TR-186

TECHNICAL REPORT

SEDIMENTS OF THE NORTHERN ARABIAN SEA

Ocean Surveys Division

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ABSTRACT

Topographically the northern Arabian Sea can be divided into two basins separated by the northeast-southwest trending Murray Submarine Ridge. The northwest Gulf of Oman Basin exhibits a more irregular topography, particularly along the continental margin, than does the southeast Arabian Sea Basin, which is dominated by the large sediment cone of the Indus River. Sediments with median grain sizes in the sand and silt range are largely restricted to the continental shelves and upper continental slopes. Basin sediments are calcareous (17 to 51 percent calcium carbonate) and become more so to the south. A band of relatively pure carbonate materials is present on the outer Indian shelf. Detrital grains of dolomite and calcite are present in small amounts in most samples, and frosted, pitted quartz grains are common in the coarse fraction of sediments from the northwest basin. The non-carbonate coarse fraction of the sediments contains much feldspar and an unstable heavy mineral suite of both metamorphic and igneous origin. Dust is an important source of sediments over the entire area. The dust contribution is relatively more important, and the overall rate of sedimentation is lowest in the Gulf of Oman Basin as compared to the Arabian Sea Basin.

FOREWORD

This technical report discusses the marine geology of the Gulf of Oman and the northern Arabian Sea.

It is based mainly on the analysis results of bottom sediment samples collected (by NAVOCEANO Scientists) during the USS REQUISITE 1961 Survey. Samples were analyzed jointly by the University of Georgia Marine Institute and the Geological Laboratory of the U.S. Naval Oceanographic Office.

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TABLE OF CONTENTS

		Page
I.	INTRODUCTION	1
II.	PROCEDURES	
	A. Field	1
	B. Laboratory	1
III.	REGIONAL SETTING	
	A. Coastal Geography	3
	B. Climate	4
	C. Regional Geology	4
IV.	MARINE ENVIRONMENT	
	A. Currents	5
	B. Temperature and Salinity	6
	C. Bottom Topography	10
V.	SEDIMENTS	
	A. Grain Size	14
	B. Calcium Carbonate Content	14
	C. Organic Carbon Content	14
	D. Carbonate Constituents	18
	E. Light Minerals	18
	F. Heavy Minerals	21
	G. Clay Mineralogy	21
	H. Carbonate Mineralogy	23
VI.	DISCUSSION	23
	REFERENCES	27

TABLES

1. Light and Heavy Mineralogy of Eight Northern Arabian Sea Samples (percent by count) 20
2. Carbonate Mineralogy of Four Samples from the Indian Continental Shelf of the Northern Arabian Sea 24

FIGURES

		Page
1.	Northern Arabian Sea Showing Important Ports, Bathymetry, and Bottom Sample Locations. (Depths in Fathoms)	2
2.	USS REQUISITE Oceanographic and Geologic Station Locations, Northern Arabian Sea	7
3.	Surface Water Temperature, Northern Arabian Sea, March 1961	8
4.	Surface Salinity, Northern Arabian Sea, March 1961	9
5.	Salinity Maximum, Northern Arabian Sea, March 1961	11
6.	Bottom Salinity, Northern Arabian Sea, March 1961	12
7.	Median Grain Size, Northern Arabian Sea Sediments	15
8.	Percent Calcium Carbonate, Northern Arabian Sea Sediments	16
9.	Percent Organic Carbon Content of Northern Arabian Sea Sediments	17
10.	Percent Quartz in Sand-size Fraction of Northern Arabian Sea Sediments	19
11.	Clay Mineral Provinces of Northern Arabian Sea Sediments	22

I. INTRODUCTION

During the first 3 months of 1961, personnel of the U.S. Naval Oceanographic Office aboard USS REQUISITE, conducted an extensive survey of the waters of the Persian Gulf, the Gulf of Oman, and the northern Arabian Sea. From the 5th of January until the 19th of February, the ship operated in the Persian Gulf. The Arabian Sea-Gulf of Oman phase of the cruise was begun off the coast of Bombay on February 26th and concluded on March 31st.

In addition to the determination of water characteristics, the party collected a number of bottom samples which are the subject of this report. These samples were analyzed jointly by the Geological Laboratory of the Oceanographic Office and by the University of Georgia Marine Institute. Information furnished by these analyses, particularly those of size and general composition, has been supplemented to some extent by other recorded bottom data from this area, principally the reports of the John Murray Expedition of 1933-34 (Stubbings, 1939; Wiseman and Bennett, 1940) and bottom chart notations (H. O. Charts 1587, 1588, 1589).

The writers (Richard A. Stewart, U. S. Naval Oceanographic Office, and Orrin H. Pilkey, University of Georgia Marine Institute) wish to express their appreciation for the efforts of Dr. Bruce Nelson, University of South Carolina, who performed the clay mineral analyses, and Mr. Robert Giles, University of Georgia, who identified the heavy minerals.

II. PROCEDURES

A. Field

Fifty-two bottom samples were obtained on a grid pattern of stations occupying the center of each one-degree square (Fig. 1). Slight deviation from this pattern was made along coastal areas. Most samples were collected utilizing a Phleger-type gravity corer. Three samples were obtained with an orange-peel grab sampler. The cores and grab samples were sealed untreated.

B. Laboratory

After arrival at the Oceanographic Office, each core was split lengthwise, described and logged; and representative fractions were taken for the determination of size, chemistry, and mineralogy. Size analyses were performed using standard techniques of sieving and pipetting as outlined by Krumbein and Pettijohn (1938). Carbonate content was determined by the EDTA (ethylenediamine tetraacetate) titration method proposed by Turekian (1956). The Allison method (Allison, 1935) was employed in the determination of organic carbon content.

FIGURE 1. NORTHERN ARABIAN SEA SHOWING IMPORTANT PORTS, BATHYMETRY, AND BOTTOM SAMPLE LOCATIONS. (DEPTHS IN FATHOMS). TOPOGRAPHY BASED ON CHARTS H.O. 1587, 1588, and 1589.

The gross compositional character of the coarse fraction of each sample was examined under the the binocular microscope, and the constituent particles were identified and counted. Heavy mineral separations were made using tetrabromoethane (S. G. 2.95), and heavy minerals were identified and counted under the petrographic microscope. The light minerals were mounted, stained with sodium cobaltinitrite to distinguish the feldspars, and similarly counted. Clay mineralogy was determined qualitatively using standard x-ray diffraction techniques. The carbonate mineralogy also was determined on total samples by an x-ray diffraction technique. All samples were visually scanned for dolomite after treatment with dilute acid and use of a dolomite stain.

III. REGIONAL SETTING

A. Coastal Geography

The Arabian Sea is the northern arm of the Indian Ocean located between the Indian and Arabian Peninsulas. The area of study is the northern portion of the Arabian Sea bounded to the south by approximately 19° north latitude (Fig. 1). The northern Arabian Sea is bordered by India, Pakistan, and Iran to the east and north, and the Al Batina and Oman Coast to the west. Major seaport cities bordering the area include Bombay, India, and Karachi, Pakistan.

The largest river in the area is the Indus; its modern delta is located south of Karachi. This river drains a large portion of the Indo-Gangetic plain and extends well into the Himalayas. The Narbada and Tapti rivers of India are smaller than the Indus and empty into the Gulf of Cambay. These rivers drain the mountainous region of central India, including the Vindhya and Satpura ranges. South of the Gulf of Cambay, drainage is eastward, and no important streams reach the sea. Drainage of the coasts of Iran and western Pakistan is accomplished by a few relatively small rivers. The Arabian coast contributes virtually no significant drainage to the northern Arabian Sea.

Physiographic provinces in this area are shown by Lobeck (1945) and are also illustrated by Heezen and Tharp (1965b). Along the Indian coast, south of and including part of the Gulf of Cambay, the area is bounded by the Western Ghats. These mountains rise abruptly from the sea to an average elevation of 3,000 feet. The Saurashtra, or Kathiawar, Peninsula is characterized by a relatively wide coastal lowland. The Indus River Delta area is low and swampy. The remainder of the Pakistan and Iran coast consists generally of a narrow coastal lowland which rises quickly to a plateau averaging 2,000 feet in elevation with individual peaks ranging up to 7,000 feet. The Arabian coast bordering the study area is generally rugged and precipitous, but south of Ra's Al Hadd the relief becomes more subdued.

B. Climate

This entire area lies under the influence of the two monsoonal seasons that typify Southern and Eastern Asia. During the summer months, southwest monsoon surface winds blow from the southwest parallel to the arid Arabian coast south of Ra's Al Hadd and, consequently, contribute little or no moisture to this area. On reaching the Gulf of Oman, there is some divergence with a southeast branch blowing into the Gulf. Southwest winds reaching the northern Pakistan coast are generally deflected eastward owing to the almost continuous presence of a series of lows. These lows move east to west over the Indo-Gangetic plain and cause a counter-clockwise circulation of air. Hot, dry continental air moving to these lows across India rises above and stabilizes the warm moist air from the Arabian Sea. This effect accounts for the extreme aridity of this northeastern region despite the inflow of abundant moisture. From Bombay southward, abundant precipitation occurs along the coastal margin due to the orographic effect of the Western Ghats.

The winter monsoon season is a time of variable northerly winds in the Gulf of Oman with a high frequency of calms. The most frequent wind direction is from the northwest although at times the northeast wind blows with exceptional force. These northeast winds are often heavily laden with dust. Along the Pakistan coast and southward, the northeast wind dominates during this season.

Spring and fall are the two transitional seasons during which northerly winds give way to southerly and vice versa. In general, the southerly winds prevail for the longer period of time.

As a consequence of topography and prevailing winds, there is little precipitation in the coastal regions of the study area, and during any season of the year, desert conditions predominate. Dust storms are common, occurring with greatest frequency during the summer months, especially along the Makran coast of Pakistan and Iran. Dust in the Makran area has been reported to a height of 15,000 feet, but it usually does not exceed 10,000 feet. Prevailing surface winds during this season of maximum occurrence would tend to prevent this material from being distributed seaward, but in the vicinity of Gwadar, winds above 6,500 feet are almost entirely northerly during this season, providing a transporting agent out over the sea.

C. Regional Geology

General reviews of the geology of the study area are presented by Wadia (1953) and Pilgrim (1908). The southern portion along the Indian coast is dominated by the Tertiary Deccan volcanics. These lavas are generally uniform augite basalts although locally more acidic and basic valcanics occur. Also exposed in the area roughly between the Aravalli and Vindhya Mountains are several complex systems of Precambrian rocks, that have been metamorphosed to one degree or another. Deccan basalt covers much of Kathiawar, but the peninsula is rimmed by a variety of Cretaceous and Tertiary sediments. Exposed in the Kutch are similar sediments including limestones, sandstones, and shales. Most of the area between the Aravalli Mountains and the west side of the Indus basin is covered by Pleistocene and Recent sediments. These sediments, which range up to thousands of feet in thickness, are mainly deposits of rivers of the Indo-Gangetic system. Wide expanses of windblown quartz sand are present. This sand contains varying amounts of calcareous grains. West of the Indus basin to the Pakistan-Iran border are exposed thick sections of Tertiary sediments with Cretaceous sediments and minor Eocene volcanics. Sandstones and shales dominate over limestones. The coast of Iran is bounded by the Miocene Fars series consisting of marls, clays, and sandstones with some limestones and interbedded gypsum.

Outcropping rocks of the Arabian coast are largely sedimentary although igneous and metamorphic rocks are present in significant amounts. The Carbo-Triassic Oman series, consisting for the most part of limestone, makes up the backbone of the Jebel Akhthar Range. Along the coast are widespread Pleistocene and Recent sediments consisting of various types of alluvial deposits and a distinctive friable limestone. Some Jurassic basic sills, made up of gabbros and diorites which are much metamorphosed, crop out in several areas along the coast. Precambrian high-grade metamorphic rocks of the Hatat series crop out in a small area near Ra's Al Hadd.

In summary, the regional geology from a standpoint of potential sediment sources consists of volcanics, metamorphics, and minor amounts of sediments in the southern portion of the study area in India. The remainder of the Indian, Pakistan, and Iranian coasts are principally sedimentary rocks. The Arabian peninsula coast is also largely sedimentary in nature with some basic igneous and and metamorphic rocks present.

IV. MARINE ENVIRONMENT

A. Currents

Detailed current data are sparse. No direct current measurements were made on the Arabian Sea phase of this survey. Current plots in the <u>Atlas of Surface Currents of the Indian Ocean</u> (H. O. Pub. 566) show a surface circulation gyre paralleling the coast of Arabia, crossing from Ra's Al Hadd toward Karachi and south along the Indian coast. For most of the year, this clockwise circulation is present, but the flow becomes slightly disrupted in October, shows some reversal in November, and is entirely counter-clockwise in December and January. In February, reversal occurs and by March a clockwise circulation is again established, while the northeast monsoon still blows. Barlow (1934) explained this apparent phenomenon by noting that, during the northeast monsoon season, water at the head of the Arabian Sea is cooled by the continental wind, producing a gradient of the sea surface to the north. Water moving in response to this gradient is deflected eastward due to Coriolus effect and, consequently, is placed in a clockwise motion apparently at odds with prevailing winds.

Surface current plots in the Gulf of Oman coincide with the dominant wind direction in that area, flowing southeast in response to the northwest wind in winter, and into the Gulf under the domination of the southeast divergence of the summer monsoon.

B. Temperature and Salinity

A summary of oceanographic data collected during this cruise is given in TR-176. Figure 2 shows the stations at which these observations were made during the Arabian Sea phase. Surface water temperature for March is shown in Figure 3. Temperatures range from 23.8°C in the Strait of Hormuz and northwestern Gulf of Oman to 26.7°C south of Ra's Al Hadd and 26.8°C along the eastern shore of the Gulf of Cambay. Temperature changes are gradual. The isotherms show some relationship to current patterns, for example, the tongue of warmer water protruding northward along the Arabian coast and the southward deflection of the isotherms along the Indian coast. The influence of colder river water runoff may be seen extending from the Gulf of Cambay.

On shelf areas, bottom temperatures range from identical to those of surface waters to a few degrees cooler. An exception is the Strait of Hormuz where bottom temperatures actually exceed those of the surface due to the outflow at depth of warm hypersaline Persian Gulf water. In deeper waters, bottom temperatures decrease rapidly with depth to values of less than 2°C at depths greater than 2,800 meters.

Surface salinity measurements for March 1961, range from 34.90‰ in the Gulf of Cambay to 36.63‰ in the Strait of Hormuz (Fig. 4). Low salinities in the Gulf of Cambay can be attributed to fresh water runoff from the Narbada and Tapti Rivers. Curiously the Indus River seems to exert little effect on the observed salinity distribution. Possibly prevailing currents during this month confine this fresh water to a narrow area along the coastline. High salinities in the Strait of Hormuz and Gulf of Oman can be attributed to outflow of Persian Gulf water into the area. The complex surface pattern in the eastern Arabian Sea may result from incomplete establishment of the summer clockwise surface current gyre. Movement of lower salinity Indian Ocean water northward along the Arabian coast is shown by the 36.4‰ isohaline.

According to Emery (1956) most of the outflow of high salinity water from the Persian Gulf is at depth and primarily along the southeastern side of the Hormuz Strait.

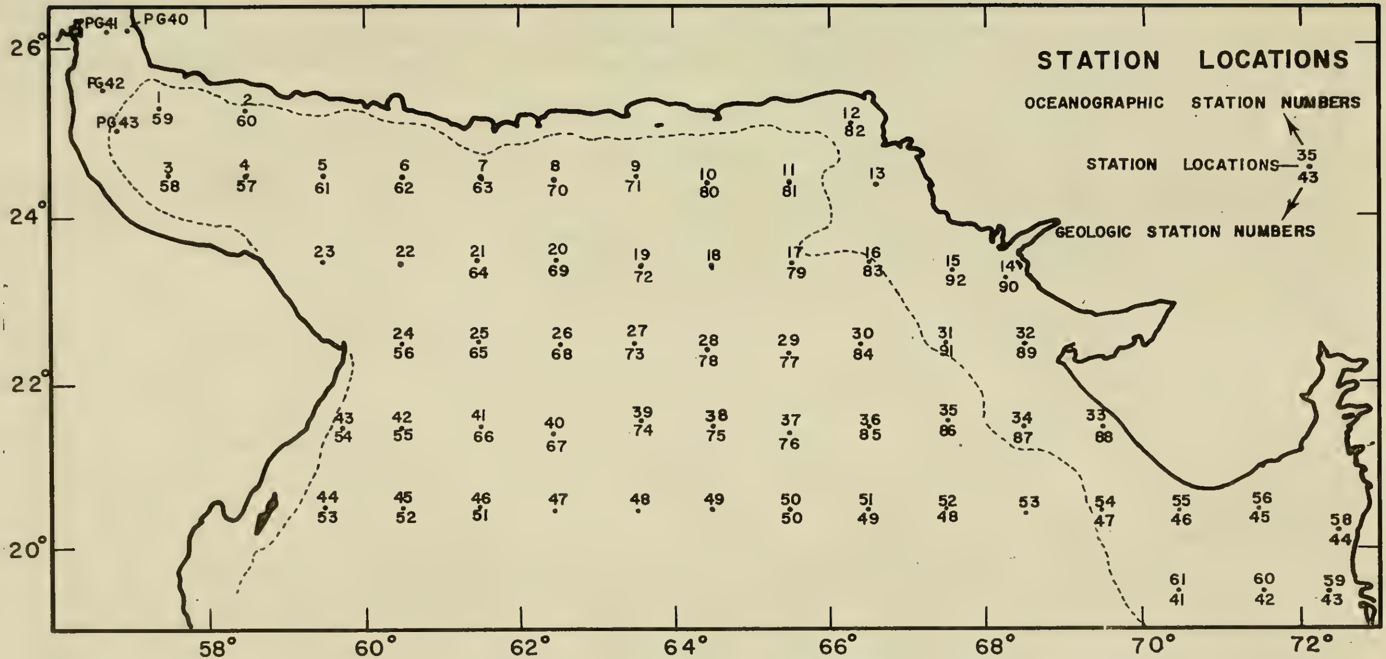

FIGURE 2. USS REQUISITE OCEANOGRAPHIC AND GEOLOGIC STATION LOCATIONS, NORTHERN ARABIAN SEA

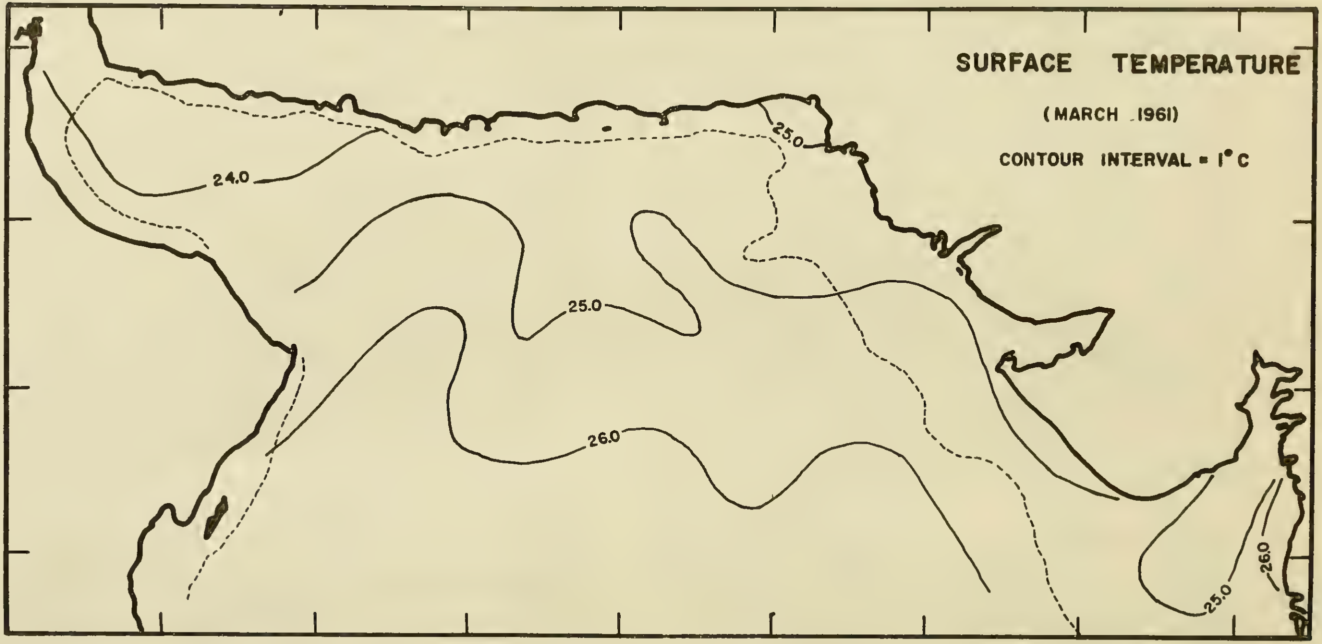

FIGURE 3. SURFACE WATER TEMPERATURE, NORTHERN ARABIAN SEA, MARCH 1961

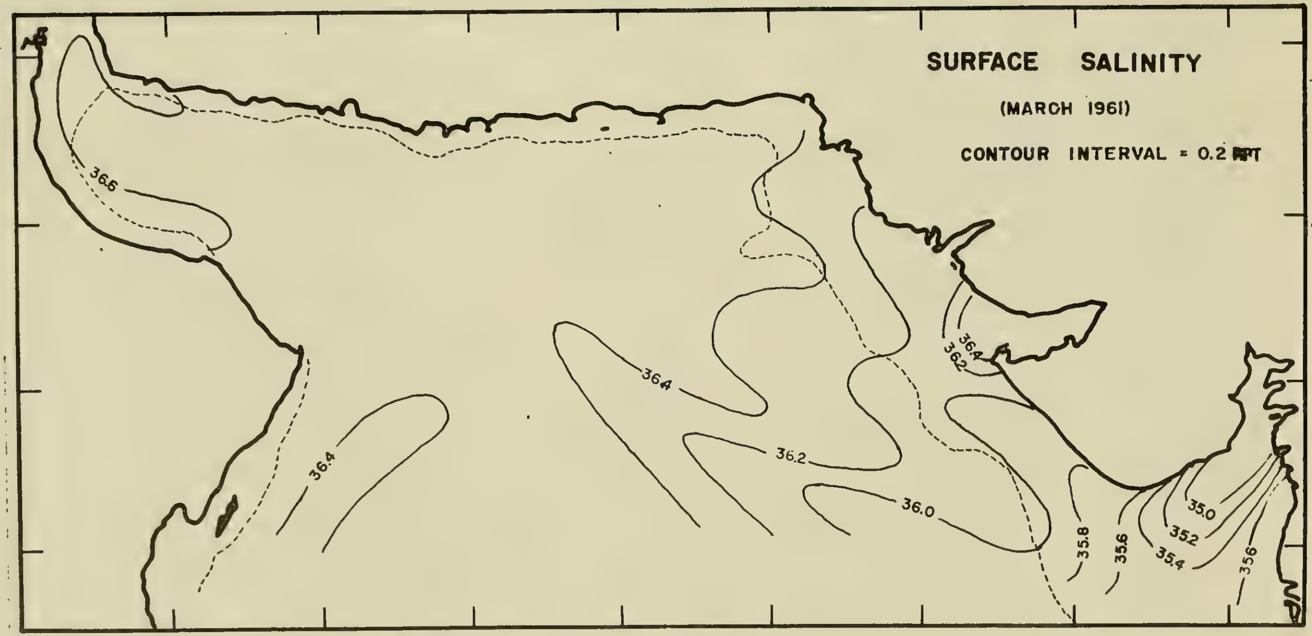

FIGURE 4. SURFACE SALINITY, NORTHERN ARABIAN SEA, MARCH 1961

Incoming water from the Gulf of Oman flows along the northeastern side of the strait. Judging from the surface isohalines for March, there is a limited amount of surface outflow from the Persian Gulf, and this occurs along both sides of the strait, extending well into the Gulf of Oman. The portion of the split flow that moves along the Arabian coast appears to be the larger, as would be expected from Emery's study.

In an attempt to trace Persian Gulf water entering the Arabian Sea, isohalines of the secondary salinity maximum were plotted (Fig. 5). This maximum occurs between 100 and 300 meters at all deep water stations in the study area. It appears to stabilize at about 300 meters upon reaching the Arabian Sea except in areas of bottom topographic highs where the maximum is found at depths between 200 and 300 meters. Isohalines again show a forking of Persian Gulf water near the Strait of Hormuz, and again the strongest outflow is along the Arabian coast. Persian Gulf water can be clearly traced to about the mouth of the Gulf of Oman. As previously stated, the secondary salinity maximum is affected by bottom topography, and in fact, the isohalines outline the northern basin, moving around high bottom features of the Murray Ridge.

Bottom salinity measurements range from 34.44‰ off the Arabian coast in deep water to 39.34‰ in the Strait of Hormuz (Fig. 6). In general, bottom water of the Gulf of Oman and Arabian Sea basins does not exceed 35.00‰. Surface and bottom salinities on the continental shelf are similar because of mixing. The exception is in the Strait of Hormuz where bottom salinities exceed those of the surface by significant amounts.

C. Bottom Topography

The bottom topography of the northern Arabian Sea, as constructed from H.O. Charts 1587, 1588, and 1589, is illustrated in Figure 1. The contour interval is 200 fathoms beginning at 100 fathoms. A clearer regional picture is presented in the excellent physiographic diagram of the Indian Ocean by Heezen and Tharp (1965 a, b).

The continental shelf is widest in the eastern portion of the area off India and eastern Pakistan. Typically, the shelf here is 60 nautical miles wide and breaks at depths ranging from 60 to 70 fathoms. Off the Gulf of Cambay it is over 150 miles wide. Only one significant submarine canyon has been located in this area, the "Swatch" near the mouth of the Indus. A report on the detailed sounding and delineation of this feature has been made by Hayter (1960). The canyon is well developed to a depth of about 650 fathoms and is developed to a lesser extent to depths of 900 fathoms.

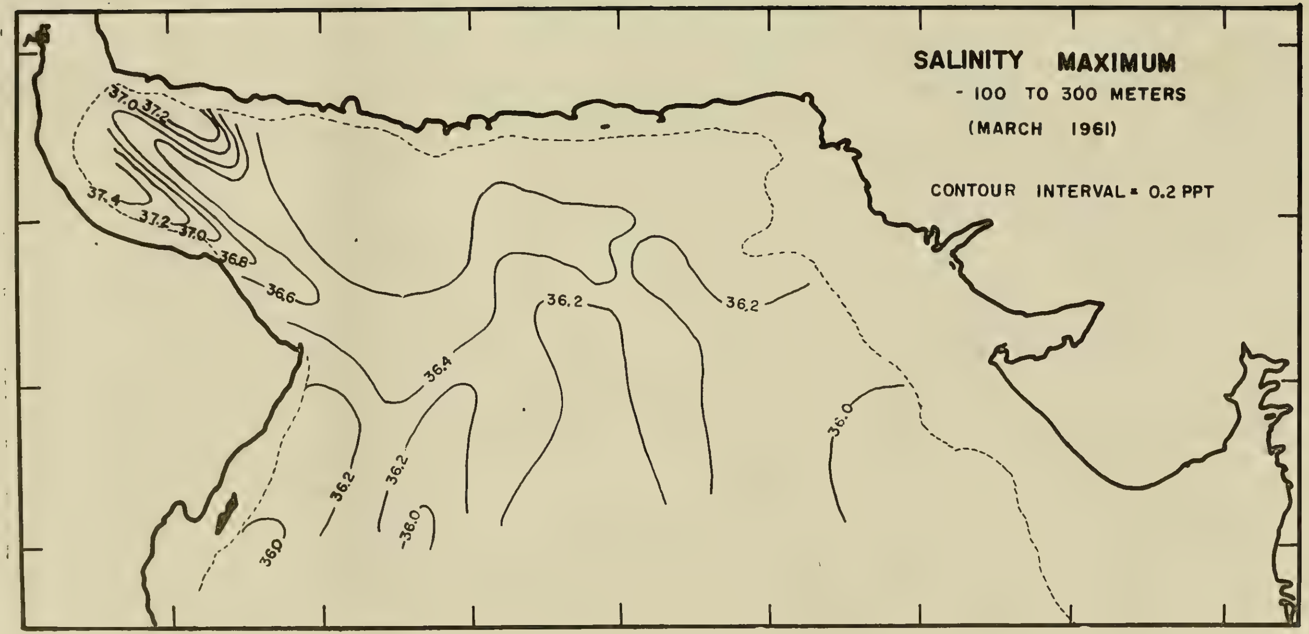

FIGURE 5. SALINITY MAXIMUM, NORTHERN ARABIAN SEA, MARCH 1961

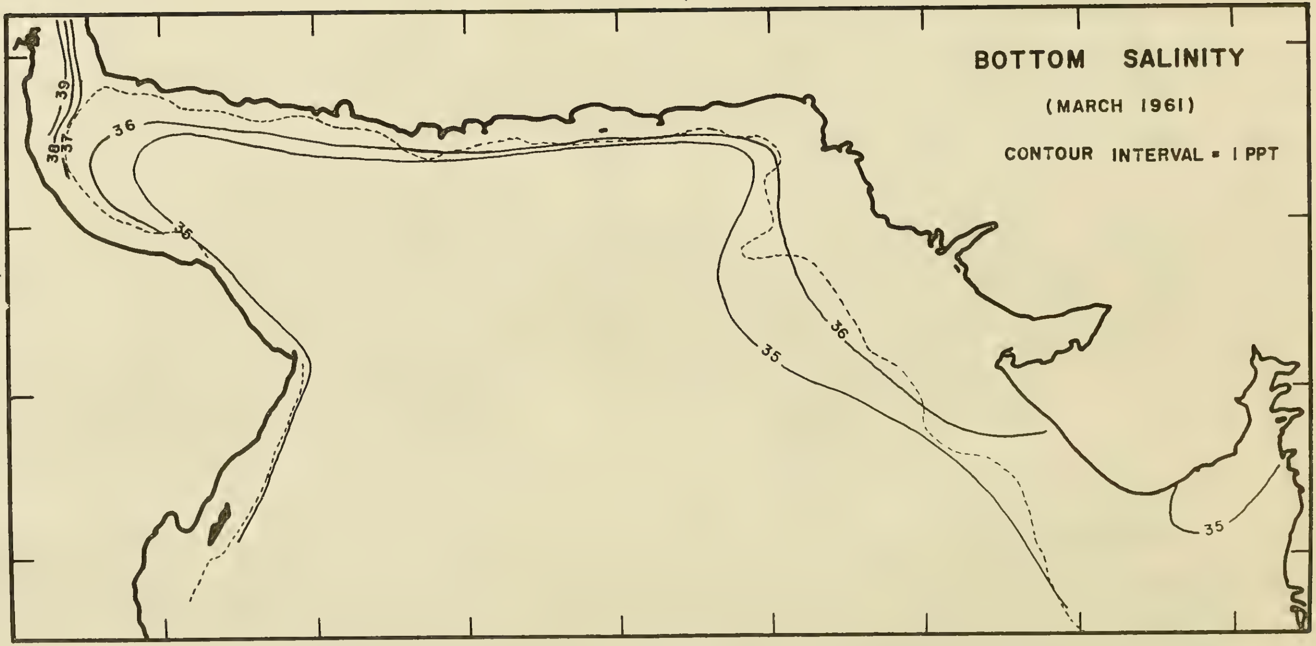

FIGURE 6. BOTTOM SALINITY, NORTHERN ARABIAN SEA, MARCH 1961

The continental margin along the northern boundary of the study area differs in several respects from the eastern margin. In general, the topography is more irregular. Off western Pakistan, the continental shelf is usually less than 20 miles wide and narrows to an average width of less than 10 miles off the Iranian coast. The shelf breaks at about 70 fathoms. The continental slope is often broken by a small marginal plateau or terrace at depths in the vicinity of 700 to 900 fathoms. The marginal plateau or terrace ranges in width from about 10 to 35 miles, and the degree or extent of development of this feature varies widely.

The shelf at the head of the Gulf of Oman is again quite broad. The depth of the Strait of Hormuz is about 40 fathoms. Between the head of the Gulf and Ra's Al Hadd, the continental shelf gradually narrows, reaching a minimum width of about a mile. At several points between Masqat and Ra's Al Hadd, the shelf is virtually absent. The continental slope here is quite steep. South of Ra's Al Hadd, the shelf again broadens, the topography becomes generally smoother, and a continental rise is well-developed.

The deep-sea floor of the northern Arabian Sea consists of two separate and reasonably distinct basins separated by the northeast-southwest trending Murray Ridge. The Arabian Sea Basin, which is located southeast of the Murray Ridge, is completely dominated by the Indus abyssal cone, a huge mass of sediment ultimately derived from the Indus River. In general it is a smooth feature broken only by a complex system of turbidity current distributaria. Heezen and Tharp (1964) note the presence of large natural levees on the Indus cone, constructed to heights of over 400 fathoms. The area northwest of the Murray Ridge comprises the Gulf of Oman Basin. Heezen and Tharp (1965 a, b) show two relatively small abyssal plains in this portion of the study area. The larger of the two is called the Oman Abyssal Plain and occupies the central floor of the Gulf. Another long narrow plain extends southward from the Oman plain between the continental rise and the Murray Ridge.

The Murray Ridge consists of a linear series of seamounts, scarps, and small basins which exhibit maximum reliefs ranging from 800 to 1,500 fathoms. Lineation of some of the scarps, particularly at the northern end of this feature, strongly suggest fault origin. The deepest spot in the study area is slightly over 2,300 fathoms and is a depression in the ridge line to the southwest. The tops of the various topographic highs making up the ridge (some of which are flat) range between 200 and 500 fathoms in depth.

V. SEDIMENTS

A. Grain Size

Figure 7 shows the distribution of the median grain size of northern Arabian Sea sediments. Extrapolation of the isopleths was aided by the recorded data and chart notations previously mentioned.

Along the western and northern margins of the study area, sand-size material is restricted to the inner shelf. To the east, a large area of sand is found on the inner and outer shelf near the mouth of the Indus and also along the outer Indian shelf. The sand-size material of the outer Indian shelf is largely carbonate whereas the wedge of sand at the mouth of the Indus is largely non-carbonate.

The median grain size of sediments on the continental slope, rise, and adjacent deep-sea floor is most commonly in the silt and clay range. In the samples observed the sand-size fraction was never more than 5% by weight of the total sample. Samples on the ridge are sometimes coarser than sediments of adjacent depths.

B. Calcium Carbonate Content

The areal distribution of the percent of calcium carbonate material in northern Arabian Sea sediments is shown in Figure 8. Except for a band of calcium carbonate-rich sediments (up to 86 percent) on the outer shelf, the Indian and eastern Pakistan shelf sediments are remarkably uniform in carbonate content, ranging from 14 to 19 percent. No figures are available for shelf sediments along the northern and western margins of the study area. In deeper water, the amount of calcium carbonate ranges from 17 to 51 percent, the lowest values being found in the Gulf of Oman Basin where concentrations of less than 20 percent carbonate are often present. In the Gulf of Oman, carbonate content ranges between 20 and 35 percent of the total sediment. In general, the amount of calcium carbonate in deep-sea sediments increases southward.

C. Organic Carbon Content

Figure 9 shows the percent organic carbon content of northern Arabian Sea sediments. The organic carbon content ranges from less than 1 to about 6 percent. In a gross way, the organic carbon content is related to grain size; fine sediments contain the most. Further than this, however, the Gulf of Oman shelf and slope sediments contain unusually high organic carbon values, and a large high is present on the slope off the Indus River Delta.

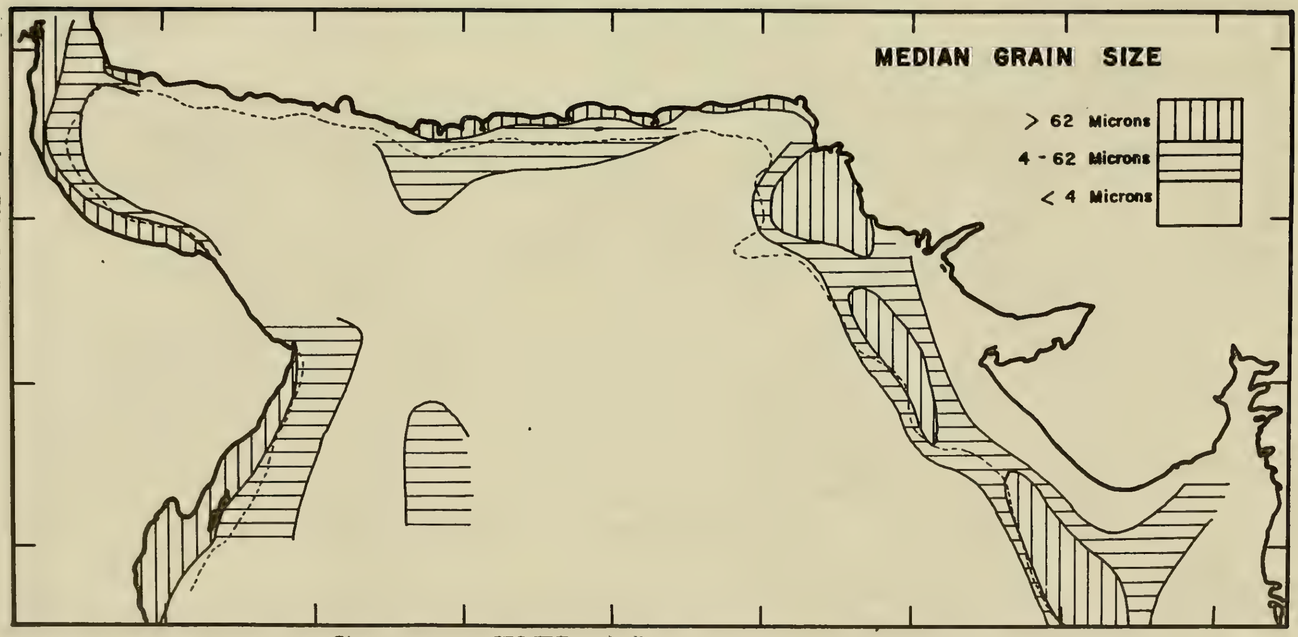

FIGURE 7. MEDIAN GRAIN SIZE, NORTHERN ARABIAN SEA SEDIMENTS

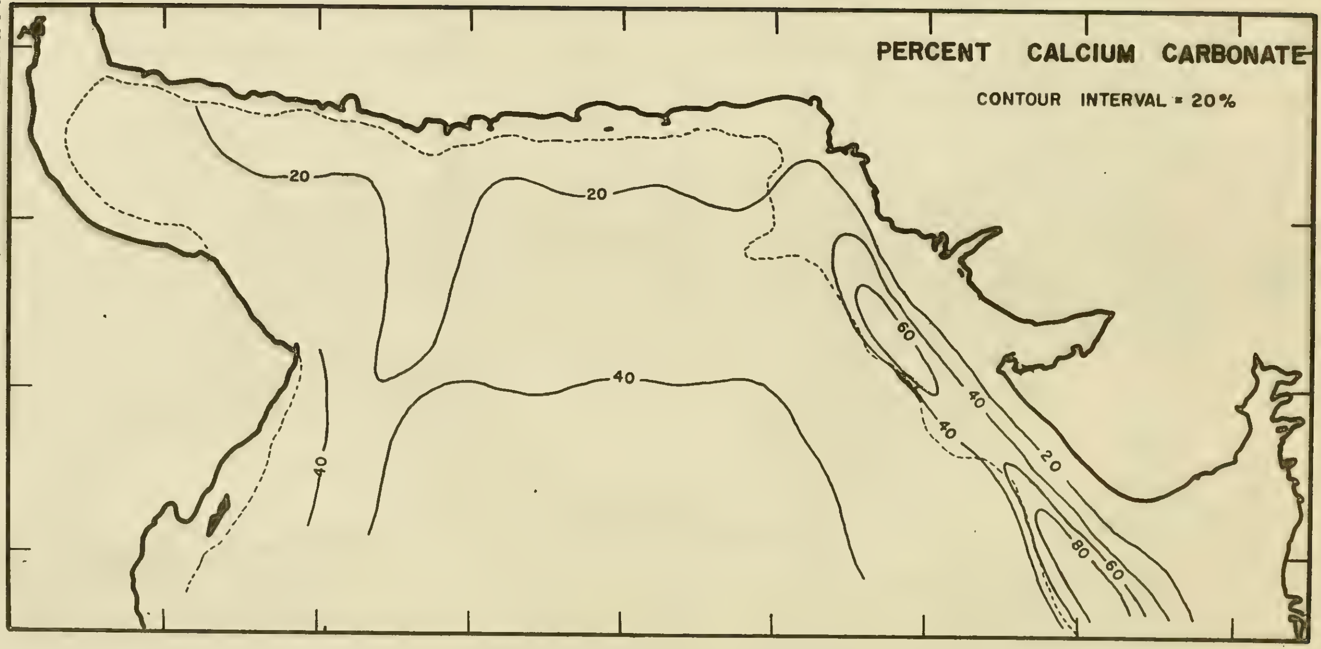

FIGURE 8. PERCENT CALCIUM CARBONATE, NORTHERN ARABIAN SEA SEDIMENTS

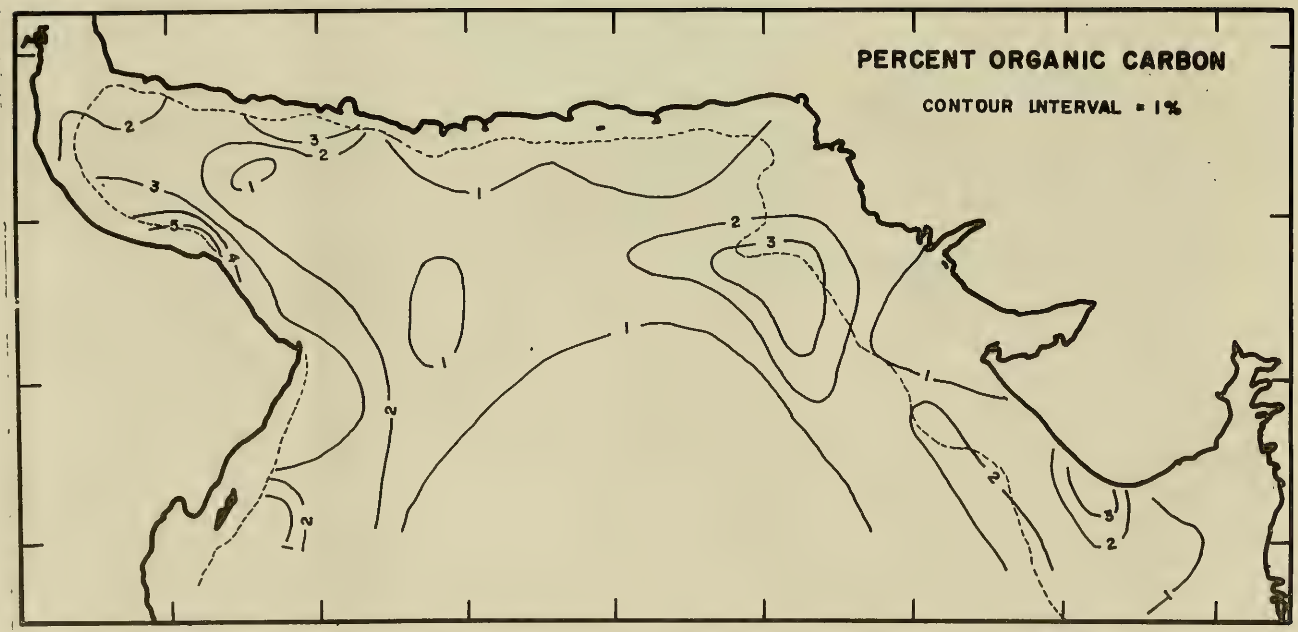

FIGURE 9. PERCENT ORGANIC CARBON CONTENT OF NORTHERN ARABIAN SEA SEDIMENTS

D. Carbonate Constituents

The most important sand-size or larger constituents of the carbonate fraction are foraminifera tests. Even in many of the continental shelf sediments, foraminifera dominate the carbonate fraction. Next in abundance are calcareous chunks and fragments which cannot be positively identified. Many appear to be fragments of foraminifera tests; others are probably windblown grains of limestone or dolomite. Mollusks are found in appreciable quantities only in continental shelf sediments. Radiolaria vary considerably in importance, ranging from 0 to 40 percent of the total coarse fraction. They are more abundant at depths below 1,000 fathoms, particularly in the southeast basin. Abundant calcareous pellets were noted on the Indian outer shelf in the aforementioned carbonate-rich band. These pellets are slightly phosphatic, and range in size from fine to medium sand and in color from salmon to dark blue gray. Some pellets strongly resemble phosphate grains.

E. Light Minerals

In the process of coarse fraction analysis, the quartz content of the material of sand size was determined. More accurately, the "quartz" fraction includes all light-colored non-carbonate minerals of which quartz is the most important constituent. Plotting these percentages (Fig. 10) reveals an interesting pattern of areal distribution. Northwest of the Murray Ridge, except for the inner Gulf of Oman, the deep-sea sediments contain much quartz (between 14 and 70 percent) in the coarse fraction. The coarse fractions of the Arabian Sea Basin sediments contain between 0 and 4 percent quartz; in fact, about one-half of the samples contained no sand-size quartz. It is significant that this quartz occurs on the ridge as well as in abyssal plain sediments.

Inner continental shelf sediments generally contain significant amounts of sand-size quartz; however, outer shelf sediments of the Indian and Pakistan coast contain mainly calcium carbonate and generally less than 5 percent quartz of this size.

Most samples contain an insufficient amount of light mineral, non-carbonate fraction of sand-size to justify quantitative mineral determinations. It was possible, however, to determine the quartz and feldspar content of the non-carbonate sand fraction of eight samples. The results of these determinations are shown in Table 1. Indian shelf samples Nos. 45 and 46 are from the Gulf of Cambay, and sample No. 89 was collected near the Gulf of Kutch (Fig. 2). The remaining five samples are deep-sea sediments from the southwestern corner of the study area near the Arabian coast. In every sample, quartz is more abundant than both of the feldspars combined, and plagioclase is more common than orthoclase. The two samples from the Gulf of Cambay exhibit unusually high plagioclase contents, 35 and 36 percent, as compared to values between 14 and 21 percent for the remaining samples. The orthoclase content is less variable and ranges between 5 and 12 percent for all samples.

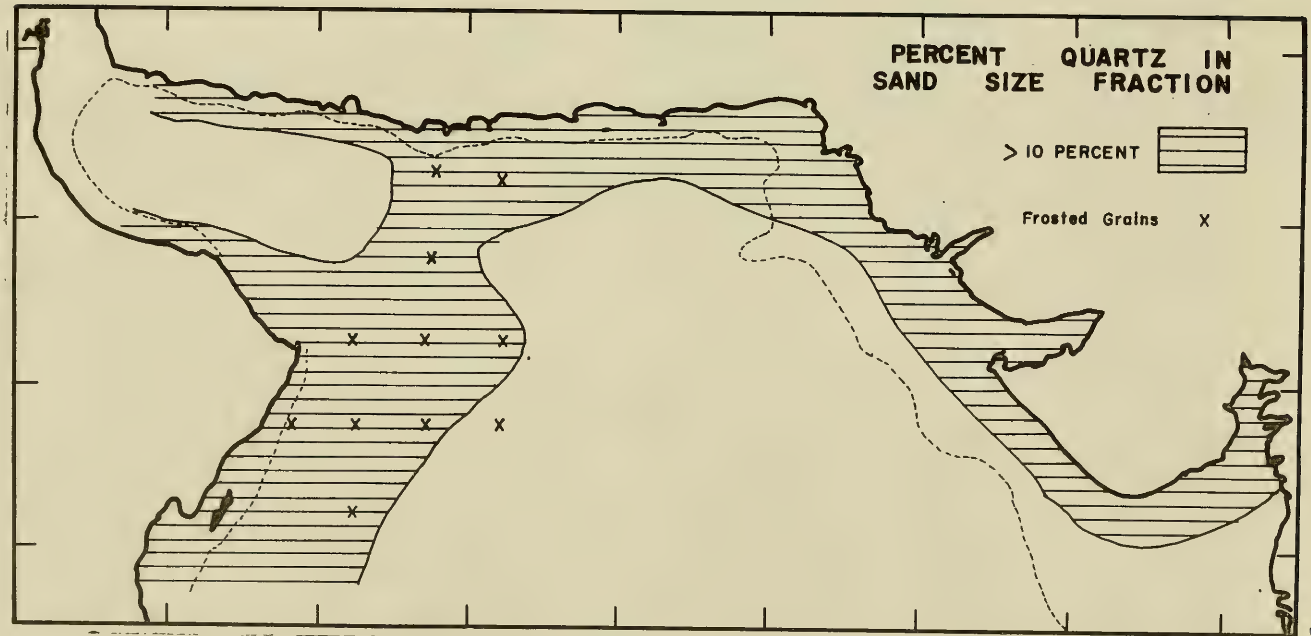

FIGURE 10. PERCENT QUARTZ IN SAND-SIZE FRACTION OF NORTHERN ARABIAN SEA SEDIMENTS

TABLE 1

Light and Heavy Mineralogy of Eight Northern Arabian Sea Samples
(percent by count)

Light Minerals	Sample Number 45	46	51	52	54	55	56	89
Quartz	47	48	62	62	62	61	68	72
Orthoclase	11	7	11	10	9	5	12	8
Plagioclase	35	36	21	20	19	16	17	14
Rock fragment	0	0	0	0	1	0	0	0
Other	7	9	6	8	9	18	3	6
	100							

Heavy Minerals	45	46	51	52	54	55	56	89
Opaques	33.5	29.5	3.5	23.0	13.5	19.5	12.0	7.0
Hornblende	2.0	9.5	1.5	18.5	16.0	12.5	13.0	6.5
Tremolite-Actinolite	5.5	10.5	7.5	17.5	27.0	10.0	17.5	8.5
Biotite	15.5	6.5	74.0	3.0	0.5	17.0	2.0	63.5
Muscovite	2.5	2.0	11.0	1.5	0	5.5	0	5.5
Olivine	4.5	6.0	0	15.5	7.5	6.5	9.0	0.5
Garnet	3.0	1.5	0.5	3.0	3.0	2.0	3.5	4.0
Epidote	23.0	21.5	0	3.0	15.0	19.0	21.0	0
Rutile	1.5	1.0	0.5	0	0.5	0	0.5	0
Sphene	1.0	6.5	1.5	5.5	5.0	2.0	5.5	1.0
Green Tourmaline	2.5	0.5	0	4.0	7.0	2.0	11.0	0
Brown Tourmaline	0	0.5	0	2.5	1.0	0	1.5	0
Staurolite	0	0	0	0	1.0	0	0	0
Zircon	4.5	1.5	0	0	1.0	2.5	0	1.5
Others	1.0	3.0	0	3.0	2.0	1.5	3.5	2.0
	100							

The sand-size quartz and feldspar grains in all samples in which they occur were checked for surface frosting and pitting effects. Sand grains from the relatively quartz-rich northwest basin are often strongly frosted, whereas frosting and pitting is much less common on quartz grains found to the east of the ridge in the southeast basin and on the Indian continental shelf. In Figure 10, samples in which frosted grains were observed are designated by X's.

F. Heavy Minerals

The heavy mineralogy of the same eight samples analyzed for light minerals is also shown in Table 1. Heavy mineral suites from the Arabian coast do not seem to differ fundamentally from those of the Indian shelf. All suites are unstable and are derived from both metamorphic and igneous rocks. Most of the mineral grains, including mica, are fresh in appearance.

Biotite shows more sample to sample variation than any other mineral, ranging from 0.5 to 74.0 percent. In two samples, Nos. 51 and 89, biotite is by far the most common heavy mineral (74.0 and 63.5 percent, respectively). In all samples, biotite is more abundant than muscovite, but it is possible that some muscovite is too light to be completely separated by treatment with tetrabromoethane. In sample No. 51, muscovite and biotite together make up to 85 percent of the heavy minerals. Along the Arabian coast, the biotite content apparently increases with distance from shore - probably a function of wind and/or water sorting processes on the flat mica grains.

Epidote is also variable in concentration, ranging from 0 to 23 percent. The average concentrations of the major heavy minerals of all eight northern Arabian Sea samples observed are: opaques, 17.7%; hornblende, 9.1%; tremolite-actinolite, 13.0%; biotite, 23.6%; muscovite, 3.5%; olivine, 6.2%; garnet, 2.6%; epidote, 12.8%; rutile, 1.0%; sphene, 3.5%; tourmaline, 4.1%; and zircon, 1.4%.

G. Clay Mineralogy

The general distribution of clay minerals from sediments of the study area is delineated in Figure 11. On the basis of the illite-chlorite-montmorillonite content, three reasonably distinct clay mineral provinces can be distinguished: (1) a montmorillonite-rich assemblage from sediments of the southeastern portion of the study area, (2) an illite-chlorite-minor montmorillonite assemblage of the central area; and (3) an illite-chlorite-no montmorillonite assemblage found in the Gulf of Oman Basin.

The montmorillonite province includes the continental shelf areas adjacent to the Saurashtra Peninsula and the Gulf of Cambay, as well as nearby deep water areas. Illite also is present in these sediments but in relatively small amounts.

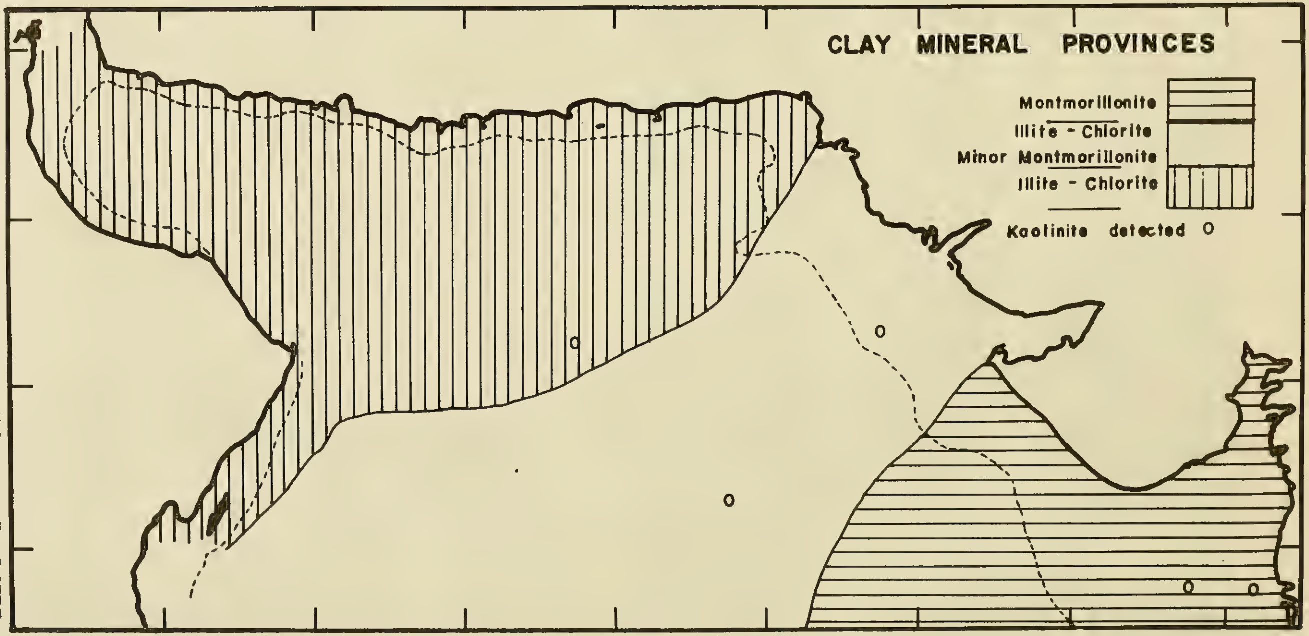

FIGURE 11. CLAY MINERAL PROVINCES OF NORTHERN ARABIAN SEA SEDIMENTS

The illite-chlorite-minor montmorillonite province is largely, but not entirely, restricted to the Arabian Sea Basin and nearby shelf areas of India and Pakistan to the northeast. These are probably largely Indus River sediments.

The illite-chlorite-no montmorillonite assemblage is generally restricted to the northwest basin, including the Gulf of Oman. Kaolinite was observed as a minor constituent in only five samples in the entire study region.

H. Carbonate Mineralogy

Quantitative analyses of the carbonate fraction mineralogy could be obtained on only four samples by the techniques used (Table 2). All of the sediments represented in Table 2 are from the carbonate-rich band of the outer Indian shelf. With one exception, mineral percentages of these samples are typical of continental shelf non-reef carbonates wherein the unstable minerals, aragonite and high Mg calcite, are dominant. The exception is sample No. 87 in which low Mg calcite makes up 51 percent of the carbonate fraction.

Semi-quantitative analysis of the carbonate fraction of the other Indian shelf samples indicates that low Mg calcite is usually more abundant than high Mg calcite and aragonite. Deep water sediments contain mostly low Mg calcite in the carbonate fraction.

Dolomite is present in variable amounts in almost all samples. The presence of dolomite was verified by both microscopic observation and x-ray diffraction analysis. In general, dolomite is more abundant in the Arabian Sea Basin and particularly on the Indian continental shelf. Dolomite is usually found in silt-size grades, but in eight samples (Nos. 45, 47, 50, 51, 63, 85, 89, and 92) grains were noted in the .062 to .125 mm. size fraction. The amount of dolomite was not quantitatively determined, but for the most part, it is present in only trace amounts and probably never makes up more than 5 or 10 percent of the carbonate fraction. Well-formed rhombs are rare and many dolomite grains are rounded, a fact which rules out an authigenic origin for this mineral.

VI. DISCUSSION

The northern Arabian Sea is an area of dominant terrigenous sedimentation, as might be expected because of the close proximity of land on three sides and the absence of barriers or sediment traps near the continental margins.

Within the deep-sea basin, the Murray Ridge has a strong influence on sedimentation. The most obvious effect of the ridge is its role in damming or containing the Indus cone, thus preventing deposition of Indus River materials in the Gulf of Oman Basin. This effect is demonstrated by the presence of the two abyssal plains

TABLE 2

Carbonate Mineralogy of Four Samples from the Indian Continental Shelf of the Northern Arabian Sea

	Sample No.			
MINERAL	41	47	87	91
Aragonite	67	82	33	54
High Mg Calcite	13	6	16	13
Low Mg Calcite	20	12	51	33
Dolomite	tr	tr	tr	tr
		100		

to the northwest of the ridge and by the change in sediment characteristics. The influence of bottom turbidity currents appears quite obvious from topographic considerations alone. The size, shape, and areal extent of the Indus cone, as well as the presence of apparent distributaries and natural levees, point to a primary turbidity current origin of this feature.

The close similarity of ridge and adjacent deep sediments is probable evidence of the importance of wind and ocean currents in sediment distribution. Dust is undoubtedly an important source of sediment over the entire northern Arabian Sea and particularly in the Gulf of Oman Basin. Sugden (1963) estimates that one-thirdof the sediments being deposited in the adjacent Persian Gulf are wind-derived. In the northern Arabian Sea area, the occurrence of wide-spread dust storms during the monsoons is well documented. The extreme aridity of the bordering land masses and the paucity of perennial streams, particularly around the Gulf of Oman Basin, increases the relative importance of aeolian material. Frosted quartz grains noted in ridge sediment are proof of the importance of wind in this area. Aeolian quartz is very likely derived from desert sands south of Ra's Al Hadd and from the Makran coast in the vicinity of Gwadar. Indirect evidence of the primary sediment source wind direction is the increase in biotite with distance from the Arabian shore, which may reflect wind sorting effects on the flat mica grains. Judging from available water current data, this is not likely to be an aqueous sorting effect.

The few coarse fraction heavy and light mineral suites that were quantitatively analyzed were highly unstable. This may reflect two factors: (1) pre-existing sediments are not major contributions to the coarse fraction and (2) the regional aridity inhibits extensive chemical weathering. Pre-existing sediments do contribute some coarse material to the northern Arabian Sea, notably the rounded dolomite and calcite grains and frosted quartz grains.

The clay mineral distribution strongly reflects source rocks. The high montmorillonite province in the southeastern corner of the study area is adjacent to and undoubtedly derived from the abundant basic rocks in the area (Deccan basalts). With increasing distance from these source rocks, the montmorillonite content of the marine sediment decreases.

The Indian continental shelf exhibits the often observed sediment distribution pattern of fine sediments near shore and coarser material on the central and outer shelves. Very likely the nearshore material is recent while the remainder of the shelf sediment is relict, having formed during lower sea level stands of the Pleistocene. The area of sand-size sediment off the mouth of the Indus River reflects a relatively high rate of sedimentation associated with the river. On the other hand, the relatively coarse patches of sediment on the outer shelf south of the present Indus River mouth are largely calcareous in composition and reflect very low rates of present day terrigenous sedimentation.

Since 1962, the research vessels of several countries (Germany, France, India, Pakistan, the U.S.S.R., and the United States) have been highly active in this particular region. Unfortunately, the results of these investigations are not yet available, but a wealth of additional information should soon be forthcoming.

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13. ABSTRACT

Topographically the northern Arabian Sea can be divided into two basins separated by the northeast-southwest trending Murray Submarine Ridge. The northwest Gulf of Oman Basin exhibits a more irregular topography, particularly along the continental margin, than does the southeast Arabian Sea Basin, which is dominated by the large sediment cone of the Indus River. Sediments with median grain sizes in the sand and silt range are largely restricted to the continental shelves and upper continental slopes. Basin sediments are calcareous (17 to 51 percent calcium carbonate) and become more so to the south. A band of relatively pure carbonate materials is present on the outer Indian shelf. Detrital grains of dolomite and calcite are present in small amounts in most samples, and frosted, pitted quartz grains are common in the coarse fraction of sediments from the northwest basin. The non-carbonate coarse fraction of the sediments contains much feldspar and an unstable heavy mineral suite of both metamorphic and igneous origin. Dust is an important source of sediments over the entire area. The dust contribution is relatively more important, and the overall rate of sedimentation is lowest in the Gulf of Oman Basin as compared to the Arabian Sea Basin.

14. KEY WORDS	LINK A		LINK B		LINK C	
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USS REQUISITE Oceanographic Survey						
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Contains a discussion of temperature, salinity, and bottom sediment data collected during USS REQUISITE oceanographic survey in northern Arabian Sea during February and March 1961.

The regional setting and the marine environment of the area are presented; field and laboratory sediment analyses procedures are explained; and figures showing the distribution of median grain size, clay mineral provinces, and percentages of calcium carbonate, organic carbon, and quartz in sand-size fraction are included.

Heavy mineralogy of several sediment samples are given in tables.

Data are published in TR-176.

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