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Distribution of Organic Carbon in Surface Sediments of the Continental Shelf off the Indus Delta of Pakistan

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ABSTRACT

Surface sediments collected from the continental shelf off the Indus delta, Pakistan, were studied to determine the organic carbon content. The results suggest that textural characteristics influence the distribution of the organic carbon content in the sediments of the Indus shelf. The surface sediments of the Indus shelf are predominantly silt, silty clay and clayey silty sand. Generally, inner shelf sediments contain 50-70% silt and ~20% clay. A belt of coarser sediments containing >50% sand occurs in the North West outer shelf region. The fine clay content in the sediments increases with depth, from 20% at the Indus river mouth to 60% at the continental slope region. Sediments of the Indus shelf contain a relatively high (~1.0%) content of organic carbon, and their distribution indicates textural influence. The coarse, silty sediments (50-70% silt) have a low organic carbon content of <1.0%. The fine-grained clayey sediments (20-40% clay) are characterized by relatively high (1-2%) organic carbon content. The highest organic carbon content of 2-3% occurs in fine-grained sediments of the outer shelf and the continental slope area, where 60% of the sediments are clayey sediments.

Keywords: Organic Carbon, Surface Sediments, Texture, Indus Continental Shelf

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1. INTRODUCTION

In continental shelf areas, sediments contain various amounts of organic carbon. The organic carbon content of these sediments is controlled by factors such as the primary productivity of the area (Calvert, 1987; Pederson and Calvert, 1990; Calvert *et al*., 1991), the bottom water dissolved oxygen (Demaison and Moore, 1980; Canfield, 1994), the sediment grain size (Premuzic *et al*., 1982; Mayer *et al*., 1985; Calvert, 1987; Ergin *et al*., 1993), the sedimentation rate (Betts and Holland, 1991) and sorption to mineral surfaces (Mayer, 1994; Keil *et al*., 1994a; Keil *et al*., 1994b). The relative importance of the different factors controlling organic matter accumulation is a controversial subject. Extensive studies on sedimentary organic matter have been undertaken to understand these factors (Hedges and Keil, 1995; Arthur *et al*., 1998; Hedges *et al*., 1999; Keil and Cowie, 1999; Vanderwiels *et al*., 2009; Zonneveld *et al*., 2010). Monsoonal upwelling and high primary productivity (Prell and Kutzbach, 1992; Qasim, 1977) characterize the study area in the northern Arabian Sea. Water columns at depths between 150 and 1,500 m have a broad, intense oxygen minimum zone (Wyrtki, 1971; Von Stackleberg, 1972). The occurrence of sediments rich in organic matter on the continental margins of Oman, Pakistan and India has been reported (Von stackelberg, 1972; Prell *et al*., 1992; Paropkari *et al*., 1992, 1993; Calvert *et al*., 1995). The organic carbon distribution in the surface sediments of the Arabian Sea and the controlling factors have been studied previously (Slater and Kropnick, 1984; Fontugne and Duplessy, 1986; Shimield *et al*., 1990; Calvert *et al*., 1995; Khan, 1999; Keil and Cowie, 1999; Cowie *et al*., 1999; Schulte *et al*., 2000; Cowie *et al*., 2009). Detailed studies of the biogeochemical characteristics of sediments undertaken by Cowie *et al*. (1999) confirmed the accumulation of rich sediments of organic matter, predominantly of marine origin.

Earlier studies showed that surface productivity and dissolved oxygen are not the only factors controlling organic carbon distribution in this area. Paropkari *et al*. (1992) suggested considering other factors such as the texture of sediments, sedimentation rates, shelf-slope morphology, clay mineralogy and hydrodynamic processes. In the deep sea area of the Arabian Sea, Khan (1999) showed the temporal changes in organic carbon accumulation are coupled both to paleo productivity and sedimentation rates. Luckage *et al*. (2012) investigated a sediment core of the Indus Canyon and suggested that the Indus River affects productivity and therefore organic matter preservation in the coastal northeastern Arabian Sea. Here, surface sediments collected in the early eighties are re-evaluated with respect to organic carbon. The sediment texture and the carbonate content are published elsewhere (Khan, 1993). Textural data (Khan, 1993) is incorporated in this study to understand the distribution of the organic carbon content of the Indus shelf sediment. In the present study, the spatial distribution of organic carbon in surface sediments from offshore of the Indus delta is investigated and discussed based on sediment characteristics only. This study supports the hypothesis that sediment texture influences the organic carbon distribution in the surface sediments of the continental shelf off the Indus delta in Pakistan.

1.1. Regional Geological Setting

The northeastern part of the Arabian Sea between the Owen-Murray Ridge and the Indian continental margin is a passive continental margin. This margin is characterized by a 100-km-wide continental shelf and a stable, gently inclined continental slope. The shelf off the Indus delta is relatively flat. The shelf break occurs at the

135 m isobath (Giosan *et al*., 2006). The most pronounced morphological feature of the Indus shelf is the Indus Canyon (Islam, 1959; Shepard and Dill, 1966; Giosan *et al*., 2006). The Indus canyon crosses the ~100-km-wide shelf and the continental slope and extends as a fan-valley or channel-levee system onto the Indus fan. The Indus Canyon has played a significant role in funneling sediment from the shelf edge to deeper areas towards the Indus submarine fan (Islam, 1959; Nair *et al*., 1982; Wells and Coleman, 1984). The Indus River has been the major fluvial source of Arabian Sea sediments since the Early Miocene (Kolla *et al*., 1981; Clift *et al*., 2001; Clift *et al*., 2004; Garzanti *et al*., 2005).

2. MATERIAL AND METHOD

2.1. Study Area

The Indus shelf extends between Cape Monz and Sir Creek along the eastern continental margin of Pakistan as shown in Fig. 1. Prior to upstream damming, the Indus River supplied $450x10^6$ t/year of sediments to the sea (Milliman *et al*., 1984; Milliman and Syvitski, 1992). The sedimentation rate on the Indus shelf is approximately 10 cm/year (Gibbs, 1981). Sediments on the modern Indus shelf are dominated by high silt and low carbonate content (Nair *et al*., 1982; Khan *et al*., 1993). The texture of the surface sediments divides the study area broadly into (i) near shore and inner shelf silt dominant sediments (~20-70 m) (ii) northwestern outer shelf zone and shelf break with sandy sediments (~70-130 m) and (iii) a deeper zone of continental slope featuring fine clayey sediments (Khan *et al*., 1993). Seasonal monsoonal upwelling results in high primary productivity and creates an oxygen minimum zone between depths of 200 to 1,500 m (Wyrtki, 1971; Von Stackleberg, 1972; Prell and Kutzbach, 1992).

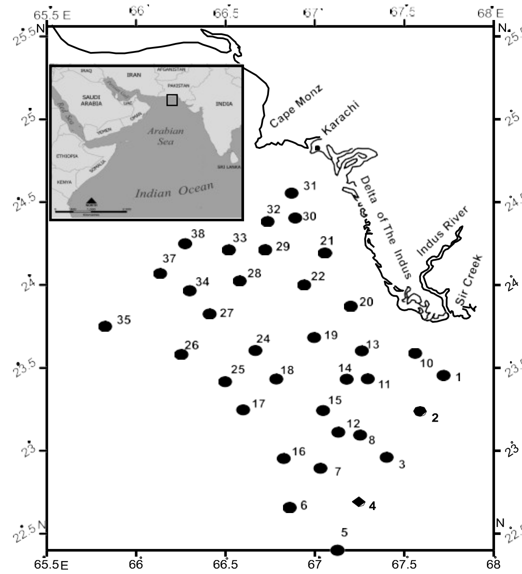

Fig.1. Location map of sediment sample stations

2.2. Sampling and Analytical Methods

2.2.1. Sampling marine sediments

Surface sediment samples from the continental shelf, off the Indus delta, Pakistan (lat. 22° 47′ 34″ N to 24° 43′ 95″ N and long. 65° 58′ 32″ E to 67° 54′ 0″ E) were collected using a Peterson grab. The location of the sediment samples is given in Fig. 1. At stations 9, 23, 36, 39 and 40, owing to failure of a grab sampler, sediments were not collected. The grab samples were transferred into plastic jars and transported onshore. The top 4-5 cm of the sediment sample was scraped with a spoon and stored in a jar for analysis.

2.2.2. Textural Analysis

Grain size analysis was performed using standard grain size analysis methods (Folk 1980). Sand-sized (2 mm to 63 µm), silt (63 to 4 µm) and clay (<4 µm) fractions were separated by wet sieving. A dispersant was added to 50 gm of the sample and wet sieved through a 63-µm sieve. The fraction retained on the sieve was transferred to a pre-weighed evaporating dish. After drying, we calculated the coarser fraction (>63 µm) in terms of sand content expressed as a percentage. Fine-sized particles (silt and clay) were characterized using their settling rates. Silt-sized material (<63 µm) was washed through the sieve and collected in a litter cylinder. The fine material (<63 µm) was concentrated by allowing a settling time and, after drying, was measured to determine the silt (<63 µm) percentage. The remaining suspended material in the liquid was measured to determine the clay content after drying the decanted water through evaporation.

2.2.3. Organic Carbon Analysis

Sediment samples were dried at 60-70° C. Bulk samples were ground to powder and homogenized. The powder sample was used for the analysis of organic carbon. A wet oxidation method using potassium dichromate and sulfuric acid as the oxidant was used (El-Wakeel and Riley, 1957). Gaudette *et al*. (1974) pointed out 100% yield can be achieved using this method.

3. RESULTS

3.1. Sediments

The surface sediments are gray, light gray, greenish gray, grayish green and brown in color. Sediment type and grain size characteristics of samples from the study area published earlier (Khan *et al*., 1993) are given in Table 1. In the present study, the textural data have been studied to determine the relationship with organic carbon content. The texture of the sediments included coarse to fine sand, silt clay and silty clay. The surface sediments of the Indus shelf are dominated by the silt size (<63 µm) fraction, which ranges between 40 and 80%. Texturally, sediments are classified as clayey silt (Folk, 1980), and the results are presented as a ternary diagram (Fig. 2). Skeletal remains and broken pieces of foraminiferal ooze, pelecypods and gastropod shells are the predominant biogenic constituents. Sediment texture and the percentage of sand, silt and clay at each station are shown in Fig. 3, and their spatial distribution pattern is shown in Fig. 4. Based on sediment texture, the Indus shelf can be classified into three distinct sedimentary zones; (i) the innermost shelf zone (20-70 m), dominated by clayey silt (Fig. 4a), (ii) the northwestern shelf zone (70-100 m), dominated by coarse grained clayey sand and sand, (Fig. 4b) and (iii) the outer shelf zone (>100 m) and inner continental slope area, which contains silty clay sediments (Fig. 4c). Sediments from the stations proximal to the contour of 100 m depth in the eastern part of the study area in Zone I are clayey silt (~40% clay content, Fig. 4c) with some shell fragments and abundant mica flakes. The silt content is highest (~70%) in near-shore stations (Fig. 4a). This amount decreases to 30% towards the outer shelf stations, where the sand content increases and represents Zone II. Sediments on the western side of the Indus Canyon in Zone II are coarser and form a sand belt between the 50-100 m isobaths (Fig. 4b). In Zone II, the shelf sediments change from silt to fine sand with abundant skeletal material. Sediments collected from station numbers 18,19, 24, 26, 27, 28, 34, 37 and 38 show high sand content ranging from 50 to 70% (Fig. 3). The highest sand content, (~60%),occurs in sediments from stations 18, 24, 27, 28, 34 and 37 (Fig. 3). Sediments of Zone III in and around the lower reaches of Indus canyon at the continental slope are fine silt and clay with less shell material (Fig. 4c). The clay size fraction is dominant in sediments from stations 5, 6, 7, 10, 12, 16, 22, 25, 31, 32, 33 and 35 and ranges between 40 and 70% (Fig. 3).

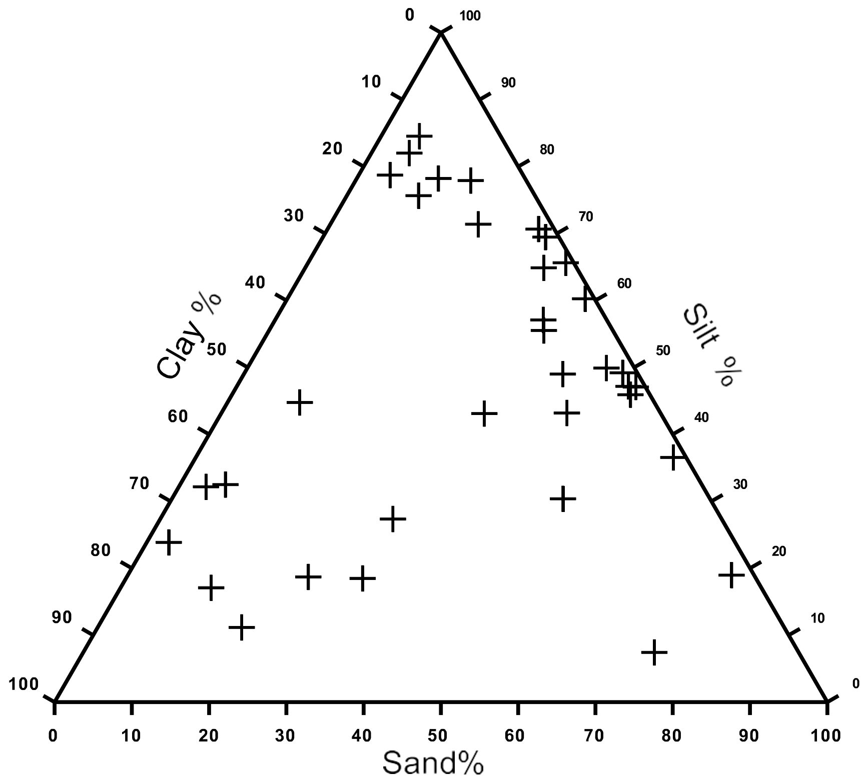

Fig. 2. Textural Characteristics of the Indus shelf sediments

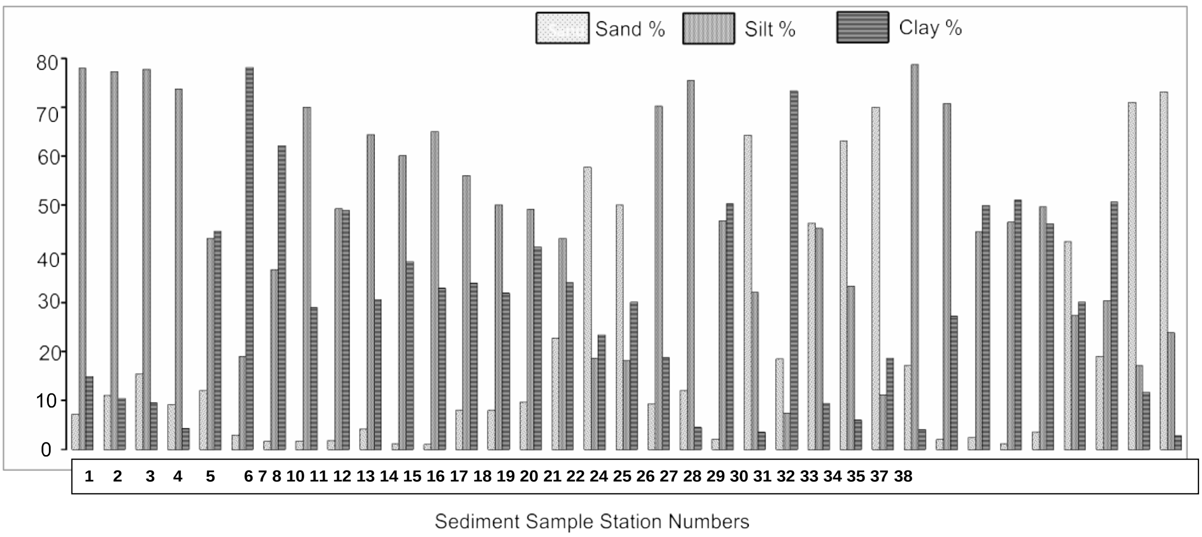

Fig. 3. Bar graph showing sand %, silt % and clay % in sediments of the Indus shelf

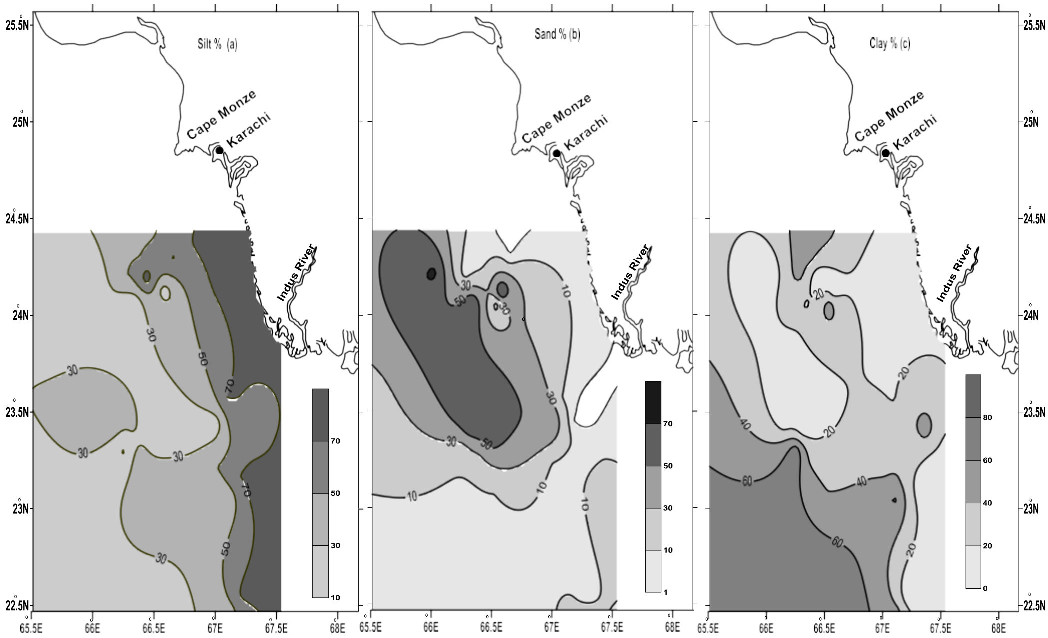

Fig. 4. Spatial distribution of sand, silt and clay % in the Indus shelf sediments

3.2. Organic Carbon Content

Sediment descriptions and organic carbon content are given in Table 1. The organic carbon content of the surface sediments from different stations is shown in a bar diagram (Fig. 5), and the surface distribution across the shelf is displayed in Fig. 6. The organic carbon content in the sediments from the continental shelf off the Indus delta ranges between 0.5% and 3.2%. Sediments present between the near shore zone and down to approximately 50 m water depth are low in organic carbon, which ranges from 0.5% to 1.0%. In general, organic carbon content in sediments increases from the inner shelf to the outer shelf regions. The sediments from the outer shelf stations (depth of ~100 m) exhibit comparatively high amounts of organic carbon (1-2%) compared to the inner shelf sediments, which exhibit an organic carbon content of 0.5% to 1.0%. Sediments from stations 5, 6, 7, 15, 16, 17, 25, 26, 34, 35, and 37 (Fig. 5) exhibit a high organic carbon content that ranges between >1.5% and 3.0%. The highest organic carbon content of ~2.50% occurs in sediments from stations 5, 6, 25, 26, 34, and 36 at depths between 100 and 200 m. Station 5 and 6 are located in the eastern part of the study area around the Indus canyon, whereas stations 25, 26, 34 and 36 are located westward and are clayey in nature.

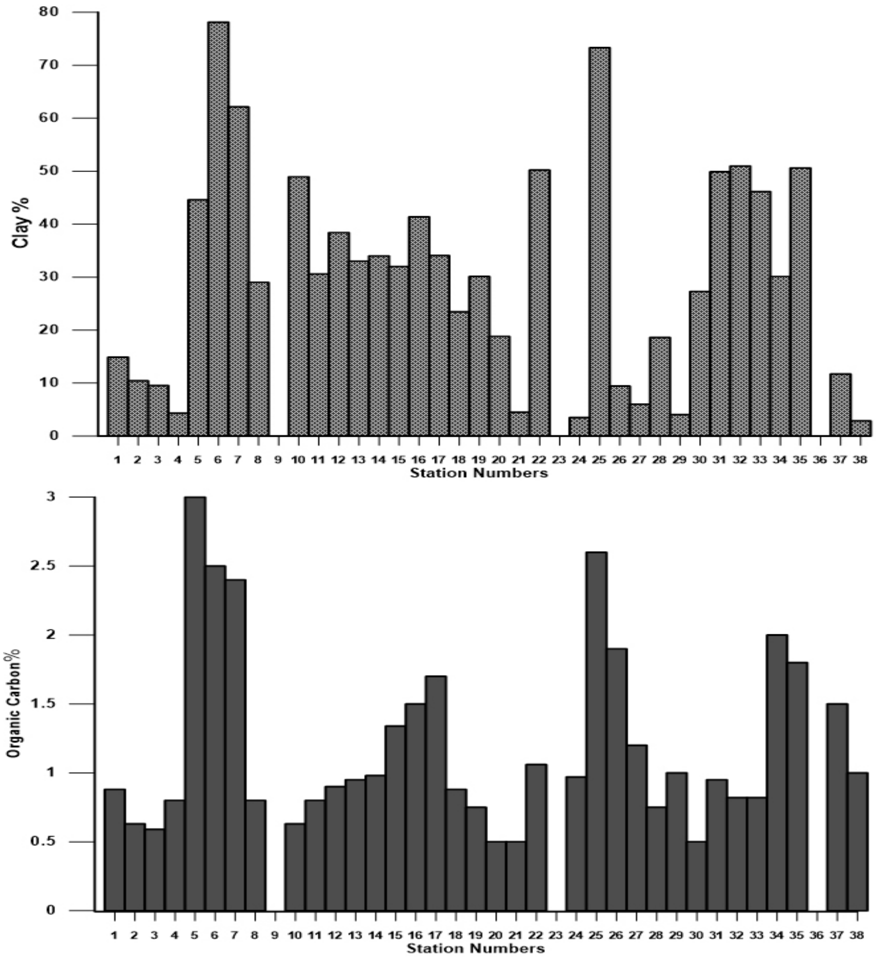

Fig. 5. Organic carbon % and clay % in sediments of the Indus shelf

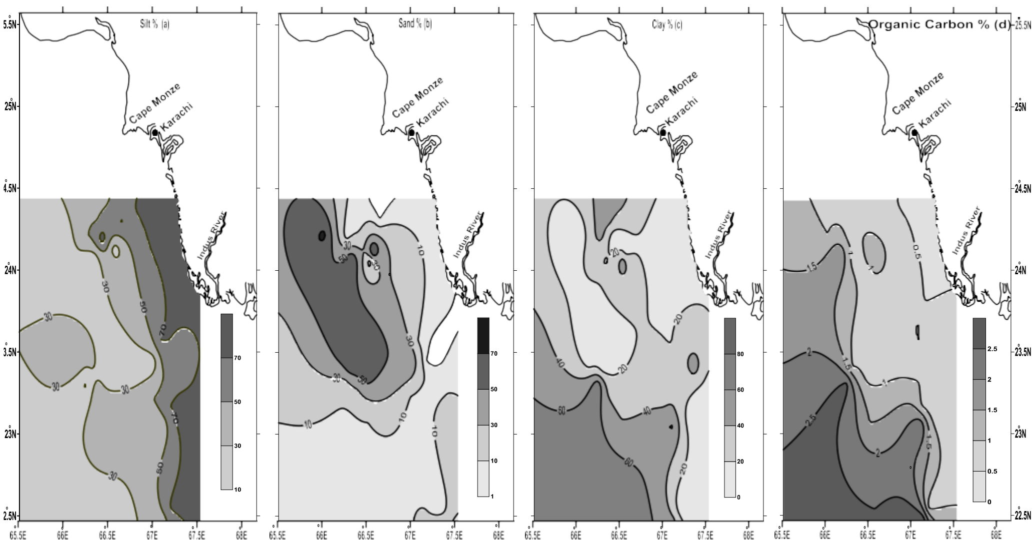

Fig. 6. Spatial distribution of sand, silt, clay and organic carbon % in the Indus shelf sediments

Table 1. Location, textural characteristics and organic carbon content of the Indus Shelf sediments

Station No	Depth(m)	Latitude (N)	Longitude (E)	Types of Sediments	Color	*Sand (%)	*Silt (%)	*Clay (%)	Organic Carbon %
1	13	23°.34′	67°.54′	Clay-silt	Dark grey	7.16	77.96	14.88	0.88
2	25	23°.23′	67°.43′	Clay-silt	Dark grey	11.05	77.26	10.42	0.63
3	26	23°.10′	67°.32′	Clay-silt	Dark grey	15.46	77.76	9.53	0.59
4	51	22°.56′	67°.22′	Clay-silt	Grey	9.16	73.74	4.3	0.8
5	113	22°.47′	67°.13′	Clay-silt	Grey	12.06	43.16	44.6	3
6	270	22°.54′	66°.58′	Silty-clay	Dark grey	2.88	19	78.12	2.5
7	112	23°.05′	67.11′	Silty-clay	Dark grey	1.65	36.78	62.13	2.4
8	49	23°.17′	67°.2′	Clay-silt	Dark grey	1.72	70	29	0.8
10	26	23°.41′	67°.37′	Clay-silt	Grey	1.85	49.23	48.92	0.63
11	295	23°.35′	67°.24′	Clay-silt	Light grey	4.2	64.4	30.6	0.8
12	712	23°.18′	67°.14′	Clay-silt	Brownish grey	1.2	60.1	38.4	0.9
13	25	23°.45′	67°.18′	Clay-silt	Dark grey	1	65	33	0.95
14	80	23°.33′	67°.19′	Clay-silt	Dark grey	8	56	34	0.98
15	96	23°.22′	67°.01′	Clay-silt	Brownish grey	8	50	32	1.34
16	137	23°.07′	66°.52′	Clay-silt	Brownish grey	9.72	49.18	41.38	1.5
17	126	23°.25′	66°.39′	Clay-silt	Brownish grey	22.8	43.13	34.06	1.7
18	90	23°.34′	66°.5′	Clay-sand	Brownish grey	57.7	18.7	23.44	0.88
19	59	23°.44′	67°.0′	Clay-sand	Brownish grey	50	18.21	30.11	0.75
20	23	23°.57′	67°.09′	Clay-silt	Greenish grey	9.3	70.2	18.8	0.5
21	30	24°.17′	67°.04′	Sandy-silt	Grey	12	75.5	4.5	0.5
22	22	24°.05′	66°.54′	Silty-clay	Grey	2.1	46.8	50.2	1.06
24	104	23°.42′	66°.32′	Silty-sand	Brownish grey	64.3	32.19	3.5	0.97
25	222	23°.30′	66°.25′	Sandy-clay	Greenish grey	18.5	7.4	73.3	2.6
26	216	23°.44′	66°.15′	Silty-sand	Grey	46.23	45.19	9.42	1.9
27	102	23°.55′	66°.24′	Silty-sand	Grey	63.11	33.34	6	1.2
28	80	24°.06′	66°.34′	Clay-sand	Greenish grey	70.04	11.19	18.6	0.75
29	79	24°.19′	66°.44′	Sandy-silt	Grey	17.18	78.7	4.02	1
30	30	24°.29′	66°.65′	Clay-silt	Brown	2	70.69	27.28	0.5
31	27	24°.44′	66°.48′	Silty-clay	Grey	2.4	44.48	49.88	0.95
32	60	24°.32′	66°.37′	Silty-clay	Grey	1.2	46.44	50.96	0.82
33	60	24°.21′	66°.28′	Silty-clay	Grey	3.57	49.61	46.14	0.82
34	93	24°.09′	66°.17′	Clay-sand	Grey	42.5	27.4	30.1	2
35	174	23°.58′	65°.51′	Silty-clay	Brownish grey	19	30.4	50.6	1.8
37	157	24°.12′	66°.58′	Silty-sand	Dark brown	71.04	17.1	11.7	1.5
38	87	24°.22′	66°.03′	Silty-sand	Brown	73.16	23.85	2.84	1

*Published data (Khan, 1993)

4. DISCUSSION

Textural characteristics (sand silt and clay percentages) and the organic carbon content of the Indus shelf sediments from the study area are shown in bar diagrams in Figs. 3 and **5.** The spatial distribution is also shown in Fig. 6. From the sand, silt, and clay percentages and their organic carbon content distribution, it is evident that sediments with a high clay percentage contain relatively high amounts of organic carbon. The correlation between the organic carbon content and the sand, silt, and clay percentages is shown in Fig. 7. These results suggest that organic carbon tends to be associated with fine sediments. Exceptions occurred only at station numbers 26 and 34 with ~2% organic carbon in coarser sediments (~50% sand). Station no. 26 is at a depth of 216 m, and station no. 34 is at 93 m. Increased organic carbon in the coarse sediments of these stations could be due to the bottom water oxygen and organic productivity, respectively.

It is known that particle size affects the organic carbon content of sediments (Trask, 1953; Brodovskiy, 1965; Van Andel, 1964; Hunt, 1996) and that clay contains more organic matter than coarse-grained sediments (Bush and Keller, 1981). In general, coarse sediments are expected to have lower organic matter content, either through less input or by winnowing of the organic content with fine-grained particles by erosive currents. Researchers (Listizen, 1972; Krissek and Scheidegger, 1983) have established a relationship between the clay content and the organic carbon content in marine sediments. Surface sediments and their organic carbon content determined in the present study (Fig. 6) reveal that bathymetry of the area and the sediment texture are the important controlling factors for the organic carbon content of sediments of the continental shelf off the Indus delta. The sediments are predominantly terrigenous. In the western part of the shelf, the sediments are coarser (silty sand) and show increased biogenic content largely composed of skeletal material of calcareous organisms (Khan, 1993). The spatial distribution (Fig. 6) of sand, silt, clay and organic carbon and the R^2 values (Fig. 7) obtained for clay and sand suggest that the organic carbon content in sediments has more affinity towards fine clayey sediments. Sediments at station no. 6, 7 and 25 that are rich in clay content (50-70%) also show the highest organic carbon content value, i.e., >2.5%. There are stations (e.g., 34, 35, 37, and 38) from Zone II of the sandy belt that have relatively high organic carbon content. In contrast, the clayey sediments from stations 10, 30, 31, 32, 33 show relatively less organic carbon. Textural characteristics of the Indus shelf sediments suggest that there is a relationship between the grain size and the water depth. Sediments from shallow stations (~50 m water depth) are predominantly silty (50-70% silt) with low organic carbon ranging between 0.5 and 1%. Deeper stations from the outer shelf and the slope feature clay as the predominant sediment, along with higher organic carbon content (>2.0%). The textural dependency of the organic carbon content is evident from the fact that the fine-grained sediments (<63 µm) have higher values (Fig. 5) compared to the coarser sediments. The relationship of a high concentration of organic carbon with high clay content is consistent with other published data (Van Andel, 1964; Reinson, 1975). Stackelberg (1972) and Paropkari *et al.* (1987) have studied the distribution of organic carbon in the sediments of the western shelf of India. According to Paropkari *et al.* (1987) the difference in the organic carbon observed between the inner shelf and outer shelf sediments could be attributed to the differences in the grain size of sediments, sedimentation rates, and activity of benthic population and to the role of oxygenated water. The high organic carbon content associated with fine-grained sediments of the slope region could be ascribed to the influence of the oxygen minimum layer on the sea floor. Oxygen poor water (<0.5 ml/l) extends from 200 m to 1,500 m in the Arabian Sea (Slater and Kroopnick, 1984). This oxygen minimum layer prevents the destruction of organic carbon through oxidation. High values of organic carbon in clayey sediments found on the outer Indus shelf and slope region could be a result of both decreased bottom water oxygen and sediment texture.

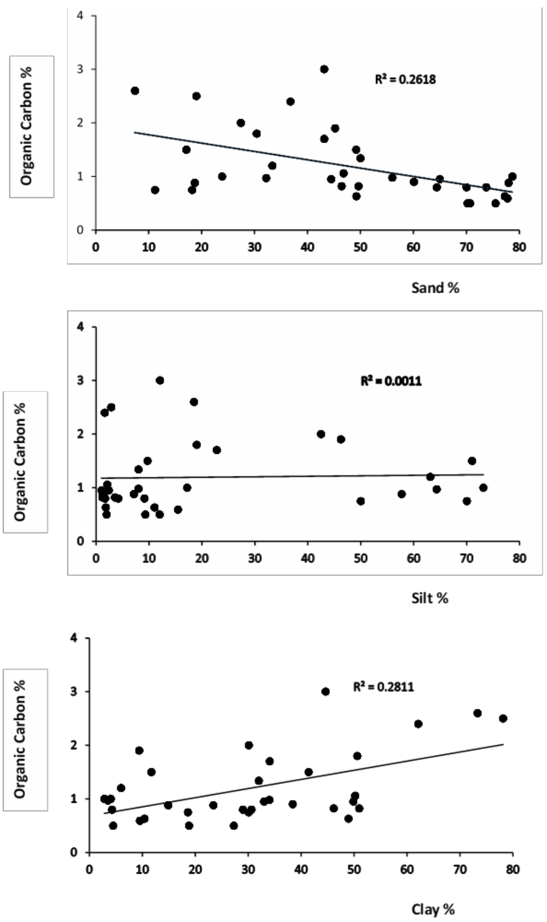

Fig. 7. Correlation between sand, silt, clay and organic carbon %

5. CONCLUSION

The organic carbon content of the Indus shelf sediments suggests a close relationship with the sediment texture. The textural dependence of the organic carbon content is evident from the fact that the fine-grained sediments (<63 µm) tend to have higher values when compared to the coarse sediments. The organic carbon content in surface sediments of the outer shelf and the slope region is higher, and clay is the predominant sediment type. This study reveals the role of sediment texture in the distribution of the organic carbon content in sediments deposited off the Indus shelf of Pakistan. In this study, the observed spatial distribution pattern of the clay percentage in sediments suggests that the fine sediments are funneling through the Indus canyon and depositing deeper offshore. The organic carbon content distribution also indicates a similar process. The presence of fine, clayey sediments with a high OC content from the eastern stations in the canyon vicinity suggests that fine sediments may be acting as carriers and depositing.

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