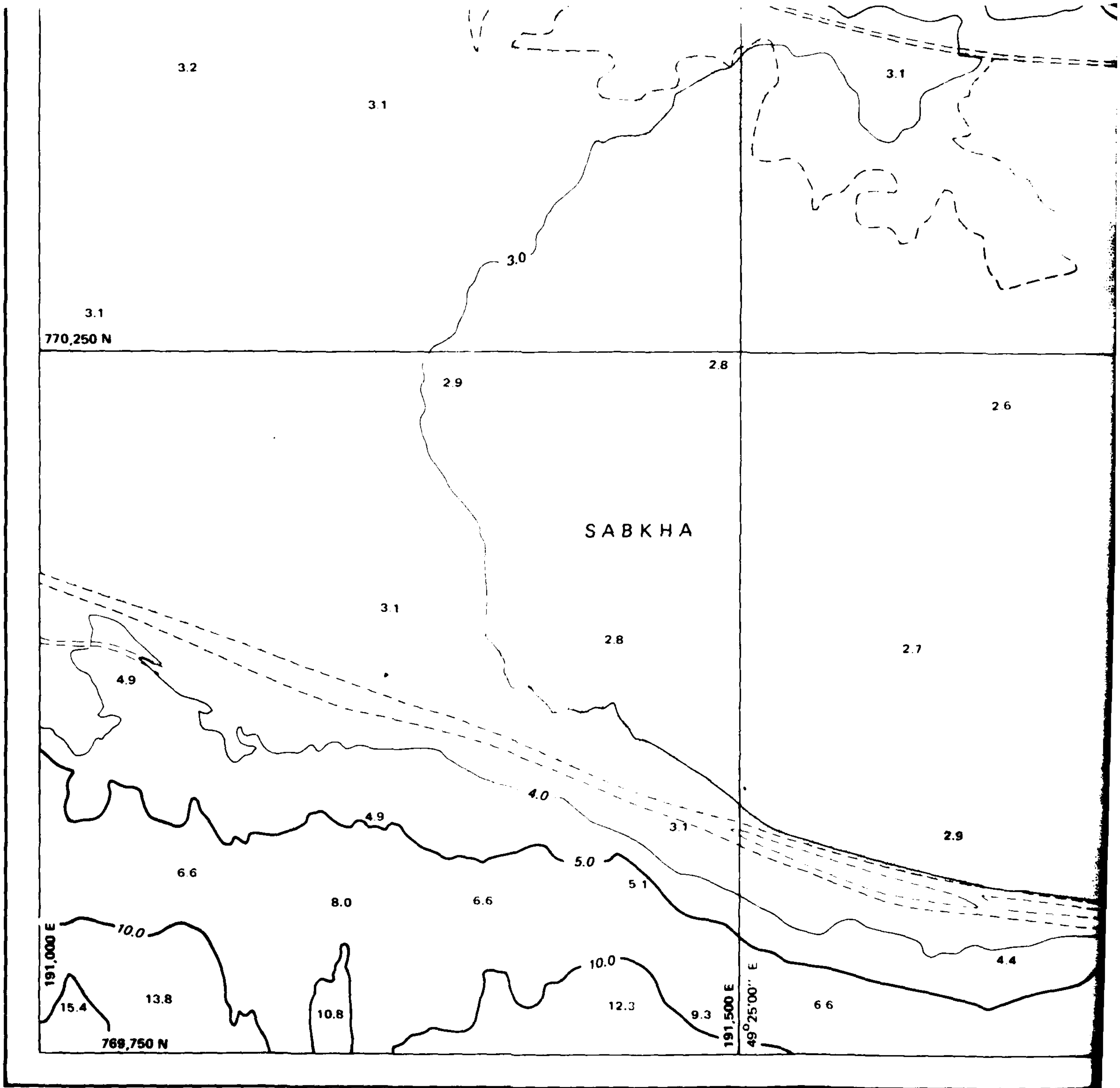
TETRA TECH, INC.	
TOPOGRAPHIC MAPS PREPARED FOR: OFFICE OF NAVAL RESEARCH	
CONTRACT No. **N00014-80-C-0366**	
CHART 1 OF 3	
SCALE: **1:3636**	4 DECEMBER 1980


771,250 N
191,000 E
191,500 E
49°25'00'' E
2.0
2.4
2.0
2.8
2.5
2.5
2.5
2.3
2.7
SABKHA
2.6
2.6
2.6
2.5
SABKHA
770,750 N
2.4
2.5
3.1
3.2
27°05'30'' N
SABKHA
3.1

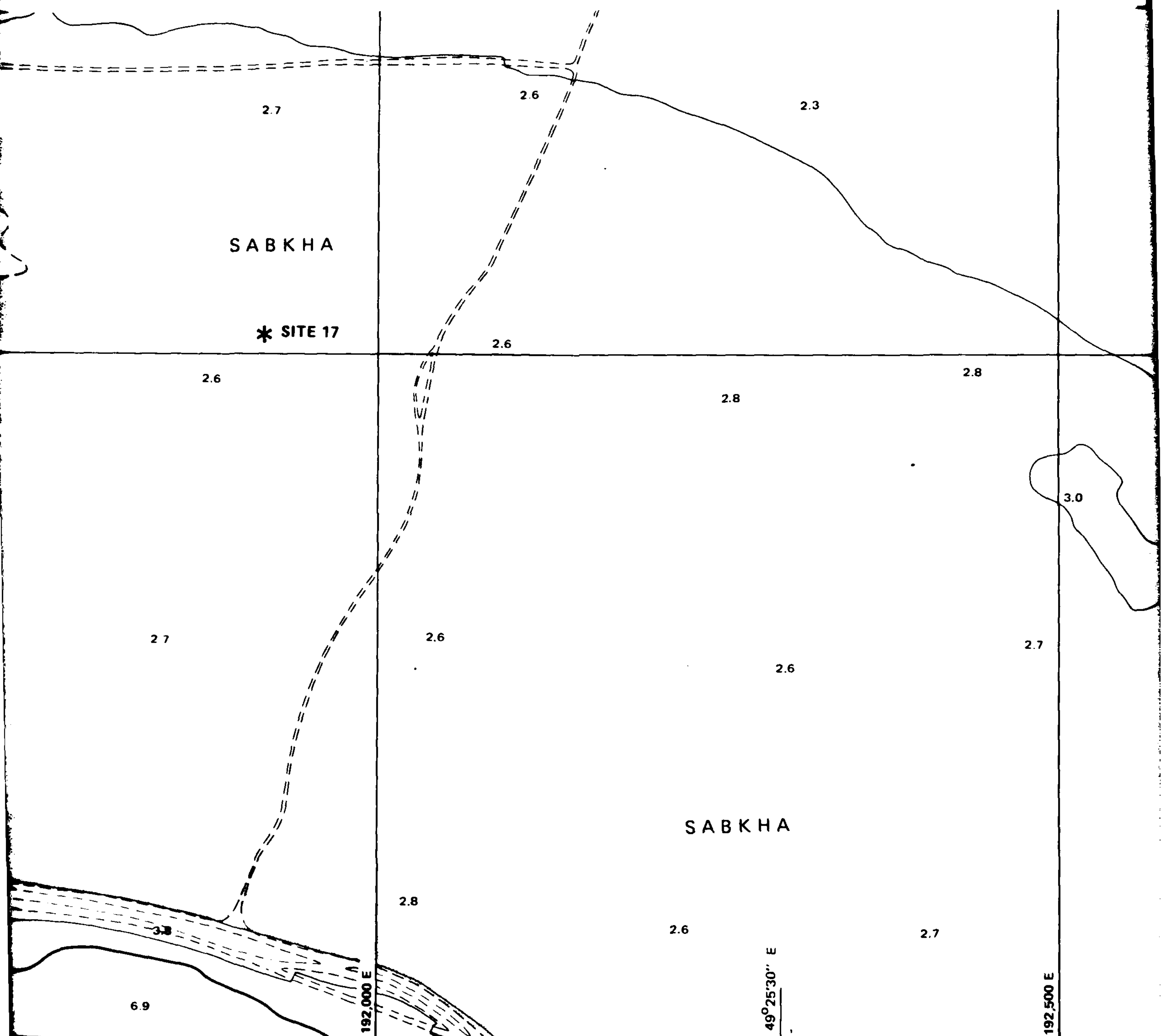


192,000 E
49°25'30'' E
192,500 E
2.8
2.9
2.6
2.5
2.4
2.7
2.5
2.4
2.4
SABKHA
2.4
2.3
2.4
2.2
2.5
2.2
2.2
2.3
2.3
S


771,250 N
192,500 E
193,000E
2.2
2.2
2.4
G. N
M. N
2°00'
2.2
2.3
SABKHA
LEGEND
UNPAVED ROAD, TRACK
WATERCOURSE
WADI SPREAD
SABKHA
PIPELINE
BENCHMARK
2.9 SPOT ELEVATION
20.0 CONTOUR
SAMPLING SITE
METEOROLOGICAL STATION
2.3
2.3
770,750 N
2.2
2.1
27°05'30" N
SABKHA

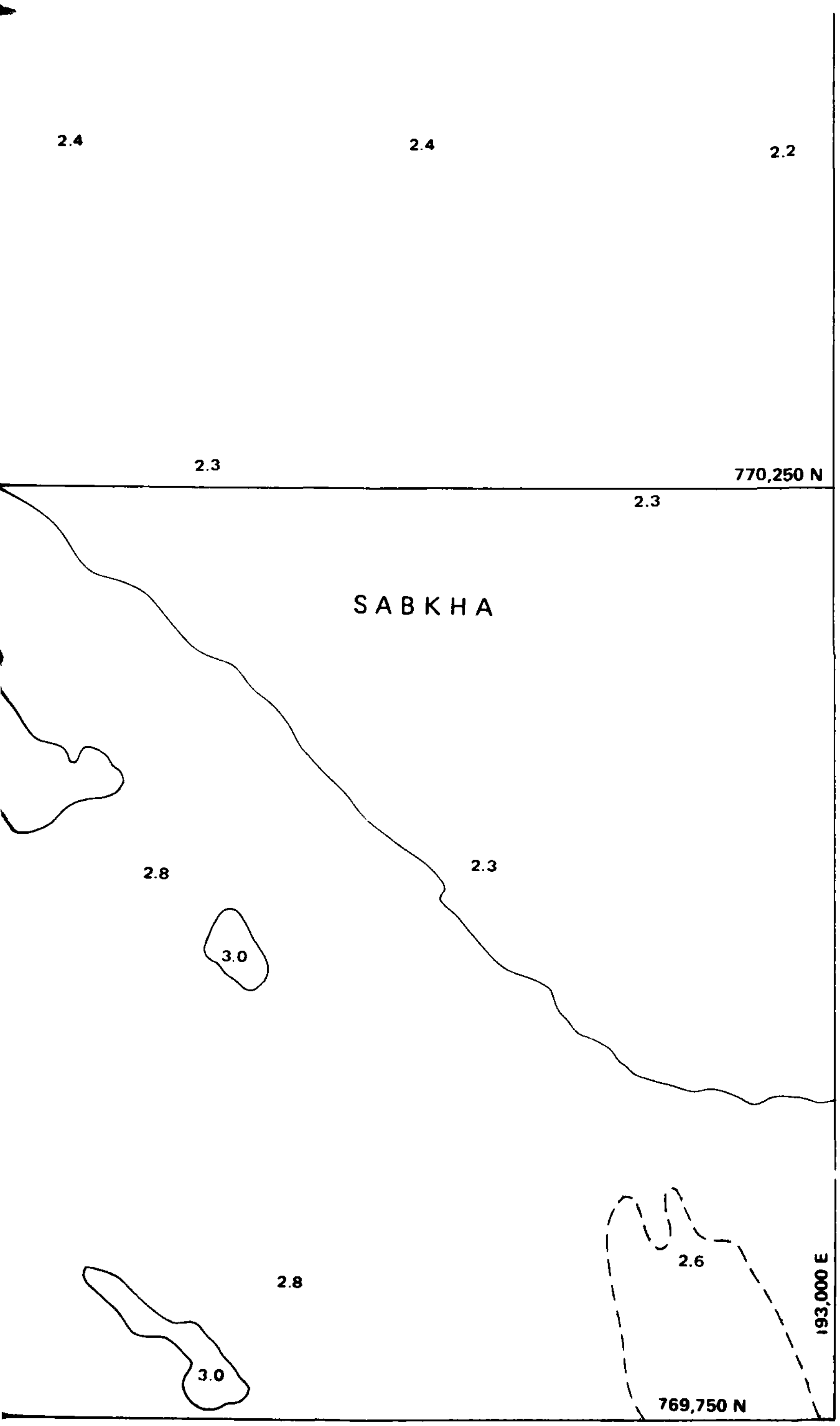


3.2
3.1
3.1
3.0
3.1
770,250 N
2.9
2.8
2 6
SABKHA
3.1
2.8
2.7
4.9
4.0
4.9
3.1
2.9
5.0
6.6
5 1
8.0
6.6
10.0
191,000 E
10.0
4.4
15.4
13.8
10.8
12.3
9.3
191,500 E
49°25'00'' E
6 6
769,750 N



2.7
2.6
2.3
SABKHA
SITE 17
2.6
2.6
2.8
2.8
3.0
2 7
2.6
2.7
2.6
SABKHA
2.8
3.8
2.6
2.7
6.9
192,000 E
49°25'30" E
192,500 E

5



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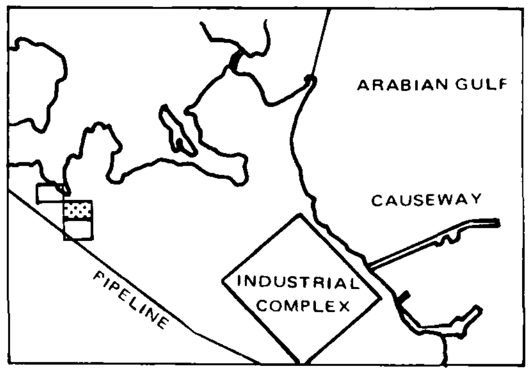

SCALE 1:3636

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TETRA TECH, INC.
TOPOGRAPHIC MAPS PREPARED FOR OFFICE OF NAVAL RESEARCH
CONTRACT No. N00014-80-C-0366
CHART 2 OF 3
SCALE: 1:3636 — 4 DECEMBER 1980

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