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Present-day sedimentation patterns of the Gulf of Cadiz northern shelf from heavy mineral analysis

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Abstract The sedimentary processes on the northern shelf of the Gulf of Cadiz (SW Spain) are basically controlled by two factors: the different rates of fluvial supply between the northern and southern sectors and the dominant water flows toward the SE. The distribution of heavy minerals shows differences between the two sectors with predominance of ultrastable minerals in the southern sector, in relation to the different supply rates. This distribution is related to the sea-level change during the Holocene, fluvial supplies, and oceanographic factors. The application of statistical multivariate methods to heavy mineral data shows the principal heavy mineral association (epidote–garnet–rutile), which is very similar to that in neighboring terrestrial areas and offers the possibility of referring factors to source areas.

Introduction

Recent nonconsolidated sediments in the study area (Fig. 1) are siliciclastic with quartz as the most abundant mineral in the sandy sediments and illite in the fine-grained deposits. The carbonates, basically bioclastic, appear systematically in amounts less than 20% (Segado et al. 1984; Gutierrez-Mas and Villanueva Guimerans 1987). The grain-size distribution shows a general orientation parallel to the coast and the isobaths as a result of active sediment dynamics towards the south. It is possible to differentiate two zones: one, with quartzite sands, on the southern shelf and coastal band, and another, with clayey muds, related to the Guadalquivir River mouth on the northern and central sectors of the shelf, which wedges towards the southeast and progressively covers the sandy zone (Fig. 2). This distribution is related to eustatic sea-level changes during the Holocene, the North Atlantic surficial water (NASW) and drift currents, and the fluvial supplies coming from river mouths situated along the northern sector of the studied area (Gutierrez-Mas 1992).

Assemblages of heavy minerals contained within sandy sediments are commonly used to analyze the source area of terrigenous sediments (Pettijohn 1975; Komar et al. 1989). Statistical analyses of sample data from the continental shelf of the Gulf of Cadiz (Fig. 1) have been used to establish the dominant heavy mineral associations. These assamblages help to define the relationships of the sediments with the different source areas, which in turn help to understand the large-scale sedimentation processes in this basin.

In the northern margin of the Gulf of Cadiz, several authors (Mabesoone 1963, 1966; Perez-Mateos et al. 1982; Melieres 1974) have studied the heavy mineral associations, the source areas of the different materials, and the subsequent dynamic sedimentary littoral areas and the deeper waters beyond the continental shelf. However, they did not use optimum statistical methods in the studies of the heavy mineral fraction in establishing the composition and provenance of the sediments and in evaluating the contribution of the different source areas.

The application of the Q-mode factor analysis method is an excellent technique for the understanding of large-scale sedimentation processes in modern basins (Flores and Shideler 1978; Bank and Chough 1983; Stattegger 1987), as it can be used as a sample classification technique that provides the mineral composition of the obtained groups and allows for the identification of the heavy mineral associations and their province.

Methods

Sample preparation

The heavy fraction components were studied in 59 sandy samples obtained by means of gravity and piston corers

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and a Shipek bottom sampler (Fig. 1). Separation was carried out using heavy liquids (bromoform, $d = 2.89$ at 20°C), after the carbonates were eliminated with HCl. One hundred milligrams of ground sample of such a heavy fraction were studied by X-ray powder diffraction (XRD) analysis using a Philips PW 1710 diffractometer.

Statistical methods

Multivariate analysis techniques have been useful in many geological studies and, although the methods differ in their objectives and mathematical models used, they have one feature in commom; the reduction of the variables to a few factors. Among the most used techniques are the main component and the cluster analysis methods. However, in this study, those methods were not suitable for the determination of the dominant mineralogical association, mainly because the large number of factors and clusters caused great data dispersion and consequently limited interpretation.

As outlined by Imbrie and Van Andel (1964), Davis (1973), and Jöreskog et al. (1976), the objectives of Q-mode factor analysis are to provide a characterization of a multivariate data system, to reduce the complexity of the model by extracting a small number of components (end members), and to classify the samples into natural groups (Mezzadri and Saccani 1988).

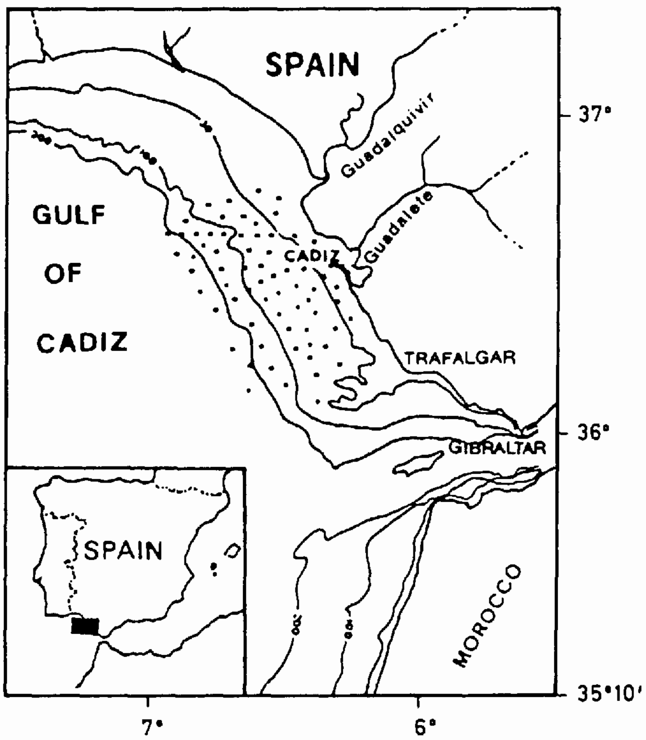

Fig. 1 Geographic setting of the study area and location of the samples

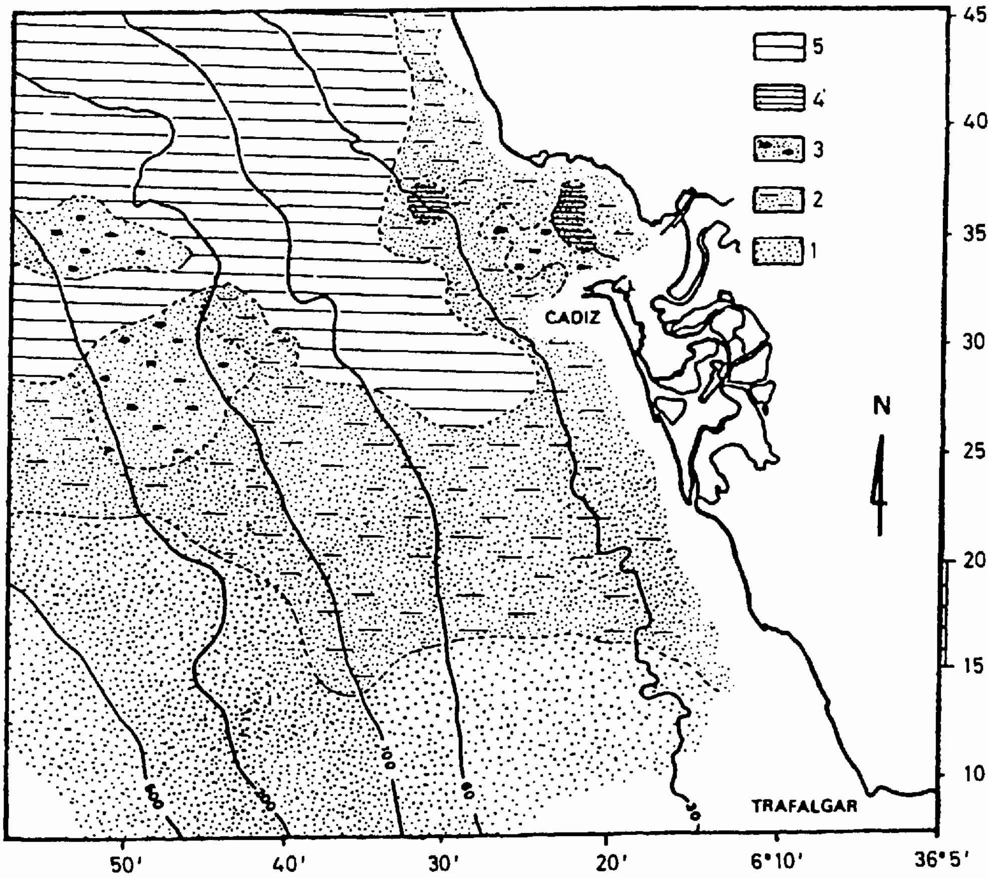

Fig. 2 Grain-size distribution patterns. 1: sands; 2: clayey sands; 3: silty sands; 4: sandy silts; 5: silty clays

In this study, the Imbrie method (1963) has been used, which is based on the use of the similarity matrix built by the cosines of the angles between each pair of sample objects considered as vectors. The factor scores represent the composition of the end members (mineralogical associations), while the factor loadings are interpreted as the relative contribution of these end members in the samples and establish the areal distribution of the mineralogical associations. Only factor loadings with values higher than 0.5 are included in a factor.

Results

The heavy fraction content of the samples was never higher than 5%, with the highest values corresponding to sandy samples in the sublittoral areas, close to the Bay of Cadiz, between 10 and 20 m of water depth (Fig. 3), while the muddy areas of the continental shelf show the smallest percentages and even the absence of heavy minerals. In deeper areas, between the 100-m isobath and the continental slope, it varies between 0.5 and 1.5%. Table 1 shows the compositional variation of the heavy minerals.

There is a correlation between the heavy mineral content and the quartz and sand contents (Table 2), which increases with the ultrastable heavy minerals, showing a predominance of these minerals on sandy floors (Ult/Met > 1), especially south of Cadiz (Fig. 4). In the NW of the shelf, the metastable minerals (Ult/Met < 0.5) predominate.

Generally, the mineral pairs that correlate well for the total area also show good correlation when the coefficients are computed for sectors with different depths (Table 3), which indicates the rather uniform distribution of these minerals.

Q-mode factor analysis shows three factors that explain 83% of the variance, with factor 1 explaining 70%, grouping the greater part of the samples, and these may be considered as representative of the studied area (Table 4). The mineral association deduced from the factor scores shows factor 1 to be: epidote, garnet, and rutile (Fig. 5) and is significant throughout the area (Fig. 6).

Factors 2 and 3 with only 7% and 6% of variance, respectively, are of lesser significance (Table 4). Factor 2 (enstatite, garnet, and rutile) is only significant in the Bay of Cadiz and neighboring areas. Factor 3 (rutile, enstatite, hornblende, tourmaline, and zircon) is related to the sandy facies of the Bay of Cadiz and the outer continental shelf (Fig. 6).

Discussion and Conclusions

From the heavy mineral correlation coefficient matrix, a preliminary description of the mineral distribution model

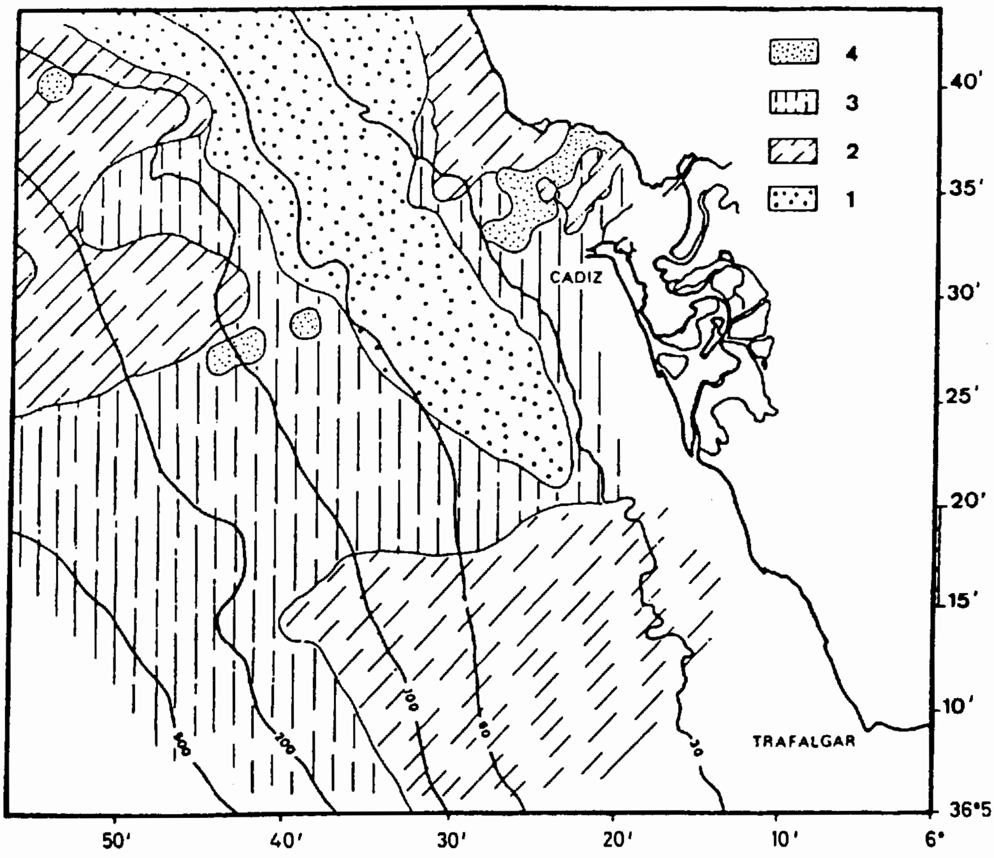

Fig. 3 Distribution patterns of heavy minerals. 1 = 0%; 2 = 0–0.5%; 3 = 0.5–1%; 4 = >1%

Table 1 Statistical values of the heavy minerals[a]

	ANAT	AND	AUG	KYAN	CHL	ENST	EPID	STAUR	HORNB	ILM	RUT	SILL	TOUR	ZIRC	GARN
Mean values	6.3	3.1	2.9	1.8	4.9	6.6	8.3	6.6	5.4	13.2	10.6	1.6	4.3	4.8	19.3
St. Deviat	2.9	2.1	4.7	3.0	3.4	9.9	6.8	6.8	4.0	6.5	4.8	2.7	2.5	5.0	10.1
Smallest value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0
Largest value	14	9	34	13	16	45	28	34	22	35	22	11	15	21	48

[a] ANAT = Anatase; AND = Andalucite; AUG = Augite; KYAN = Kyanite; CHL = Chloritoid; ENST = Enstatite; EPID = Epidote; STAUR = Staurolite; HORNB = Hornblende; ILM = Ilmenite; RUT = Rutile; SILL = Sillimanite; TOUR = Tourmaline; ZIRC = Zircon; GARN = Garnet

Table 2 Correlation coefficients between heavy minerals quartz and sand fractions

Heavy Mineral	Quartz	Sand
Epidote	0.8	0.6
Garnet	0.7	0.7
Rutile	0.7	0.42
Tourmaline	0.9	−0.74
Zircon	0.7	—
Chloritoid	−0.8	−0.7
Andalucite	−0.9	−0.66
Estaurolite	−0.9	−0.65

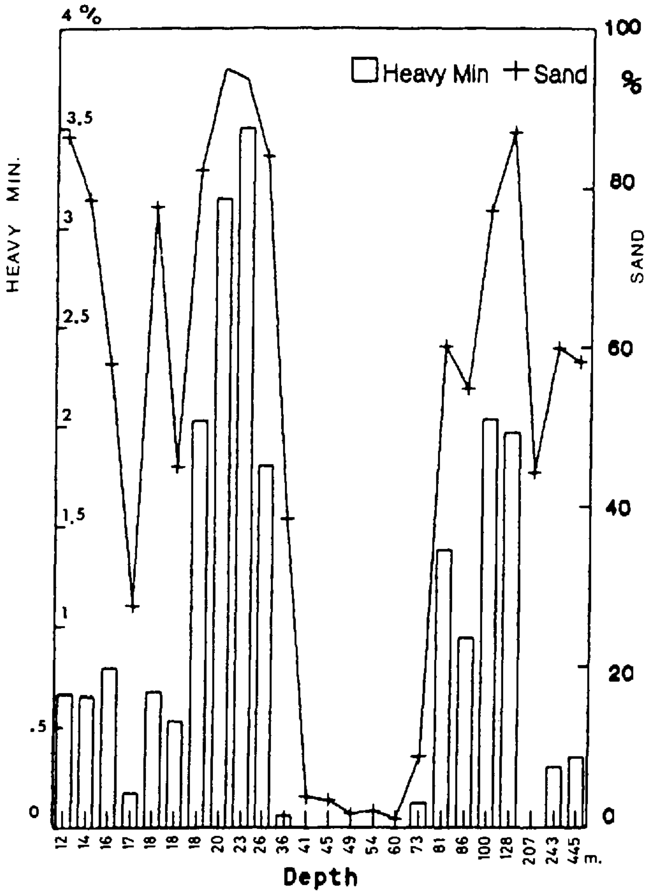

Fig. 4 Variation of the heavy mineral content within the sands and the water depth

can be obtained. Those mineral pairs with high correlation coefficients for the whole area also show correlation when depth intervals are considered (Table 3). The mineral pairs with smallest variation are tourmaline–garnet and epidote–rutile. Due to their uniform distribution in the sediments, the hornblende–tourmaline pair is significant to a water depth of 50 m, whereas the sillimanite–chloritoid pair shows a very irregular distribution with depth. This allows the samples to be divided in two popula-

Table 3 Variation of most significant correlation coefficients between mineral pairs with depth

	Global	<20 m	20–50 m	50–100 m	100–200 m	>200 m
Tourmaline–garnet	−0.5	−0.58	−0.44	−0.25	−0.5	−0.95
Hornblende–Tourmaline	0.4	0.55	0.7		−0.5	
Epidote–rutile	0.44	0.5	0.38	0.58	0.37	
Sillimanite–chloritoid	0.4	0.26		−0.3	0.37	0.9

Table 4 Factor scores of "end members" (heavy minerals) by Q-mode factor analysis (values less than 0.25 are not included)

Minerals	Factor 1	Factor 2	Factor 3
Anatase	0.63		0.8
Andalucite		0.25	
Augite	0.27		0.3
Kyanite		0.35	
Chloritoid	0.25		0.74
Enstatite	−1	2.8	1.8
Epidote	2.9		
Staurolite	0.4		−0.6
Hornblende			1.5
Ilmenite	0.65		1.1
Rutile	1.25	−0.6	1.9
Sillimanite			0.3
Tourmaline			1
Zircon	−0.6		0.6
Garnet	1.6	2.5	1.3
% var. expl.	70	7	6

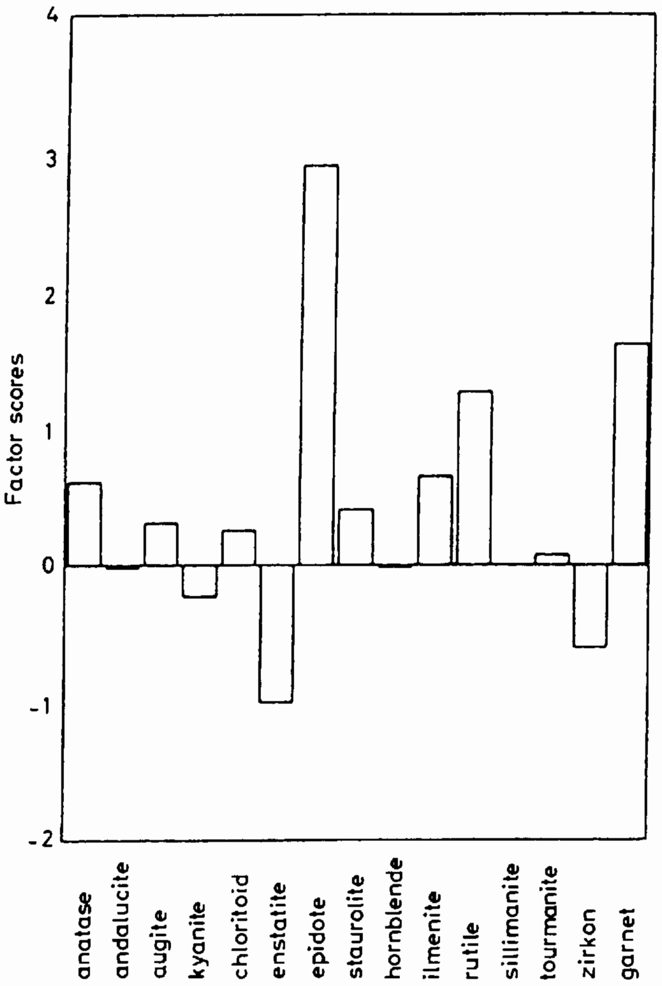

Fig. 5 Factor scores of the "end members" (heavy mineral assemblages) of factor 1 obtained in Q-mode analysis

tions, one based on the ultrastable heavy minerals, and the other on sillimanite–chloritoid in agreement with the Ult/Met ratio. Sandy sediments with an Ult/Met ratio > 1 are distributed in the southern sector while the sediments with a value of this ratio smaller than 0.5 are located towards the north.

The results of the Q-mode factorial analysis demonstrate that the dominant mineralogical association, deduced from the highest factor scores (Table 4), in the studied area is represented by factor 1 (epidote, garnet, and rutile: E > G > R) (Figs. 5 and 6), which explains 70% of the variance. The mineral associations defined by factors 2 and 3 may be explained as mixture areas with local supplies.

The mineralogical association defined by factor 1 (E > G > R) is similar to the one defined by Mabesoone (1963, 1966) in adjacent terrestrial areas (Petrographic Province of Jerez) made up of epidote, garnet, and andalucite (E > G > A) genetically related to the Betic Range and Sierra Morena (Iberian Massif). Viguier (1974) agrees with Mabesoone but distinguishes two subprovinces, one close to Medina Sidonia (province of Cadiz) made up of zircon, garnet, and tourmaline (Z > G > T) and the other in the alluvials of the Guadalete river basin with epidote, garnet, andalucite and tourmaline, and rutile (E > G > A + T > R). On beaches close to Cadiz E > G > A predominates (Mabesoone 1963); between Cape Trafalgar and Tarifa A > G > E predominates, and towards the north, between Cape Trafalgar and Sanlucar de Barrameda, G–E (Pérez-Mateos et al. 1982).

This similarity of the mineralogical associations shows the permanence of the source areas and the sedimentary dynamics in the zone. However, the small mineralogical variations observed on the present samples may be explained if density, morphology, and grain-size differences are taken into account, which can influence the hydrodynamic behavior as the result of selective sorting (Komar et al. 1989).

The most probable source areas for the continental shelf are: the Neogene Guadalquivir Basin, since there is evi-

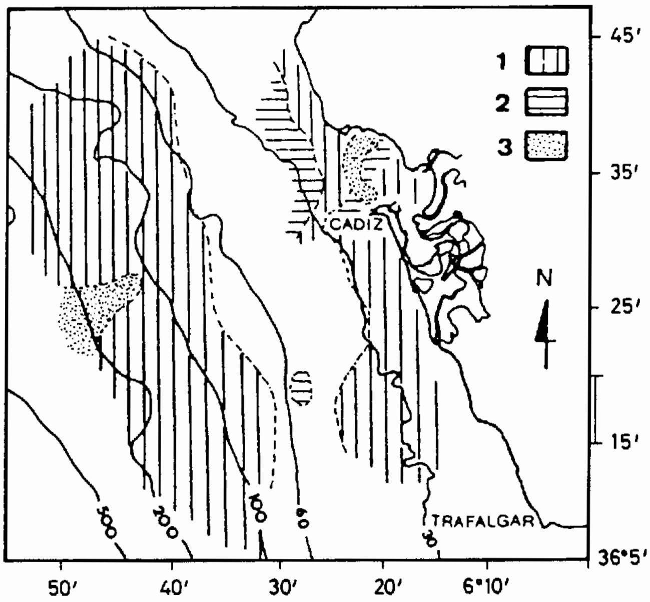

Fig. 6 Sketch of the distribution of assemblages minerals by Q-mode factor analysis. 1: epidote–garnet–rutile; 2: enstatite–garnet; 3: rutile–enstatite–hornblende–tourmaline; 4: no avalaible mineral content data (clayey mud sediments)

dence of the predominance and reworking of the ultrastable heavy minerals (Perez-Mateos 1982; Gutierrez-Mas 1992) drained by the Guadalquivir and Guadalete rivers; the units of the Occidental Betic Range (subbetics and flysch of Gibraltar) drained by the eastern tributaries of the Guadalete River; and the internal zones of the Betic Range and Sierra Morena (Iberian Massif) because of the presence of relatively less stable igneous and metamorphic minerals.

Present-day sediment dynamics on the continental shelf of Cadiz are mainly conditioned by the sediment input from rivers in the northern sector, mostly fine-grained sediments, which prograde towards the SE due to the predominant marine currents (NASW and drift currents) aided by the coastal direction. In the southern sector the absence of abundant fluvial supplies has permitted the preservation of relic sandy sediments on the shelf represented by the predominance of ultrastable heavy minerals, which were deposited before and during the major last sea-level rise.

From temperature and salinity data (Bray 1986; Shull and Bray 1989; Gutierrez-Mas 1992), it is deduced that the Mediterranean outflow water does not influence the present-day sedimentary activity in this sector of the continental shelf since it runs in deeper waters. The distribution of the more significant heavy minerals, present in the sediments on the continental slope and deeper bottom, shows that they follow the path of the Mediterranean flow (Melieres 1974), and their contents are clearly discordant with those existing on the continental shelf.

In the littoral zones, the influence of the main circulation pattern is small, and sedimentation is controlled by local factors such as: the stepped shape of the coast, supplies from small rivers and gullies, wave erosion of coastal cliffs, and the direction of the drift currents. Mabesoone (1963) indicated an andalucite impoverishment concomitant with a garnet, hornblende, zircon, and augite enrichment southwards of Cadiz, reflecting the minor influence, in the coastal band, of the general circulation pattern.

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