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Influence of the prevailing current regime on sedimentation in the Alboran Sea*

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Abstract—The extent to which the prevailing current regime controls the nature of surface sediments in the Alboran Sea is suggested. Hydrographic data and surface sediments collected during the Polymède II cruise of the R.V. *Jean Charcot* in 1972 strongly suggest that the sediment distribution is controlled by the current system resulting from the difference in density between the Intermediate and Deep Mediterranean Water and Atlantic Surface Water. Clay, mainly montmorillonite, and planktonic Foraminifera are carried into the Mediterranean by east-flowing Atlantic Surface Water. As the suspended particles settle through the water column, they are redistributed by the westward-flowing deep currents and accumulate on the floor of the sea, where they constitute a clearly recognizable fraction of the surface sediments.

INTRODUCTION

SEVERAL authors have recently made detailed studies concerning the stratigraphy and processes of sedimentation of Alboran Sea Quaternary deposits (VERGNAUD-GRAZZINI and BARTOLINI, 1970; BARTOLINI and GEHIN, 1970; BARTOLINI, GEHIN and STANLEY, 1972; HORN, EWING and EWING, 1972; DIESTER-HAASS, 1973). None of these investigators has found evidence of widespread activity of high-velocity turbidity currents, and according to STANLEY, GEHIN and BARTOLINI (1970), hemipelagic mud, predominantly silty clay, accounts for at least 95% of the Holocene fill. BARTOLINI and GEHIN (1970) suggest that this deposit accumulated under one or more of three different regimes: 'normal' oceanic circulation, distal turbidity current flows, and low-velocity gravity-assisted bottom currents of the type considered by EWING and THORNDIKE (1965).

A principal purpose of this paper is to define more closely to what extent the accumulation of surface sediments in the Alboran Sea is controlled by the prevailing pattern of circulation.

The data on sediment samples derive from the Polymède II cruise of the R.V. *Jean Charcot*. Hydrographic and surface current data were acquired earlier by one of us (LANOIX, 1972). Samples were collected using a Reineck (box) corer that allows approximately 30 cm of the sedimentary column to be sampled without disturbance or loss. It was therefore possible to isolate with some confidence approximately the uppermost 1 cm of sediment (Table 1; Figs. 1 and 2).

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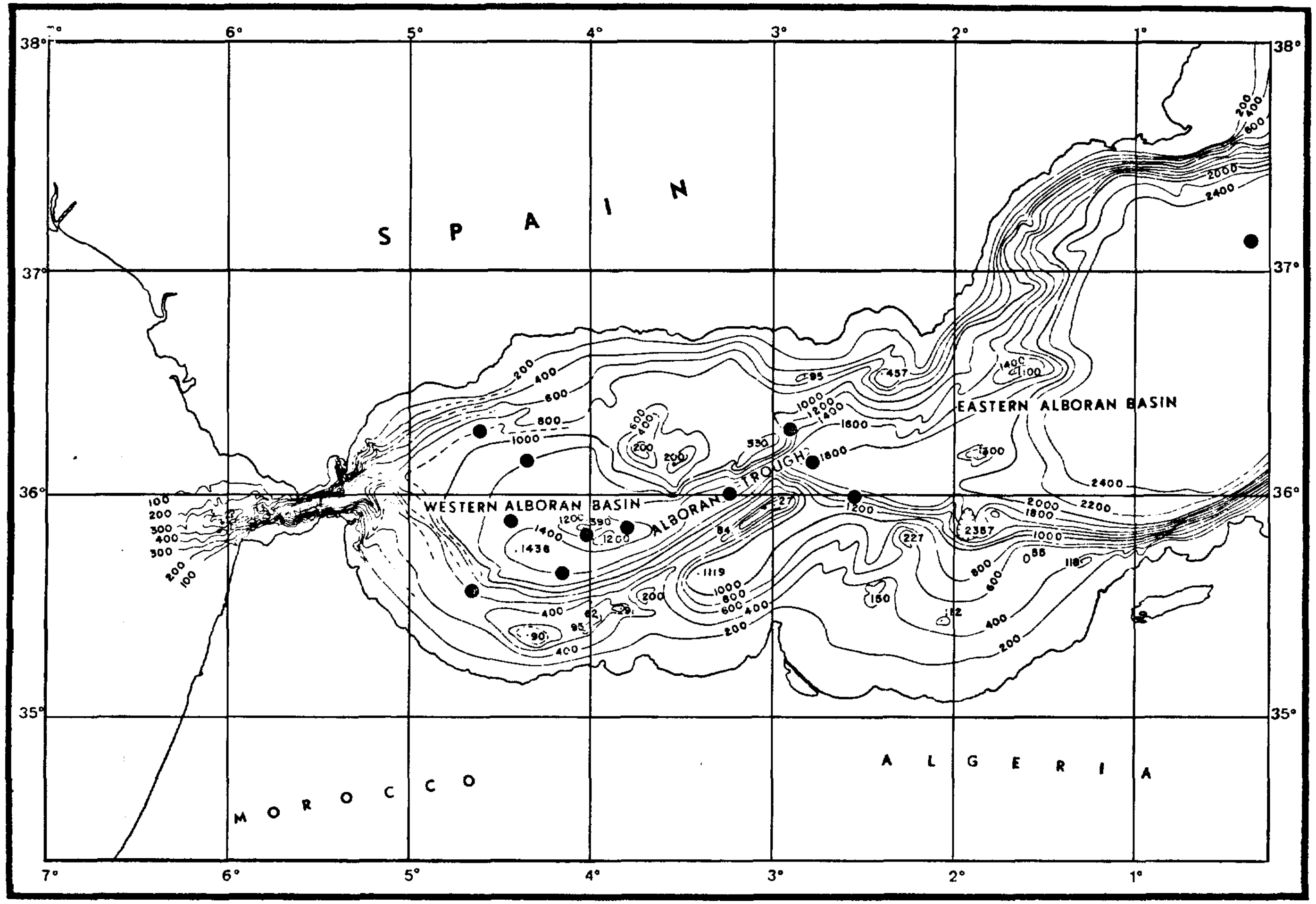

Fig. 1. Bathymetric map and core locations (soundings in corrected meters).

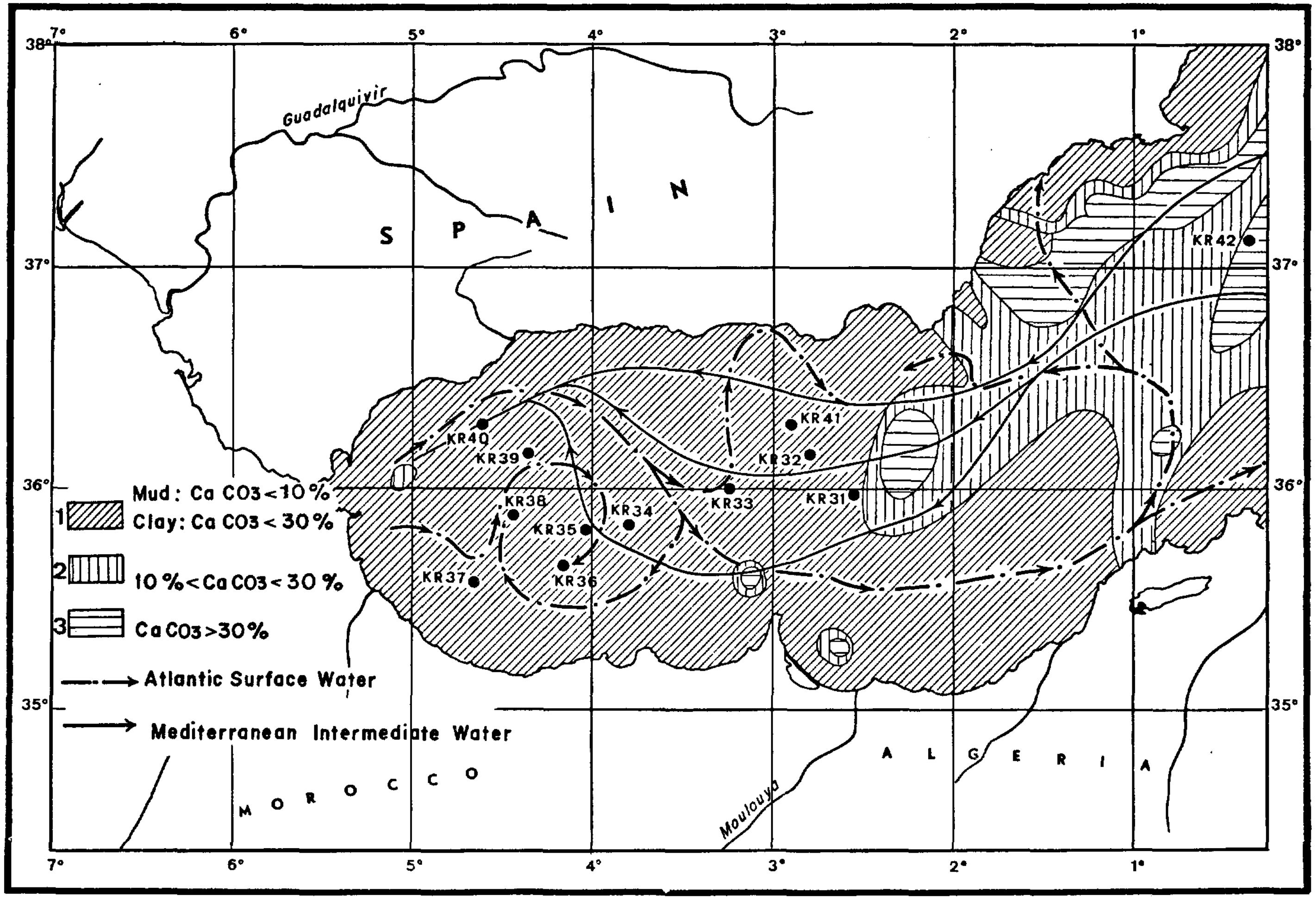

Fig. 2. Sedimentological map modified from FRAZER, ARRHENIUS, HANOR and HAWKINS (1970), showing the general current directions (dashed line, Atlantic Surface Water; continuous line, Mediterranean Intermediate Water). Core locations shown by solid circles. 1. Clay: median diameter less than 4 µm, less than 30% skeletal remains of microorganisms and $CaCO_3 < 30\%$, or mud: fine-grained terrigenous deposits, $CaCO_3 < 10\%$. 2. Calcareous mud ($10\% < CaCO_3 < 30\%$). 3. Calcareous ooze ($CaCO_3 > 30\%$).

Table 1. Analytical results.

	Position φ G	Depth (m)	Location	% Coarse fraction (> 63 μm)	% Water content	% Carbonate content	Mineralogy: Quartz	Felds.	Calcite	Arago-nite	Clay	Clay fraction: I	Esc	M	Ch	K	Q	F
KR 42	37°07′7N 00°17′9E	2640	SE Carthagene	21	55	44	+++		++++	++		5·5	0·5	1	1·5	1·5	+	+
KR 31	35°58′0N 02°30′8W	1234	SE Alboran	5	61	22	+++		++++	+++	++++	5	1	1·5	2·5		+	+
KR 32	36°09′5N 02°44′9W	1800	E Alboran Trough	7	62	25	+++		++++	++	+++	4·5	1	2	2·5		+	+
KR 41	36°19′2N 02°52′5W	1247	NE Alboran Trough	6	60	24	+++	+	++++	+++	++++	4·5	1	2	2·5		+	+
KR 33	36°02′4N 03°12′7W	1565	Alboran Trough	7	60	24	+++		++++	+++	++++	4·5	1	2	2·5		+	+
KR 34	35°51′5N 03°48′5W	1354	W Alboran Trough	4	59	18	+++		++++	+++	++++	4·5	1	2·5	1	1	+	+
KR 35	35°48′7N 03°58′0W	755	W Alboran Trough	22	55	29	++++		++++	+		4·5	1	2·5	1	1	+	+
KR 36	35°40′9N 04°12′8W	1481	South of W Alboran Basin	3	57	14	++++		++++	++++	++++	4·5	1	2·5	1	1	+	+
KR 37	35°33′3N 04°41′9W	557	SE of W Alboran Basin	4	62	18	+++		++++	++++	++++	4·5	1	2	2·5		+	+
KR 38	35°54′0N 04°26′2W	350	Centre W Alboran Basin	5	56	19	+++		++++	++++	++++	4	1	3	1	1	+	?
KR 39	36°10′5N 04°19′6W	1116	NW Alboran Basin	3	61	16	+++		++++	+++	++++	4·5	1	2·5	1	1	+	+
KR 40	36°18′5N 04°33′7W	768	NW Alboran Basin	2	62	16	+++		++++	++++	++++	4·5	1	2·5	1	1	+	+

I: illite; Esc: expanding stratified complex; M: montmorillonite; Ch: chlorite; K: kaolinite; Q: quartz; F: feldspar.

MINERALOGY

FRAZER, ARRHENIUS, HANOR and HAWKINS (1970) have compiled a map of the surface sediments of the Mediterranean (Fig. 2) that shows that almost all the Western Alboran Basin and the southern part of the Eastern Alboran Basin are covered by clayey or muddy terrigenous deposits. Calcareous mud (10–30% $CaCO_3$) or calcareous ooze (> 30% $CaCO_3$) covers the northern and eastern parts of the eastern basin.

The upper 1 cm of our samples are light brown and fine-grained with less than about 7% coarse material (> 63 μm). The coarse fractions consist almost entirely of planktonic Foraminifera. Pteropods, which are reported to be common in surface sediments of the Western Mediterranean (FROGET and PASTOURET, 1972) were found only in samples KR 42 and KR 35, both of which also contain a higher proportion of foraminiferal tests than the other samples.

The carbonate content of the sediments in the Western Alboran Basin, measured using a Bernard calcimeter, ranges between 15 and 26%, with the exception of sample KR 35, which contains 22%, at least part of which is in the form of reworked Pleistocene Foraminifera. In the Eastern Alboran Basin, the carbonate content ranges between 20 and 25%. Further east, in the Southern Balearic Basin, it reaches 44%. These data are in good agreement with those of FRAZER, ARRHENIUS, HANOR and HAWKINS (1970).

Smear slides and X-ray diffraction patterns of total sediment show that quartz and aragonite are notably present although in small quantities, in addition to calcite and the clays.

The X-ray diffraction patterns of the clay fractions (< 2 μm) were made using standard procedures and oriented samples treated with weak hydrochloric acid (N/10) to remove carbonate.

Illite, ubiquitous in the Western Mediterranean (CHAMLEY, 1971), is the dominant phase making up 40–50% of the total clay fraction. The second most abundant component is montmorillonite and associated irregularly interstratified phases: mainly chlorite (14 Å)—montmorillonite (14 Å) and illite (10 Å)—chlorite (14 Å). Small quantities of quartz are present in all the clay fractions. This clay association, which appears to be characteristic of Holocene sediments in the Alboran Sea, has been reported in the same region by NESTEROFF, SABATIER and HEEZEN (1963), BISCAYE (1965), BARTOLINI, GEHIN and STANLEY (1972) and VALETTE (1972).

The absence of any abrupt change in the clay mineralogy associated with the Alboran Trough is what would be expected if local influences had been rather unimportant. Our data permit additional observations. There is, in fact, a remarkably uniform trend in the relative amount of montmorillonite, which increases gradually from east to west, from about 10% of the total clay content in KR 42 (0°17′9E) to about 30% in KR 38 (4°26′2W). This increase does not seem to be related to variations in lateral input from the continent; near-coast samples, such as KR 37, show only a slight increase, whereas sample KR 38 from the middle of the western basin contains the largest amount of montmorillonite in any of our samples. Rather than an homogeneous mineralogical background of sediment type, it appears that the montmorillonite gradient reflects a net pattern of sedimentation unrelated to downslope transport.

FORAMINIFERA

The faunal content of the twelve samples was evaluated by counting 400–600 specimens larger than 160 μm each. Benthic and pelagic species were separately enumerated. The most abundant planktonic species (more than 1 %) are the following (Fig. 3):

warm water species: *Globigerinella aequilateralis* (Brady), *Globigerinoides quadrilobatus quadrilobatus* (d'Orbigny), *Globigerinoides quadrilobatus sacculifer* (Brady), *Globigerinoider ruber* var. *rosea* and var. *alba* (d'Orbigny), *Orbulina universa* d'Orbigny and *Globorotalia truncatulinoides* (d'Orbigny) with sinistral coiling;

transition species: *Globorotalia inflata* d'Orbigny;

cold water species: *Globigerina bulloides* d'Orbigny and *Globigerina pachyderma* (Ehrenberg) with dextral coiling.

Globorotalia inflata and *Globigerina bulloides* are the dominant species in Alboran sediments. Their frequency ranges from 35 to 50% and 30 to 45%.

The following species are relatively rare in many samples (less than 1 %): *Globorotalia hirsuta* (d'Orbigny), *Globorotalia scitula* (Brady), *Globigerinoides tenellus* Parker, *Globigerina falconensis* Blow, *Globigerina quinqueloba* Natland, *Globigerina rubescens* Hofker, *Globigerina digitata* Brady and *Globigerinita glutinata* (Egger).

Benthic species constitute only a small part of the foraminiferal population. Their frequency decreases with sample depth from 25% for KR 37 (557 m) to only 1% in KR 42 (2640 m). The most abundant species are *Uvigerina mediterranensis* Hofker, *Nonion barleeanum* (Williamson), *Hyalinea balthica* (Schroeter) and *Rhabdammina*

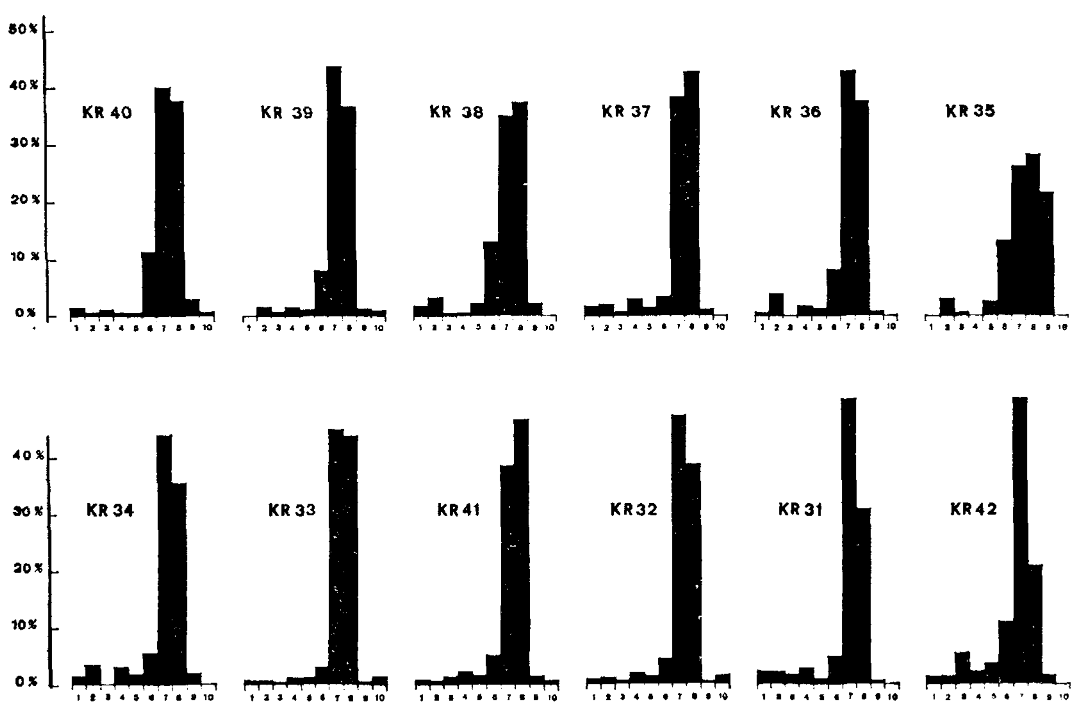

FIG. 3 Frequency of planktonic Forminifera population in surface sediments: 1. *Globigerinella aequilateralis* (Brady); 2. *Globigerinoides sacculifer* (Brady) including *Globigerinoides quadrilobatus* (d'Orbigny); 3. *Globorotalia truncatulinoides* (d'Orbigny); 4. *Orbulina universa* d'Orbigny; 5. *Globigerinoides ruber* (d'Orbigny) var. *rosea*; 6. *Globigerinoides ruber* (d'Orbigny) var. *alba*; 7. *Globorotalia inflata* (d'Orbigny); 8. *Globigerina bulloides* d'Orbigny; 9. *Globigerina pachyderma* (Ehrenberg); 10. Others.

abyssorum Sars. Our observations do not agree with the assumption that many benthic Foraminifera derive from the littoral and *circa* littoral zones (MATEU, 1971). The species noted by Mateu as abundant, and as having derived from such sources, were found in our samples only in small numbers.

The distribution of the Alboran planktonic foraminiferal associations observed is fairly uniform. As also noted by PARKER (1955), cold-water species (*Globigerina bulloides*, *Globigerina pachyderma*) are more numerous than in sediments from the other parts of the Western Mediterranean (TODD, 1958; BLANC-VERNET, 1969). Furthermore, *Globorotalia inflata* and the warm group, particularly *Globorotalia truncatulinoides* and *Globigerinoides ruber* var. *rosea* and var. *alba*, are less abundant in the Alboran Sea than in the Algero-Provencal Basin.

CURRENT REGIME

Surface currents

The surface water of Atlantic origin (S > 36·5‰, $t > 14$°C) constitutes a 220-m anticyclonic gyre in the Western Alboran Basin (LANOIX, 1972) (Fig. 2). The current flows first east, then southeast from the Strait of Gibraltar. At about 3°W the southeastward-flowing current separates into three branches. The northern branch disappears at about 2°30′W. The southern vein flows east parallel to the north African coast; at about 1°W it divides, one branch pointing to the north up to the Spanish coast, the other one continuing east along the African coast. The third branch constitutes the anticyclonic gyre of the Western Alboran Basin.

Calculated and measured current speeds (LANOIX, 1972) and the G. E. K. (CAPART and STEYAERT, 1963) indicate intensities as high as 70 cm s^{-1} in the Surface Atlantic Water lying north of the Western Alboran Basin. In the southern part of the Eastern Alboran Basin the high-speed vein of Atlantic Water widens while the speed decreases to 35 cm s^{-1} (1°36′W).

Deep currents

The Intermediate Water ($S > 38{\cdot}45$‰, $t = 14$°C), coming from the Eastern Mediterranean, penetrates the Algero-Provencal Basin through the Strait of Sicily (LACOMBE and TCHERNIA, 1972; TCHERNIA, 1960). The cooler Deep Water, with salinity below 38·42‰, occupies the level below 1000 m in the Eastern Alboran Basin. Its influence decreases notably in the Western Alboran Basin.

Between 1° and 2°W the influence of the Intermediate Water is greatest near the Spanish coast. Three branches can be seen near 2°30′W. The southern branch penetrates the deep channel separating the South Alboran Ridge from the African continental slope (Fig. 1). A central branch flows into the Alboran Trough and a northern branch seems to flatten against the Spanish continental slope. There are only two branches at 4°W and only one at 5°W. This current pattern suggests strongly that the path of the Deep Water is characterized by a deflection to the right in response to the Coriolis force and the local topography.

An average flow of Atlantic Surface Water into the Mediterranean of 10^6 m^3 s^{-1} (LACOMBE and TCHERNIA, 1972) would imply a mean speed of 2 cm s^{-1} for the westward-flowing under-current (assuming a cross-section of 5×10^7 m^2). According to HEEZEN and HOLLISTER (1964) these inferred deep current intensities are adequate for the transport of particles up to 200 μm.

DISCUSSION

Sedimentological evidence and hydrologic data suggest the following:

(1) Carbonate-poor muds are restricted to the western and southeastern part of the Alboran Sea.

(2) Montmorillonite and cold water planktonic Foraminifera are more abundant in the Western than in the Eastern Alboran Basin.

(3) The frequency of warm water Foraminifera decreases toward the northwest.

(4) Sediments relatively rich in carbonate are the most common in the area that lies under the influence of Intermediate and Mediterranean Deep Water.

(5) Average velocity of the out-flowing Mediterranean Water seems to be adequate for the transport of most of the surface sediment.

With regard to points (2) and (3), HUANG, STANLEY and STUCKENRATH (1972) suggested an eastern volcanic origin for the montmorillonite during the Pleistocene. The occurrence of montmorillonite in marine environments is often related to a primary volcanic source (GRIFFIN and GOLDBERG, 1963; HATAWAY and SACHS, 1965; SIEVER and KASTNER, 1967; MURRAY, 1970; JACOBS, 1970). Recent work in the Eastern Mediterranean (CHAMLEY, 1971) and the central North Atlantic (HOFFERT, 1973) shows that the neogenesis of montmorillonite from volcanic material is strongly influenced by the size of the volcanic glass and the presence of diatoms in the deposit. Furthermore, dredges in the Alboran Sea during the Polymède II cruise on reliefs ot suspected volcanic origin showed the presence of tuffaceous materials; X-ray diffraction analyses of the fine components show the presence of montmorillonite in only two samples from one dredge northwest of the Alboran Strait (DESFORGES, 1973). Dredges from the Balearic zone indicated only the presence of indurated calcareous sediments. Hence it appears to us that the present-day distribution of montmorillonite is not directly related to the volcanic outcrops. On the other hand, the area of montmorillonite occurrence in the Alboran Sea could be an eastward extension of the zone of common occurrence lying east of the Strait of Gibraltar (BISCAYE, 1965). MELIERES (1973) pointed out the abundance of montmorillonite in the Guadalquivir estuary (Fig. 2), and this could be one source for montmorillonite in the Alboran Sea after transport through the Strait of Gibraltar by the Atlantic Surface Water.

Following BERGER'S (1970, 1971) results, it should be possible to explain the cold character of the planktonic foraminiferal population in the Alboran Sea (relative to the other part of the Western Mediterranean) by the selective dissolution of spined species like *Globigerinoides ruber* and *G. quadrilobatus*, whereas species with thick-walled tests like *Globigerina pachyderma* and *Globorotalia inflata* should not be destroyed and would hence concentrate, thus giving to the sediment a 'cold' character. This hypothesis does not seem to hold in the present case, for no indications of dissolution of calcareous tests were noticed during examination of the sediments.

Settling velocity values for Foraminifera, as estimated by BERTHOIS and LE CALVEZ (1960), BOLTOVSKOY and LENA (1970) and BERGER (1971) are sufficient to insure their sedimentation from the Atlantic Surface Water within a time span consistent with the inferred bottom current intensities.

The above discussion suggests that clays, principally montmorillonite, and planktonic Foraminifera are carried into the Mediterranean by eastward-flowing Atlantic Surface Water and settle in the Alboran after successive stages in the Intermediate and Mediterranean Deep Water. The fraction of Atlantic-derived materials in the bulk sediment is difficult to ascertain, because other minerals or organisms found in the Alboran Sea could have the same origin. For example, an Atlantic 'character' has also been reported for the Echinoderma fauna in the Alboran Sea (SIBUET, in press). This affinity may be because of the possibility of introduction of larvae, or conditions for growth and reproduction, or both, similar to those in the central and northeast Atlantic. It is obvious that other sources, including Intermediate and Mediterranean Deep Water, rivers from both Europe and Africa, and Saharan eolian dust, might provide sediments, but a substantial fraction of the sediments is likely to be deposited under the control of the prevailing current regime.

CONCLUSION

The surface sediments of the Alboran Sea indicate that it is a sedimentary province distinct from the Western Mediterranean Basin. The Alboran Sea sediments are characterized by lower carbonate contents and larger detrital fractions, particularly quartz and clays, than the Balearic and Algero-Provencal Basins sediments. Montmorillonite is more abundant in the clay fraction while the planktonic Foraminifera population contains more cold water and fewer warm water species. These characteristics can be explained by assuming an Atlantic origin for a significant part of the Alboran Sea sediments. The transport and deposition of this sediment should be under the control of the prevailing current regime. The study appears to demonstrate the important sedimentary role played by the inflow of Atlantic Surface Water through the Strait of Gibraltar.

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