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Letter Section

Frontal instabilities and suspended sediment dispersal over the shelf of the Cilician Basin, southern Turkey

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Abstract

A narrow band of coastal waters with high sediment content, which develops along the southern Turkish coastline, is identified in satellite imagery. Such waters are present during periods of high freshwater runoff.

The suspended sediment-laden waters extend from this narrow nearshore belt as a series of eddies, which are not normally seen on this scale in shallow waters. These eddies are produced by instability at the front, or density difference, between the nearshore waters and the offshore (more saline) continental shelf waters; they are analogous to similar phenomena produced in the laboratory. Flow within the eddies is initially perpendicular to the front, then *across* the general shore-parallel circulatory system over the area. The eddies extend over the whole width of the shelf and appear to be important agents for the seaward dispersal of fine-grained suspended sediments.

1. Introduction

The dispersion of fine-grained sediment supplied to seas and oceans from adjacent coastlines, by fluvial systems or coastal erosion, is controlled by oceanographic processes in the nearshore and adjacent shelf areas (see McCave, 1972, for general view). Some of the material is trapped in coastal lagoons (Meade, 1972), or stratified flows lead to its entrapment in estuaries (Biggs, 1970); elsewhere, tidal processes result in accumulation in embayments or on intertidal flats (Evans and Collins, 1975). However, much of this sediment becomes entrained usually in the shelf circulatory systems, which normally parallel the coastline and the shelf edge. The sediment is transported parallel to the coastline, from its point of entry, leaking slowly offshore by dispersive processes. This results commonly in a nearshore mud-belt whose inner boundary is controlled by wave turbulence sometimes associated with tidal processes, and whose outer boundary is dependent upon the efficiency of dispersive processes. On the continental shelf off Washington, for example, sediment motion is caused by: bottom currents related to wind stress and tides (22 days/year); and near-bed wave-induced oscillatory currents (53 days/year) (Sternberg and Larsen, 1976).

Where filaments of shelf currents move offshore, the sediment may be transported across the entire

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shelf (Emery, 1963). In other situations, topographical barriers may force the shelf waters and their suspended sediments to seaward (Nota, 1958): two such different circulatory systems may meet and deflect the flow of water and sediment in the same direction (Curray, 1960). In other circumstances, wind-forced currents generated by storms and hurricanes may cause the dispersal of fine-grained (as well as coarse-grained) sediment over the adjacent shelf beyond the usual limits representing 'normal' conditions (Morton, 1975, for review). On continental shelves exposed to open oceanic swell (Larsen, 1982), silt- to sand-sized particles may be transported across the mid-continental shelf by currents forced by the radiation stress of variable-amplitude waves. Under all such conditions, the mud-sheet will encroach across the shelf. Some material will reach the continental slope, where it may: be transported parallel to the slope by geostrophic currents; or be displaced into adjacent basins, by gravity-induced flows.

Where large rivers debouch into the sea, particularly in times of high river discharge, fine-grained material may be carried across the whole width of the shelf in relatively buoyant (hypopycnal) surface plumes. A shelf-parallel water circulatory system will displace this sediment alongshore to produce a mud sheet which extends slowly in the same direction over a broad front (Nittrouer et al., 1979; Sternberg, 1986); this is much wider than when the coastal sources are of lower magnitude (Curray, 1960). Rarely, (the Yellow River appears to be the only well known example) where there is a high content of material in suspension in the incoming fluvial waters, the sediment-laden fresh water is sufficiently dense to produce sub-surface (hyperpycnal) flows; these transport fine-grained sediments widely over the adjacent continental shelf (Wright et al., 1986; Wright, 1989). The shelf muds may be resuspended and dispersed farther offshore, by exceptional hydrodynamic conditions during storms or enhanced shelf circulation (e.g. Palanques and Drake, 1990). In the case of fluid muds on the Amazon continental shelf, observed salinity and temperature anomalies within the muds imply that they are often *not* the result of such erosion and resuspension. Rather, the muds are the result of trapping processes at the bottom salinity front, and are then transported across the shelf (Kineke and Sternberg, 1995).

Hence, as coarse grained-sediment is retained close to the shoreline by breaking wave systems, fine-grained sediment tends to be restrained from seaward advection by the normal shelf circulatory systems. However, as described above, it escapes to seaward to extend across the shelf and reach the adjacent deep waters.

There is comparatively little known about suspended sediment and its dispersal in Eastern Mediterranean waters; this is particularly true of the north-eastern Mediterranean. The present short contribution discusses the significance of some features revealed by satellite images of part of the shelf area of southern Turkey, on the northern flanks of the Cilician Basin. The local area of interest lies between the delta of the Göksu River and the coastal city of Mersin, on the southwestern flank of the Seyhan–Tarsus delta (Fig. 1). Nonetheless, the sediment dynamic processes identified may be capable of extrapolation to other areas.

2. Area under investigation

The coast of southern Turkey lies along the foot of the Taurus mountains. In the southwest of the area under discussion are the coastal plains of the protruding delta of the Göksu River. To the north-east, between the flat deltaic plains of this delta and Erdemli, the coast is formed mainly by cliffs cut into Miocene limestones. Small pocket beaches are present and narrow valleys of very small ephemeral streams reach the coast (Fig. 1). North eastwards of the mouth of the Lamas river is a narrow coastal plain, formed of coalescing fans and fronted by a thin cordon of beaches and dunes, crossed by numerous ephemeral streams; these grade into the broad deltaic plains of the combined Seyhan–Tarsus–Ceyhan rivers.

The shelf bordering this coast is relatively narrow and forms the northern flank of the Cilician Basin; it is only approximately 9 km wide off the Göksu delta in the southwest and widens to approximately 40 km off Mersin, to the northeast.

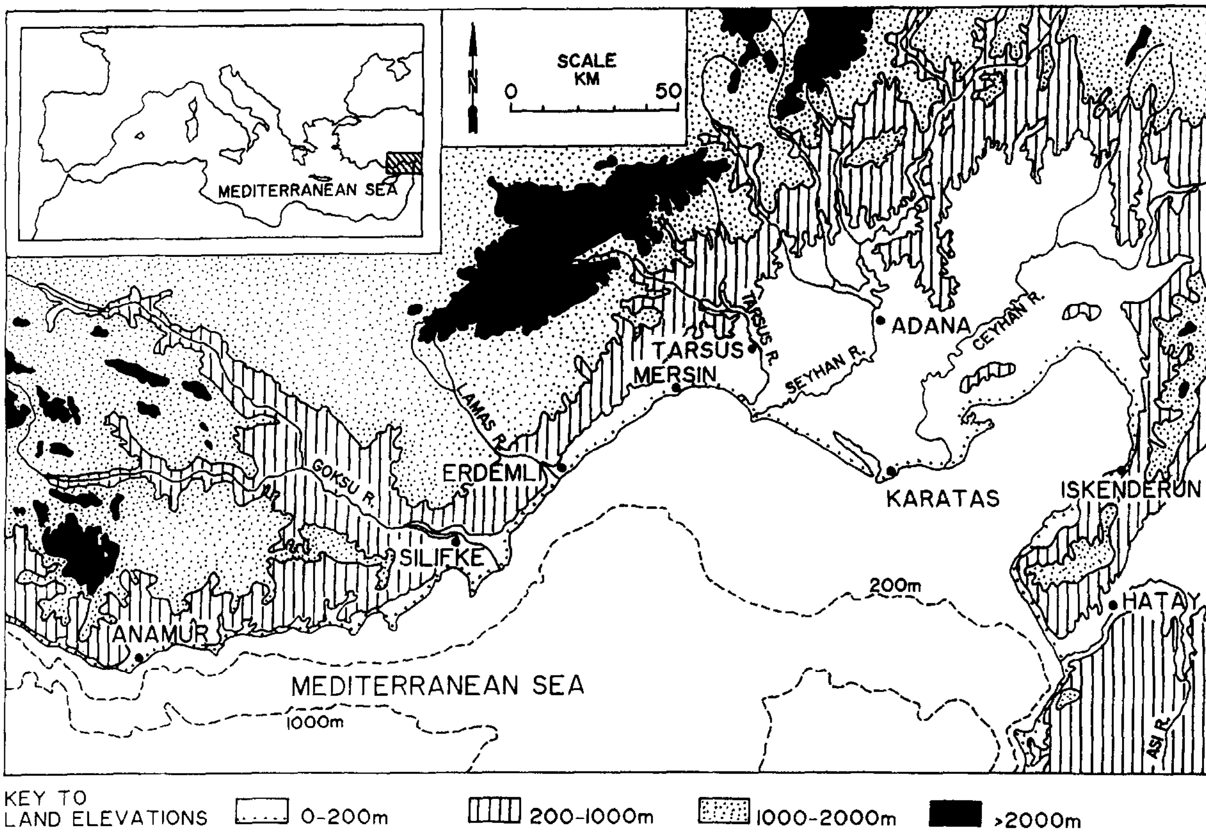


Fig. 1. General location of the study area and river systems, in relation to onshore topography and offshore bathymetry.

The shelf has a gentle seaward gradient, varying from 0.31° to 0.81° in the southwest to 0.29° in the northeast. Generally, the surface is smooth except for some minor irregularities on the middle shelf, metres in scale, which are probably old coastal barriers cloaked by modern shelf mud.

The general setting of the area has been described by Evans (1971) and Evans et al. (1978), (1988), the general distribution of the sediments and their geochemistry and mineralogy by Shaw and Bush (1978), Shaw (1978), Shaw and Evans (1984) and Mange-Rjetsky (1983) and the distribution of the microfauna by Alavi (1980). More detailed studies of part of this shelf have been reported in Bodur and Ergin (1988a, b) and Ergin et al. (1992) and are provided in the unpublished theses of Gulumser (1978), Bodur (1987), Ediger (1990) and Okyar (1991).

An inner zone of terrigenous sands and muds lies immediately adjacent to the coastline; this passes seawards into a zone, between 50 and 100 m water depths, which is covered with a veneer (centimetres thick) of shelly sand, mud, muddy shelly sand and shelly sand which overlies the mud[1]. Beyond, in its outer part, the shelf is covered with muds, as are the adjacent slopes of the Cilician Basin.

The large-scale oceanography of the area has been reviewed recently and comprehensively by Ozsoy et al. (1989) and a few papers have described currents on the shelf (Ünlüata et al., 1978;

[1] Note: This shelly zone is not the main subject of this particular contribution, but will be discussed elsewhere. However, it may be stated that it is probably of anthropogenic origin.

Atakturk, 1980). Collins and Banner (1979) have provided a compilation of the suspended sediment distribution in the waters of the area, based largely upon Secchi-disc readings taken during NERC sponsored cruises on RRS *Shackleton* (by an Imperial College research group). However, very little detailed information is available on the oceanography of the shelf and that which does exist is found mainly in relatively inaccessible reports of the Institute of Marine Sciences of the Middle East Technical University.

Oceanic waters enter the region between Cyprus and southeastern Turkey and flow along the shelf off the Seyhan delta, before turning southwesterly to flow parallel to the southern Turkish coast in the area under consideration. Some small secondary eddies develop in the indentation of the Bay of Iskenderun, where they react with the incoming waters of the Ceyhan river. Current speeds here are generally low (4–10 cm/s). However, during periods when strong winds blow down the Göksu valley, in the southwest of the area, the inner shelf currents are sometimes reversed (Ünlüata et al., 1978). At such times, speeds of up to 10 cm/s have been measured at depths of 10 m below the water surface.

Tidal currents are insignificant over the region, as the tidal range is low (<50 cm). Waves are only of a limited height (2 m maximum, at their break point). For much of the year the waters are remarkably calm, except for periods of strong winds. There is a noticeable diurnal effect, with the sea surface becoming markedly rougher in the afternoons in summer due to strong onshore winds, produced by the development of low pressure areas on the adjacent landmass.

The supply of fresh water from surface drainage is rather limited and markedly seasonal over most of the area (Fig. 2). However, there appears to be a considerable amount of subsurface water leaking seawards, particularly between Erdemli and the Göksu delta, through the fractured Miocene limestone. In some bays, there is a well defined subsurface layer of cold, fresh water present.

The Göksu river to the southwest and the Seyhan and Tarsus in the northeast are perennial streams. However, between these, all other streams which reach the coast (except for the Lamas river, which flows all the year) carry only a trickle of water for much of the year. High discharges occur after heavy rains, or mainly in spring and early summer when the snow melts in the adjacent

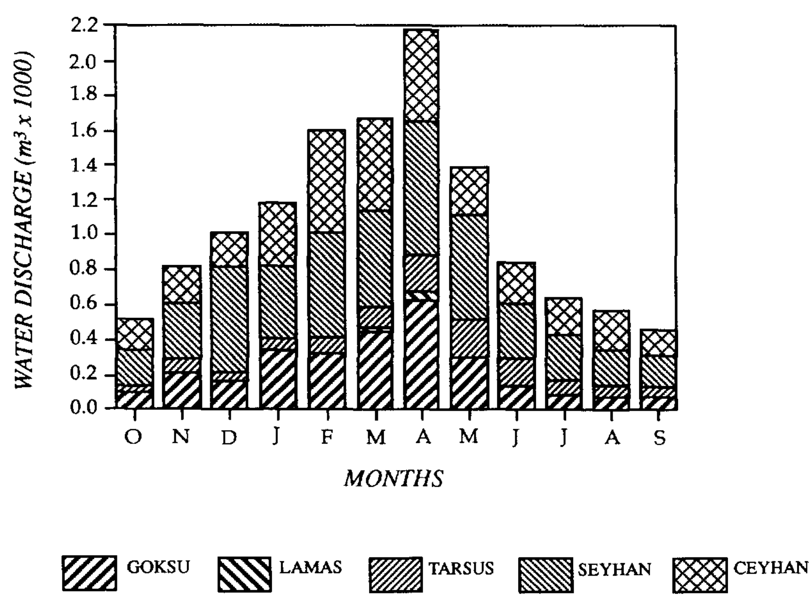


Fig. 2. Monthly discharges in the main river systems draining southern Turkey, showing seasonal variability (from EIE, 1989).

Taurus mountains. During these periods, the rivers have bankfull discharges and often cause local flooding of the adjacent farmlands.

Consequently, the supply of fresh water and sediment to the nearshore waters of this coast-line is, except during the aforesaid periods, dominated by water supplied by the Seyhan and Tarsus rivers. The Ceyhan also supplies fresh water to the northeastern Mediterranean, but probably not much of this reaches the coastal areas being discussed here. Also, water supplied by the Göksu river only spreads to a limited extent over the area, as the prevailing southwesterly shelf currents carry it away to the southwest.

3. Results and interpretation

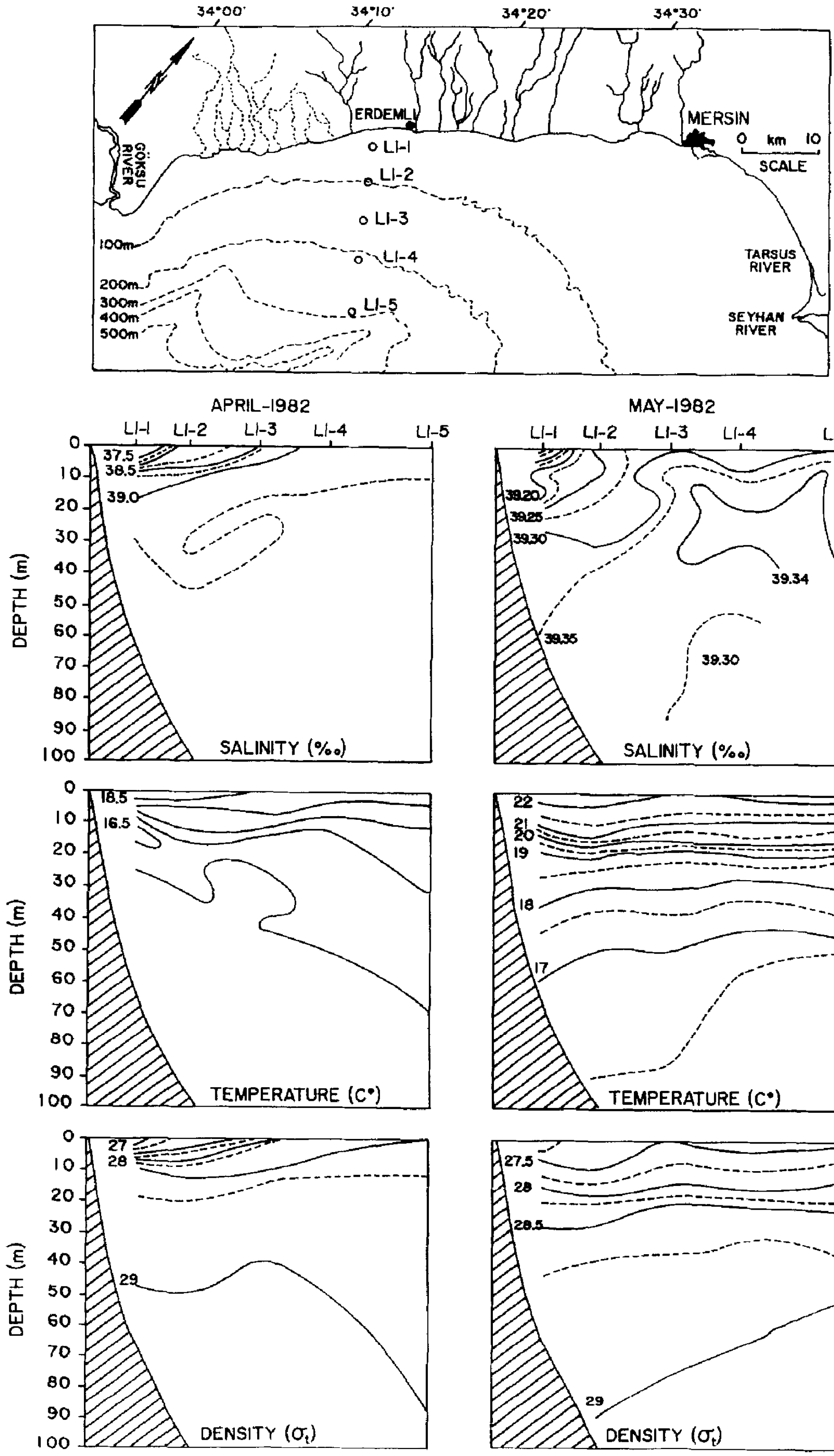
Examination of various LANDSAT images, together with numerous airborne observations of the Göksu river mouth, show that a plume of river water rich in suspended matter is always directed towards the southwest. During periods of heavy rain or snowmelt in spring and early summer, small plumes of turbid water can be observed off most of the ephemeral streams reaching the coast between the Göksu and the Seyhan delta. Depending upon local winds, these are diverted either northeast or southwest along the coast. These various inputs amalgamate to produce a belt of (turbid) low salinity inshore waters along the coast, with a well marked outer boundary (see Fig. 3). During such periods of run-off, a well marked salinity stratification is developed. This pattern is not seen in summer, due to the small influx of fresh water and is absent in winter because of mixing.

A satellite image (LANDSAT, Band 4: 3 February 1979) of the area shows conditions when there is considerable inshore turbid water (Fig. 3) which, on this occasion, extends onto the middle shelf. As can be seen from the image, the Seyhan–Tarsus water completely covers the shelf off the Seyhan–Tarsus delta to the northeast of the area, as far seaward as the outer shelf. However, of particular interest and the subject of this note, are the large eddies of turbid water, which carry muddy coastal waters to the shelf edge between Mersin and the Göksu delta.

Structures similar to the eddies seen in Fig. 4, shown schematically on Fig. 5, have been observed associated with fronts at various and generally larger scales. In the deep ocean they occur often at the boundary between water masses of different temperature (e.g. the Gulf Stream, Fofonoff, 1981) and in shallower water at the boundary between stratified and tidally-mixed fluid (e.g. the North Sea, Hill et al., 1993). In the latter case the front is advected by the tide and there are also variations in tidal mixing, so that the front is not so well defined.

The basic process in the generation of the eddies is that the density difference across the front drives a flow (e.g. light fluid over dense), with the flow direction initially perpendicular to the front. The Coriolis force results in the flow direction turning until (after a timescale of about a day) the flow is parallel to the front, with flow in opposing directions either side of the front. The flow is then in geostrophic balance, with the pressure difference due to the density difference opposed by the Coriolis force. If the front is stable it presents a barrier to mixing between the water masses either side of the front. However, the flow may be unstable due to waves on the front which grows into eddies and this will enhance mixing across this feature. The eddies shown in the LANDSAT image here are rotating in the correct sense and are of the correct scale for this type of instability.

This type of instability has been modelled in the laboratory (Griffiths and Linden, 1981, 1982) and mathematically (Killworth et al., 1984). A fresh water layer was produced next to a vertical boundary either by the constant introduction of fresh water at the boundary or by the sudden release of freshwater retained originally behind a solid wall. In both cases, waves formed on the front between the fresh and salt water (provided particular instability criterion were satisfied). The instability is a mixed one in that some energy is drawn from the mean shear and some from the potential energy released as the fresh water spreads out. The waves grew into eddies similar to those described here, with the centre of the eddies lying initially on the approximate position of the original front.


34°00'
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N
ERDEMLI
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SCALE
GÖKSU RIVER
LI-1
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LI-4
LI-5
100m
200m
300m
400m
500m
TARSUS RIVER
SEYHAN RIVER
APRIL-1982
MAY-1982
DEPTH (m)
SALINITY (‰)
37.5
38.5
39.0
39.20
39.25
39.30
39.34
39.35
39.30
TEMPERATURE (C°)
18.5
16.5
22
21
20
19
18
17
DENSITY (σt)
27
28
29
27.5
28
28.5
29

Fig. 4. Contrast-enhanced satellite (LANDSAT, band 4 (visible)) image of a section of the southern Turkish coastline (Silifke, in the southwest, towards Mersin (see Fig. 1)). High turbidity inshore waters and flow features are shown dark, against the lighter low turbidity offshore waters.

Griffiths and Linden (1981, 1982) found the condition for instability in terms of a Froude number $F=f^2L^2/(g'h)$ where f is the Coriolis parameter (10^{-4} s^{-1}, in the present case), L the width of the current (about 10 km if taken to be distance from the coastline to the centre of the eddies), h the depth of the upper layer (about 10 m here) and g' the reduced gravity, equal to the gravitational acceleration scaled by the relative density difference between the layers (here about 0.1%, giving g' approximately 0.01 m s^{-2}). Thus, in the present case (Fig. 3) the Froude number is approximately 10. The theoretical analysis by Griffiths and Linden (1981) give critical Froude numbers in the range 2 to 5 (for the depth ratios appropriate to the present case), but their experiments did not exhibit instability until F was at least 10 and sometimes up to 100. The Froude number for the low salinity water layer off the Turkish coast is thus in the range where instability would be expected.

A useful quantity when considering this type of flow is the Rossby radius of deformation, $R=(g'h)^{\frac{1}{2}}/f$, which is about 3 km for the example being considered now. Killworth et al. (1984) calculated non-dimensional wave numbers and wavelengths for the fastest growing instabilities in terms of the ratio of total depth to that of the upper layer, $r=H/h$. For the present case the total depth changes rapidly, but the value $H=100$ m (giving $r=10$) is a reasonable approximate average. For the fastest growing wave the wave number is found to be $\varepsilon_{max}=1.15\ (r\text{-}1)^{-1/4}$ for which the growth rate is $\varepsilon c_i=0.31\ (r\text{-}1)^{-3/4}$. For the present case this gives a wave number of 0.66, and thus a wave length of $2\pi R/0.66=29$ km, which compares well with the observed distance between the centre of the eddies. The dimensional growth rate is $(f\varepsilon c_i)=0.53$

Fig. 3. Hydrographic structure of the continental shelf waters, showing the presence of low salinity nearshore surface waters in April and May 1982 (see text). Hydrographic stations shown on the figure.

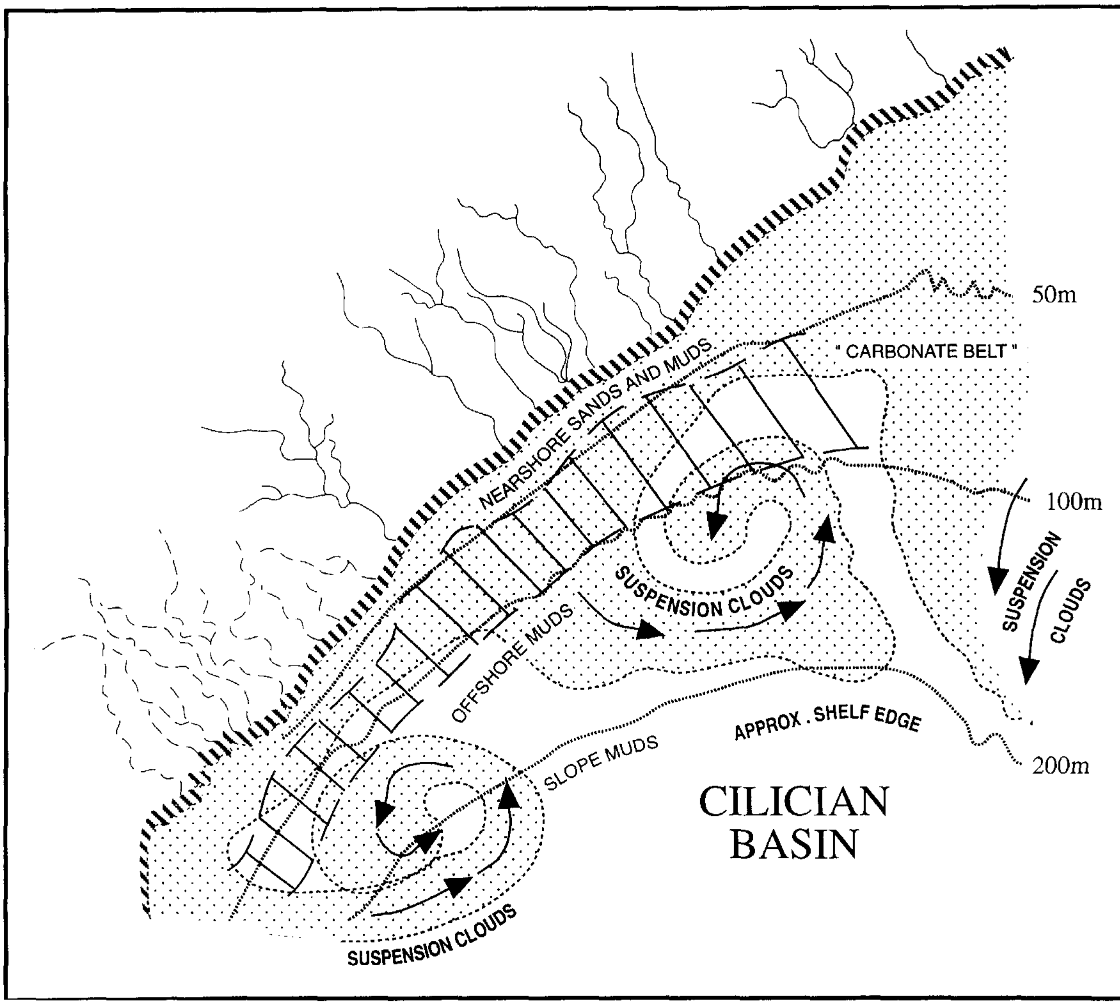

Fig. 5. Generalised interpretation of the image shown as Fig. 4, in relation to the coastline, river supply, shelf sediment distribution and offshore bathymetry.

days^{-1}, which gives growth by a factor of exp (0.53) = 1.7 in one day. The predicted frequency for the oscillation of the wave is $(f\varepsilon c_r) \approx (f\varepsilon c_i) =$ 0.53 days^{-1}, giving a period of $2\pi/0.53 = 12$ days, and the predicted phase speed is $fRc_r = 2.8$ cm s^{-1}. Unfortunately, no observations are available over the period of time which would be necessary for the comparison of these estimates for the oscillation, propagation and finally growth of the waves into the observed eddies. The effect of the sloping bottom has not been fully analyzed, but the experiments of Griffiths and Linden (1981) suggest that the sloping bottom would result in shorter wave lengths.

Well-defined fronts and eddies as observed here are not normally seen at this scale in shallow water. They are only possible where a front can be established and allowed to develop in the absence of the strong tidal mixing and advection, which occurs normally in shallow seas. Where such fronts develop they obviously provide a barrier to the transport of suspended sediment. If the conditions for instability exist, however, eddies will form and can be important agents of transport across the front. For the type of situation being discussed, the instability criterion (Froude number higher than about 10) will be satisfied once the width of the low salinity water layer is sufficiently large enough.

Only some of the theoretical predictions could be tested in this short note. The predictions are known to be reasonable for large scale flows (Killworth et al., 1984), but it would be useful if they could also be established for smaller scale flows, such as the one presented here.

The system of gyres described in the short note appears to be an effective process whereby fine-grained sediment normally trapped in a shore parallel stream close to be coastline, can be dispersed over the adjacent shelf. These gyres, which develop along the density discontinuity between the nearshore sediment-laden waters and the offshore shelf water can extend a considerable distance seawards and lead to supply and deposition of mud over the entire shelf, as they do off the southern Turkish coastline (Fig. 5); they even supply sediment to the neighbouring deep water areas. As these gyres migrate alongshore they may lead, therefore, to deposition over a considerable area parallel to the coastline. This situation may in many cases not be continuous, but occur only episodically, when the necessary contrasts between coastal and shelf waters develop. This, it appears, is largely controlled by discharge of water and sediment from the adjacent land areas, as generally this factor is much more variable than the shelf circulatory system.

With the increasing availability of spaceborne and airborne imagery, the identification and extent, here and elsewhere, of such phenomena will undoubtedly become easier and may assist in the understanding of the dispersion distribution of sediments over continental shelves.

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