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Marine Geology 192 (2002) 321–333

MARINE GEOLOGY
INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS

www.elsevier.com/locate/margeo

Upper slope sediment waves in the Cilician Basin, northeastern Mediterranean

V. Ediger [a], A.F. Velegrakis [b,*], G. Evans [b]

[a] *Institute of Marine Sciences, Middle East Technical University, Erdemli/Icel 33731, Turkey*
[b] *School of Ocean and Earth Science, University of Southampton, Southampton Oceanography Centre, European Way, Southampton SO14 3ZH, UK*

Received 10 May 2000; received in revised form 11 January 2002; accepted 2 August 2002

Abstract

Large sediment waves have been observed within the upper slope deposits of the Cilician Basin (northeastern Mediterranean), at the interfluve between two submarine canyons present offshore of the Mersin Shelf. There are several generations of sediment waves stacked within the sedimentary sequence, with the most recent bedforms found on the seabed in an area consisting of fine-grained sediments. The surficial sediment wave field, estimated to cover an area of ∼55 km^2, is found at water depths between 250 and 310 m. The buried sediment wave fields have similar dimensions, but they are located further downslope. Wave dimensions increase with water depth and depth in the sedimentary sequence. The largest bedforms reach 40 m in height and 1.8 km in length. Most waves appear to have been migrating upslope, i.e. towards the north/northeast, and this migration direction is mostly consistent throughout the sedimentary sequence. This consistency indicates similar mechanisms of formation and maintenance over a considerable time interval. The morphology and migration pattern of the observed bedforms suggests that sedimentation in the Cilician Basin during wave formation has been controlled by near-bed flows resembling those generated by the present Asia Minor Current, although these flows may have been stronger in the past than they are at present.

Keywords: deep-water sediment waves; submarine canyons; continental slope; northeastern Mediterranean; Asia Minor Current

1. Introduction

The rugged morphology of the eastern Mediterranean is associated with complex and climatically sensitive flows (Malanotte-Rizzoli and Hecht, 1988; Roether et al., 1996; Aksu et al., 1999; Tsimplis et al., 1999; Tsimplis and Baker, 2000). Such flows, particularly those along the continental margins (Wu and Haines, 1998) and those related to the sills between adjacent sub-basins (e.g. Tsimplis et al., 1997; Astraldi et al., 1999), are likely to interact with the bottom sediments and alter the seafloor sedimentary morphology. However, there have been limited reports of flow-generated bedforms, such as deep water sediment waves, from the area; those that have been described are mostly restricted to the western and

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* Corresponding author. Present address: Department of Marine Science, University of the Aegean, University Hill, Mytilini 81100, Lesvos, Greece. Tel.: +30-2510-36814.
E-mail address: afv@aegean.gr (A.F. Velegrakis).

0025-3227/02/$ – see front matter © 2002 Published by Elsevier Science B.V.
PII: S0025-3227(02)00562-5

central Mediterranean basins (e.g. Marani et al., 1993).

The objective of the present contribution is to report the presence and describe the morphological characteristics and seismostratigraphy of sediment waves observed in deposits of the upper continental slope of the northeastern margin of the Cilician Basin (northeastern Mediterranean Sea).

2. Environmental setting

2.1. Physiography and sediments

The study area (Fig. 1) is located offshore of the Mersin Shelf at the northeastern margin of the Cilician Basin. The Cilician Basin is a small peripheral basin of the eastern Mediterranean (Wong et al., 1971; Hsu and Bernoulli, 1978; Biju-Duval et al., 1979) located between the Cyprus and the southern Asia Minor (Turkish) coast. The basin is bounded to the north and south by the Taurus Mountains and northern Cyprus coasts, respectively, and to the east by the Misis fault block, which forms a submarine ridge between the Misis Mountains (Asia Minor) and the northeastern extremity of Cyprus (Evans et al., 1978). The shelf bordering the Cilician Basin to the north is generally narrow, with the distance between the coast and the shelf break (located at ~200 m water depth; Ediger, 1990; Evans et al., 1995; Ediger et al., 1997) being generally less than 15 km; however, offshore of the Seyhan/Tarsus/Ceyhan deltaic system the shelf widens significantly, reaching a width of ~40 km. Two submarine canyons, the relief of which exceeds 200 m at some sections, are present offshore Erdemli. These canyons, which may represent major conduits for sediment transfer from the Mersin Shelf to the deep environments of the Cilician Basin, merge on the lower slope at ~850 m water depth to produce a single canyon (Fig. 1).

The continental shelf bordering the Cilician Basin to the north has a low relief except for some minor irregularities (a few metres in scale) on the mid-shelf, which are considered to be old coastal barriers cloaked by modern sediments (Evans et al., 1995). Shelf sediments consist of terrigenous sediments inshore and shells/shell debris at the mid-shelf (at water depths of 50–100 m), whereas pro-deltaic sediments are found offshore of the Seyhan/Tarsus/Ceyhan and the Goksu rivers (Fig. 1). The outer shelf, between the 100 m bathymetric contour and the shelf edge, is associated with fine sediments with abundant planktonic skeletal debris, whereas the surficial sediments of the continental slope and basin consist of clayey silts and silty clays (Shaw, 1978; Shaw and Bush, 1978; Aksu et al., 1992; Ediger et al., 1997). Seven depositional units, considered to represent different progradational phases of the deltaic systems of the area during the Quaternary, have been identified above the acoustic basement at the Cilician continental margin; their total age is interpreted to be 0.6 Myr (Aksu et al., 1992).

Few studies exist on the nature/mechanisms of the recent sedimentation in the area; these have shown that the Seyhan/Tarsus/Ceyhan River system and the Lamas and Goksu rivers (Fig. 1) are the major sources of terrigenous sediment on the Mersin Shelf (Bodur, 1987; Ediger, 1990; Evans et al., 1995; Ediger et al., 1997). The sediment supply varies seasonally, with high discharge following the spring thaw of the snow caps of the adjacent Taurus Mountains. The confinement of high turbidity water to the inner and mid-shelf (Collins and Banner, 1979; Evans et al., 1995) suggests that the riverine sedimentary input generally remains close to the coast. However, coastal gyres, which develop at certain periods due to frontal instabilities (Evans et al., 1995), may present an effective mechanism for dispersion of fine sediments supplied by the rivers to the outer shelf and the adjacent deep basin.

2.2. Hydrodynamics

Today, the major water circulation feature of the study area is the Asia Minor Current (AMC), a jet of open sea water which enters the region from the east and flows along the shelf off the Seyhan/Tarsus/Ceyhan delta (Fig. 1); it then turns southwest to flow parallel to the southern Asia Minor coast in the region of the study area

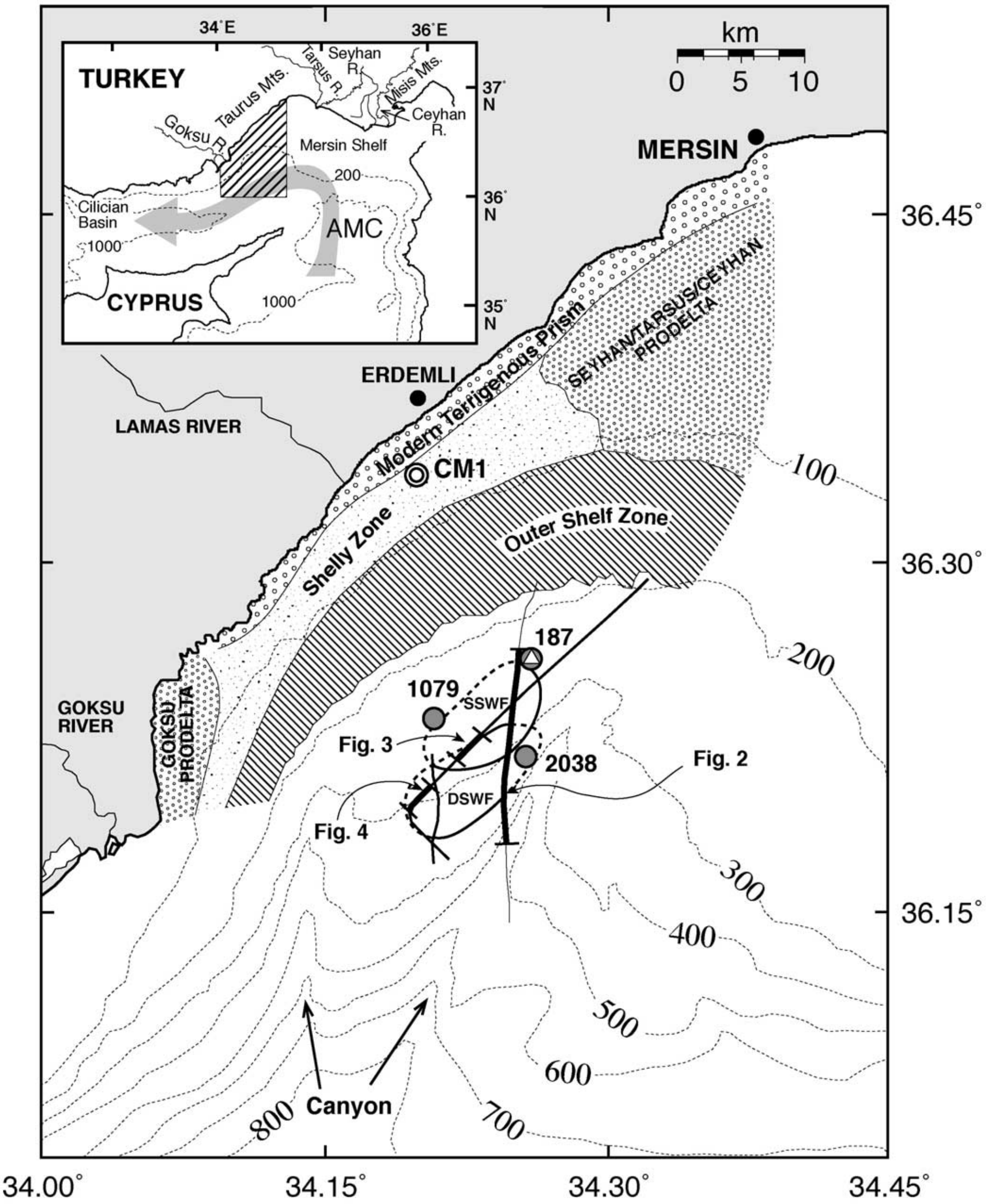

Fig. 1. Location map showing bathymetry in metres (after Hall, 1994), seismic tracks (shown in Figs. 2–4), location of the vibrocore (triangle) and grab samples (circles) and position of the current meter observations (CM1) available from this area (Unluata et al., 1978, 1983). The limits of the surficial (most recent) sediment wave field (SSWF) are also shown; note that sediment waves found lower down in the sedimentary sequence form a field (DSWF) which is located further downslope. The surficial sediment distribution shown on the shelf is according to Ediger et al. (1997). The prevailing course of the Asia Minor Current (AMC), shown in the inset figure, is also indicated.

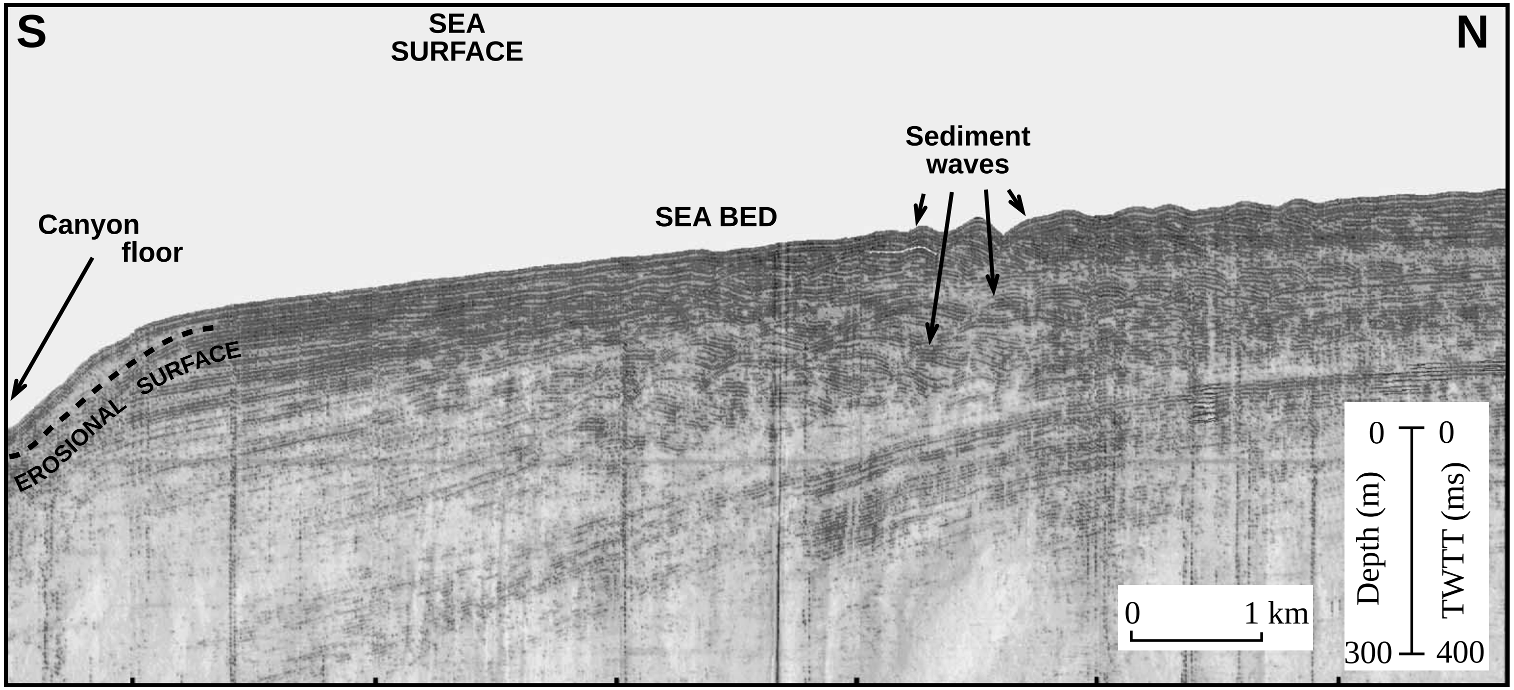

Fig. 2. Sparker seismic profile and its interpretation across the interfluve between two submarine canyons offshore of Erdemli (for location see Fig. 1). Note the stratified reflectors on the offshore (left) section of the record and the presence of sediment waves in the middle and inshore sections. Also note the presence of an erosional surface and an onlapping homogeneous and more acoustically transparent unit at the canyon wall.

(Ovchinnicov, 1966; Roussenov et al., 1995). The AMC results from the re-organisation of different filaments/jets produced by the interaction between different water circulation cells of the eastern Mediterranean (Malanotte-Rizzoli and Hecht, 1988; Ozsoy et al., 1989). Although the AMC is instrumental in the maintenance of the water circulation patterns of the eastern Mediterranean (Ovchinnicov, 1966; Ozsoy et al., 1987, 1989; Malanotte-Rizzoli and Hecht, 1988; Tsimplis et al., 1997; Wu and Haines, 1998), there is little information on its course, intensity, depth of flow and temporal variability. Our knowledge of its specifics is based mainly on numerical modelling (Roussenov et al., 1995; Wu and Haines, 1998) and sparse hydrographic observations (e.g. Ozsoy et al., 1989); no hydrodynamic measurements, to our knowledge, are available from the offshore areas of the Cilician Basin.

On the basis of the available information, the present-day AMC characteristics can be summarised as follows. Firstly, it is thought that the AMC flows along the isobaths of the northern margin of the Cilician Basin (Roussenov et al., 1995; Wu and Haines, 1998). Secondly, model results have shown that the AMC reaches its peak intensity in the winter and early spring (with mean speeds of ~5 cm/s), but is much weaker in the summer and autumn (Roussenov et al., 1995). Finally, the AMC has been shown to have a temporally variable baroclinic component, i.e. whereas the AMC is a well-developed westerly/southwesterly water jet occupying the whole water column in winter/spring, the deep water flow (below ~200 m) weakens and reverses during the summer. The AMC also penetrates onto the shelf, where it has been observed to flow towards the SW (off the Erdemli coast, Station CM1 in Fig. 1) and to be significantly stronger (mean speeds which may reach ~15 cm/s) than predicted by modelling results (Unluata et al., 1978, 1983). The shelf flow is also influenced by wave- and wind-generated currents (Unluata et al., 1983), as well as density-related fronts (Evans et al., 1995); in contrast, tidally generated flows are negligible in the micro-tidal Mersin Shelf (maximum tidal range less than 0.5 m) (Ediger et al., 1997).

3. Data

A standard EG&G sparker source was used during the survey. Its energy and firing interval varied between 1 and 6 kJ and 1 and 4 s, respectively, and returns were recorded in the 80–200-Hz frequency range. Information from three surficial sediment samples (obtained with a large grab having a sampling depth of 10–15 cm) and a gravity core (1.4 m long) collected during the 1974 RV/RRS *Shackleton* cruise, is also used in the present study (Fig. 1).

4. Results

4.1. The sediment wave fields

The sediment waves were observed offshore of the Mersin Shelf break, on the eastern side of an interfluve between two submarine canyons offshore of Erdemli (Fig. 1). In this area a sedimentary wedge is present, which is shown in seismic records to contain a large number of sub-parallel, medium to high amplitude reflectors which dip with a small angle towards the canyon thalweg (Fig. 2). The distal end of these reflectors is truncated by an erosional surface, on which a homogeneous and acoustically more transparent unit appears to onlap, forming a high-angle deposit at the canyon wall. Such reflector geometry suggests that this part of the sedimentary wedge may have an erosional margin (Ross et al., 1994), generated by erosion from (a) strong currents present at the heads of submarine canyons (Hotchkiss and Wunch, 1982; Gardner, 1989; Noble and Butman, 1989) and/or (b) gravity-related processes.

The sedimentary wedge is also intergradational in character, as its distal section is characterised by parallel and sub-parallel reflectors, whereas its proximal and middle sections (from 250 to 360 m water depth) are associated with complex stacking patterns of generations of sediment wave fields (Fig. 2), the most recent of which are found on the seabed (at water depths between 250 and 310 m); this suggests that the mechanisms responsible for wave generation could still be active.

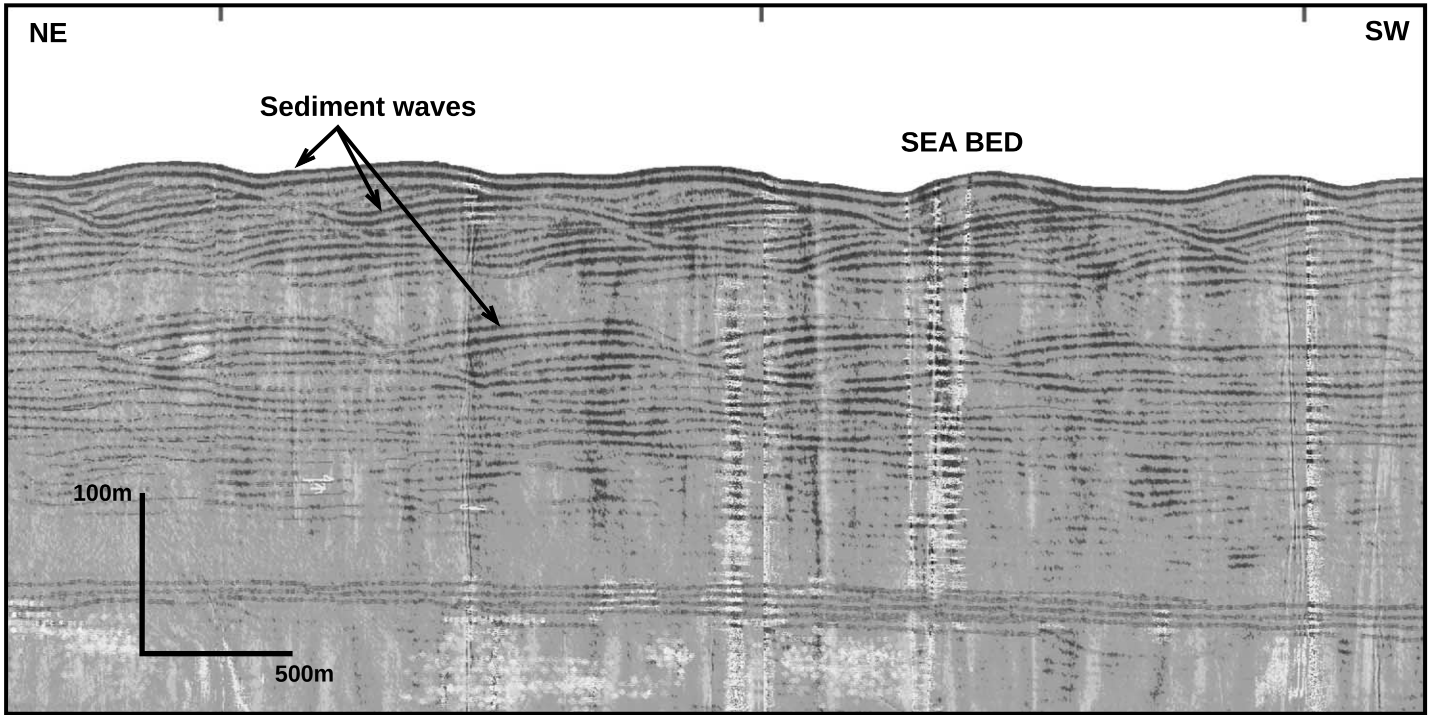

Fig. 3. Seismic profile showing the internal structure of sediment waves in the inshore part of the deposit. For location see Fig. 1.

4.2. Sediment wave characteristics

The surficial sediment waves are commonly asymmetrical in cross-section, with their steeper flank facing upslope, i.e. towards the north/northeast (Fig. 2). They have heights reaching up to 30 m (mean height of ∼20 m) and apparent wavelengths of up to 700 m (their true wavelength and crest orientation could not be determined due to the low spatial resolution of the seismic survey and the lack of side-scan sonar observations). Their internal structure is characterised by alternating strong and weak reflectors, the geometry of which appears to follow the seabed morphology (Figs. 2–4).

Below the surficial bedforms, an older generation of sediment waves is found (Figs. 3 and 4), which are also characterised by mean heights of ∼20 m. However, these sediment waves appear to be generally longer than those found on the seabed. Their apparent wavelengths vary with distance from the coast, i.e. from the shallower to the deeper waters, with wavelengths reaching ∼900 and ∼1400 m in the northeastern and the deeper southwestern portion of the sediment wave field, respectively.

The oldest generation of sediment waves within the sedimentary sequence consists of large asymmetric bedforms (with mean heights from trough to crest of approximately 40 m and apparent wavelengths of 1800 m). These bedforms lie above a flat (or slightly undulating) bounding surface, which overlies a more uniform and acoustically transparent unit (Fig. 3). The waves exhibit complex patterns. Each wave is confined by major bounding surfaces and contains moderate to high amplitude reflectors (secondary bounding surfaces) with an apparent similar orientation; these dip gently upslope at an average angle of 2°–3° and are commonly truncated on the downslope flank of the wave (Fig. 4). In addition, the vertical distance between reflectors also appears to be larger on the upslope flank of the waves (Fig. 4), suggesting higher sedimentation rates on this flank. The sediment waves appear to migrate towards the northeast at a low angle to the horizontal.

Generally, it appears that the morphology of

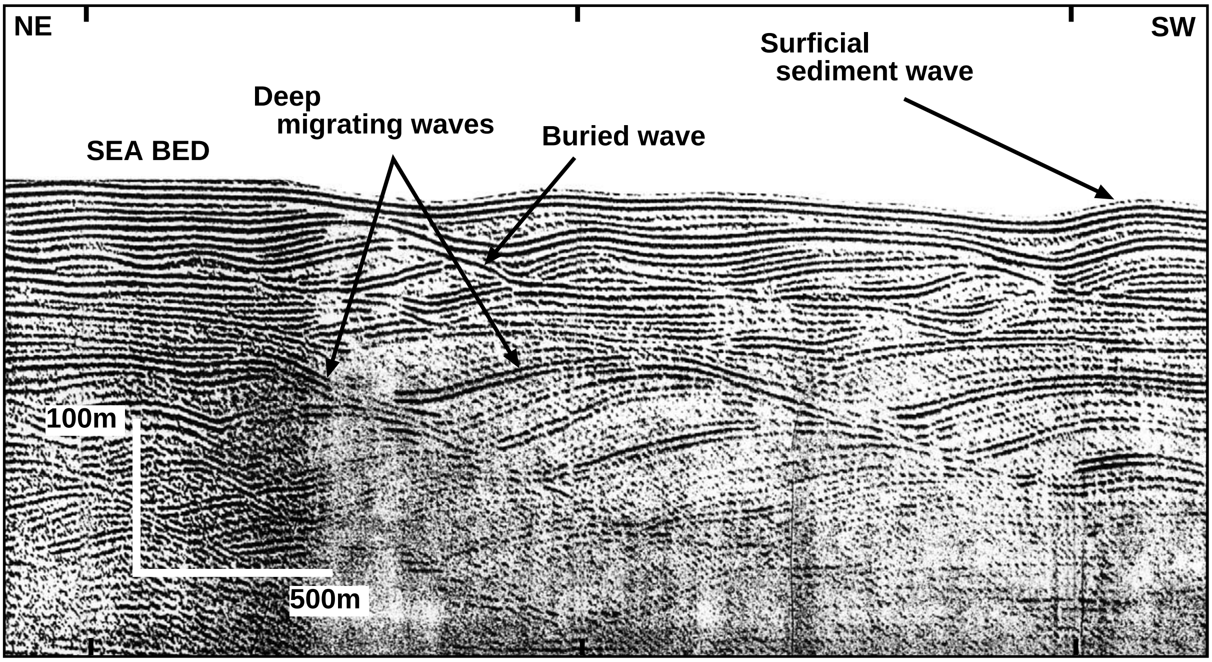

Fig. 4. Seismic profile showing differences in morphology and internal structure between different generations of waves. For location see Fig. 1.

the sediment waves observed in the study area is variable, with their overall shape and size depending on the location both with regard to the coast (and water depth) and also the depth in the sedimentary sequence. The dimensions of the observed sediment waves appear to increase from northeast to southwest (from shallower to deeper waters) and with depth in the sedimentary sequence. Moreover, although the aerial extent and spatial resolution of the seismic survey do not allow accurate delimitation of the stacked fields of sediment waves, it appears that (a) the different fields have similar dimensions, each covering an area of ∼55 km^2 and (b) the surficial (most recent) field is displaced towards the northeast, i.e. towards shallower water in relation to those fields deeper in the sedimentary sequence (Fig. 1).

4.3. Sediments

With regard to the nature of the sediments forming the sediment waves, information is available only for the uppermost part of the deposits on the basis of a few samples collected during the 1974 RV/RRS *Shackleton* cruise. Grab samples show that surficial sediments in this area are fine-grained (sand content less than 4%), containing significant quantities of $CaCO_3$, but little organic carbon (Table 1). A core recovered from the area also shows that the uppermost 1.4 m of the deposits is likely to be mostly fine-grained, poorly bedded, bioturbated, with rare primary laminations and occasional shell fragments and concentrations of *Mycelia* fungi (Fig. 5). However, the uppermost sedimentary layer in the core (between 2 and 9 cm from the surface) appears to consist of coarser material and forms a sharp, erosional basal contact with the underlying finer sediments, suggesting either sediment winnowing under intensified bottom currents (e.g. Viana et al., 1998) or changes in the nature of sedimentary inputs. This apparent grain-size difference between the surficial (grab) and core sediment samples for the topmost layer of the deposit is likely to be the result of mixing of the thin layer of coarse surficial sediments with the underlying finer sediments during grab sampling.

Table 1
Characteristics of the surficial sediments at the area of sediment waves

Sample no.	Sand (%)	Silt (%)	Clay (%)	Mud (%)	$CaCO_3$ (%)	$C_{org.}$ (%)
1079	4.1	46.6	49.3	95.9	78.2	0.67
187	2.3	42.6	55.1	97.7	74	0.36
2038	3.7	47.7	48.6	96.3	68.7	0.31

For location of the grab samples, see Fig. 1.

Without deeper ‘ground-truth’ data, the textural characteristics of the sediments forming the sediment wave fields cannot be ascertained. The sedimentary sequence of the continental margin of the Cilician Basin is likely to consist mostly of fine-grained sediments (see Aksu et al., 1992). However, the abundance of moderate to high amplitude reflectors within the seismostratigraphic sequence indicates frequent changes in the sediment acoustic impedance, which may also suggest changes in the texture, density and/or structure of the deposited sediments. Thus, it may be possible that layers of coarser sediments generated by increased seabed winnowing and/or changes in the nature of the sedimentary input are also present.

5. Discussion

The different generations of sediment waves found between the submarine canyons off the shelf break of the Mersin Shelf indicate significant sediment mobility in this area for a considerable part of the Quaternary, when the Cilician margin deposits are considered to have been formed (Aksu et al., 1992). Moreover, the processes involved in wave formation appear to have been active until recently, as sediment waves still control the seabed morphology. Whether these bedforms have been formed as a result of processes which are (a) bottom current-controlled, (b) gravity flow-controlled or (c) a combination of both, cannot be determined on the basis of the available data. The proximity of the submarine canyons to the sediment wave fields indicates that gravity flows might have influenced their formation (e.g. Weber et al., 1994; Rebesco et al., 1996; Faugères et al., 1999; McHugh and Ryan, 2000). However,

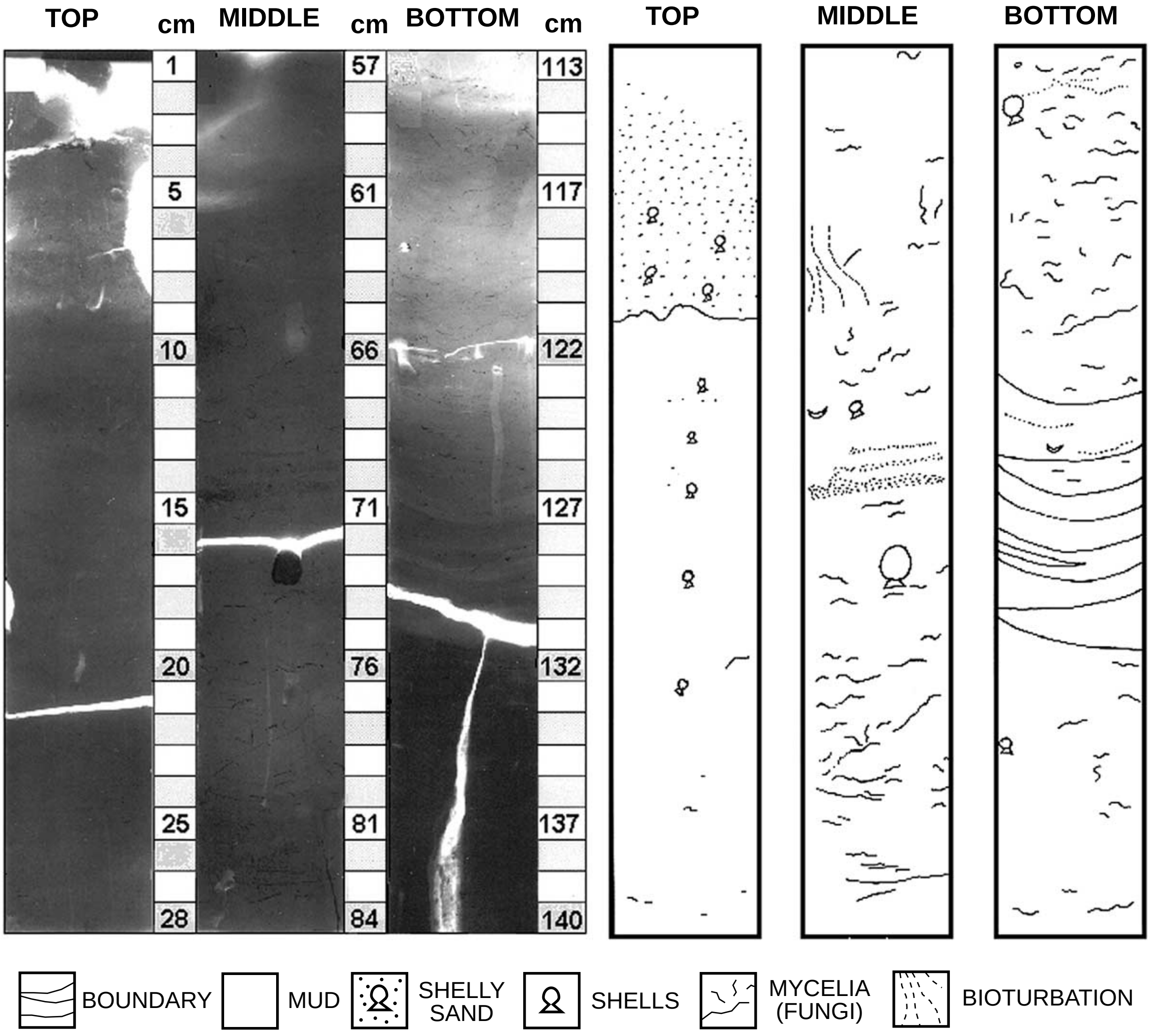

Fig. 5. X-ray radiographs of Core 187 with interpretation (for location see Fig. 1). Note that only selected parts of the core are shown.

the location of the sediment wave deposits, which occur on the upper slope and are separated from the canyon heads and walls by zones with no waves, may instead suggest dominance of bottom current-related processes.

With regard to the direction of the flows that could have generated and maintained the stacked sediment wave fields, an insight might be gained by a closer look at their seismostratigraphy. The internal architecture of the large sediment waves at the bottom of the sequence appears similar to that of the Type 1 subaqueous dunes of Richards et al. (1987) (see also Jopling and Walker, 1968), suggesting dominance of the traction (bedload) mode of sediment transport over the suspension fallout. In contrast, the sediment waves found higher up in the sedimentary sequence are less asymmetric and have an internal architecture similar to that of the Type 2 subaqueous dunes of Richards et al. (1987), suggesting increased fallout from suspension. Richards et al. (1987) have suggested that, in both cases, erosion occurs upstream and sedimentation downstream of the wave crest. Thus, according to this model, the upslope migration of the observed sediment waves indicates the presence of an upslope-flowing current, while their internal reflector patterns suggest particular relationships between the suspension and traction modes of sediment transport.

The interpretation of Richards et al. (1987) was based on analogies with shallow-water sand dunes. However, due to different hydraulic characteristics of fine-grained sediments, such interpretation might not be appropriate in the case of fine-grained sediment waves found in deep waters. Flood (1988) showed that such internal reflector patterns in deep-water fine-grained bedforms do not necessarily translate into downstream bedform migration; instead, they may be the result of internal lee waves generated over the bedforms. Under these conditions, sediment deposition (and bedform migration) occurs upstream of the wave crest, whereas less deposition (and possibly erosion) takes place downstream. Therefore, if the sediment waves found in the study area have been formed (or modified) by such flow–sediment interactions, then their migration direction would indicate a current flowing to the southwest.

With regard to the magnitude of the flows that may have generated the observed bedforms, a simple estimation can be carried out. Assuming recently deposited sediments are non-cohesive (but see Mehta, 1989, 1991) and an absence of organic clay aggregates (Van Rijn, 1993; Jago and Jones, 1998), using the Mantz (1977) threshold approximation and a drag coefficient (C_D) of 0.003 at 1 m above the bed (Dyer, 1986), it was found that currents of 36.5 cm/s and ~13 cm/s at 1 m above the bed are required for the mobilisation of sediments with grain size of 0.064 and 0.002 mm, respectively. Therefore, it appears that substantial near-bed flows (greater than 13 cm/s at 1 m above the bed, at least) are necessary for mud erosion and transport. These estimations are not very different from those of Flood (1988), who estimated that sediment erosion and transport across a mud wave (and, thus, wave migration) occur at current speeds of 17–25 cm/s (at 20 m above the bed).

The Asia Minor Current flowing through the Cilician Basin has been regarded as the major hydrodynamic forcing in the area at present (Ovchinnicov, 1966; Roussenov et al., 1995; Wu and Haines, 1998). However, it is now known that secondary flows, induced by either riverine/coastal interactions (Evans et al., 1995) and/or wind forcing (Unluata et al., 1978, 1983) are superimposed upon the Cilician Basin continental margin circulation. Our results show that, if the observed sediment waves have indeed been formed by upslope-flowing currents according to the Richards et al. (1987) model, then more complicated flow patterns than those existing at the present time are likely to have been operating during the time of sediment wave generation. In contrast, if the observed bedforms have been formed in accordance to the Flood (1988) model (i.e. indicating upcurrent wave migration), then the present investigation provides the first evidence of the effects of a persistent southwesterly flow through the Cyprus Strait on the seabed sediments. It appears that the Asia Minor Current has been fixed in its present position for a long period of the Late Quaternary (at least since the time of formation of the deepest waves in the sedimentary sequence). In addition, the flow-speed estimations carried out in the present study suggest stronger flows for this current (i.e. in excess of 13 cm/s at 1 m above the seabed) than those predicted for the present Asia Minor Current by numerical models (Roussenov et al., 1995).

The importance of the nearby canyons in flow generation/modification cannot be established on the basis of the available evidence, as there are no comprehensive data sets to analyse and fully understand even the present hydrodynamic environment of the study area. Nevertheless, it is now known that non-linear flows are generated by flow–topography interactions at the continental slope (Thorpe, 1992). The flow regime within submarine canyons is particularly complex with both up- and down-canyon secondary flows generated by interactions of the primary flow with the high relief topography (e.g. Hotchkiss and Wunch, 1982; Gardner, 1989; Noble and Butman, 1989). Karl et al. (1986) found large fields of sand sediment waves at the heads of the Bering Sea canyons, which exhibit similar characteristics (in terms of location, water depth, dimensions and migration direction) to the waves found on the upper slope of the Cilician continental margin. These authors suggested that the Bering Sea sediment waves have been formed and maintained by internal wave-generated currents at the canyon heads. Although there is no hydrodynamic (or other) evidence available to support a similar mechanism influencing the formation of the sediment waves in the study area, there is some evidence to suggest at least the present presence of internal waves in the area; Velegrakis et al. (1999) observed internal waves in a similar area (in terms of morphology and hydrodynamics) of the southern Asia Minor coast, in the vicinity of the Rhodes Strait to the west. However, the fact that the sediment waves investigated in the present study are several km from the canyon heads as well as the finer texture of their sediments suggests that such flows are not likely to be the dominant forcing responsible for their formation and maintenance.

6. Conclusions

Stacked fields of sediment waves have been identified within the deposits of the upper slope of the Cilician Basin (northeastern Mediterranean) at the interfluve between two submarine canyons offshore of the Mersin Shelf break. The most recent waves are found on the seabed, at water depths between 250 and 310 m, and their topmost layer is formed of fine-grained sediments. Due to the lack of suitable ‘ground-truth’ data it has not been possible to identify the exact nature of the sediment wave bearing deposits deeper in the sedimentary sequence; nevertheless, it is likely that they consist mainly of fine-grained sediments, probably intercalated with layers of coarser material. To our knowledge, these bedforms are the first deep-water sediment waves reported in the eastern Mediterranean, and the shallowest large fine-grained sediment waves observed anywhere in the world.

It seems that the processes responsible for wave formation and maintenance have been active for a considerable part of the Quaternary, since there are several generations of these waves within the sedimentary sequence. Moreover, as the most recent of these waves are found on the seabed, the processes involved in their maintenance have remained active until relatively recently.

The sediment wave dimensions vary with location and depth within the sedimentary sequence, with larger waves found at greater water depths and deeper in the sequence. The surficial sediment wave field is estimated to cover an area of $\sim$55 km^2, whereas the buried wave fields are thought to have similar dimensions, but appear to be displaced downslope.

It appears that wave migration has been consistently upslope (or towards the north/northeast), opposite to the present water circulation pattern of the area, which is dominated by the southwesterly/westerly flowing Asia Minor Current; this is in agreement with existing models of fine-grained sediment wave migration. However, flow speeds estimated for sediment mobilisation across the waves (and, thus, wave migration) are much higher than those predicted for the present Asia Minor Current by numerical models.

Acknowledgements

This contribution is the result of a multidisciplinary programme of the Institute of Marine Sciences-METU (Erdemli, Turkey) and the School of Ocean and Earth Sciences (Southampton University, UK); the support of the British Council is gratefully acknowledged. We also acknowledge the help of the captain, crew and scientists onboard RV *Shackleton*, during the Imperial College (University of London) research cruises in 1972–1974, as well as Kate Davis (School of Ocean and Earth Science, University of Southampton) for her masterful figure drawing. R.B. Wynn, G. Ercilla and M.B. Collins, whose comments immensely improved the manuscript, are gratefully acknowledged.

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