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Russell B. Wynn [a,*], Douglas G. Masson [b], Dorrik A.V. Stow [a], Philip P.E. Weaver [b]

[a] *SOES, Southampton Oceanography Centre, University of Southampton, Empress Dock, European Way, Southampton, Hampshire, SO14 3ZH, UK*

[b] *Challenger Division, Southampton Oceanography Centre, European Way, Southampton, Hampshire, SO14 3ZH, UK*

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[b] *Challenger Division, Southampton Oceanography Centre, European Way, Southampton, Hampshire, SO14 3ZH, UK*

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Abstract

Two sediment wave fields have been identified on the flanks of the western Canary Islands of La Palma and El Hierro, using a high-quality 2-D and 3-D dataset that includes GEOSEA and TOBI imagery, 3.5-kHz profiles, and short sediment cores. The La Palma sediment wave field covers some 20,000 km^2 of the continental slope and rise, and consists of sediment waves with wave heights of up to 70 m and wavelengths of up to 2.4 km. The wave crestlines have a complex morphology, with common bifurcation and a clear sinuosity. Waves have migrated upslope through time. Cores recovered from the wave field contain volcaniclastic turbidites interbedded with pelagic/hemipelagic layers. The wave field is interpreted as having formed beneath unconfined turbidity currents. A simple, previously published, two-layer model is applied to the waves, revealing that they formed beneath turbidity currents flowing at 10–100 cm/s^{-1}, with a flow thickness of 60–400 m and a sediment concentration of 26–427 mg/l. The El Julan sediment wave field lies within a turbidity current channel on the southwest flank of El Hierro. The sediment waves display wave heights of about 6 m and wavelengths of up to 1.2 km. The waves are migrating upslope, and migration is most rapid in the centre of the channel where the flow velocity is highest. This wave field has been formed by channelised turbidity currents originating on the flanks of El Hierro.

Keywords: Canary Islands; sediment waves; turbidity currents

1. Introduction

Sediment waves formed by turbidity currents have been described from a number of deep-water environments, including channel levees (Damuth, 1979; Normark et al., 1980; Carter et al., 1990; Piper and Savoye, 1993; McCave and Carter, 1997; Nakajima et al., 1998), channel floors (Malinverno et al., 1988; Kidd et al., 1998), and the margins of submarine fans (Howe, 1996). These sediment waves display wave heights of 1–70 m and wavelengths of 0.1–6 km, and generally occur on slopes of $< 1°$. Wave crests may reach 60 km in length and are aligned roughly perpendicular to the turbidity current flow direction. Profiles of 3.5-kHz indicate that the waves are often asymmetric, with a thicker upslope flank suggesting upslope migration. Wave dimensions generally decrease downslope.

* Corresponding author. Tel.: +44-1703-595000; fax: +44-1703-593052; e-mail: rbw1@soc.soton.ac.uk

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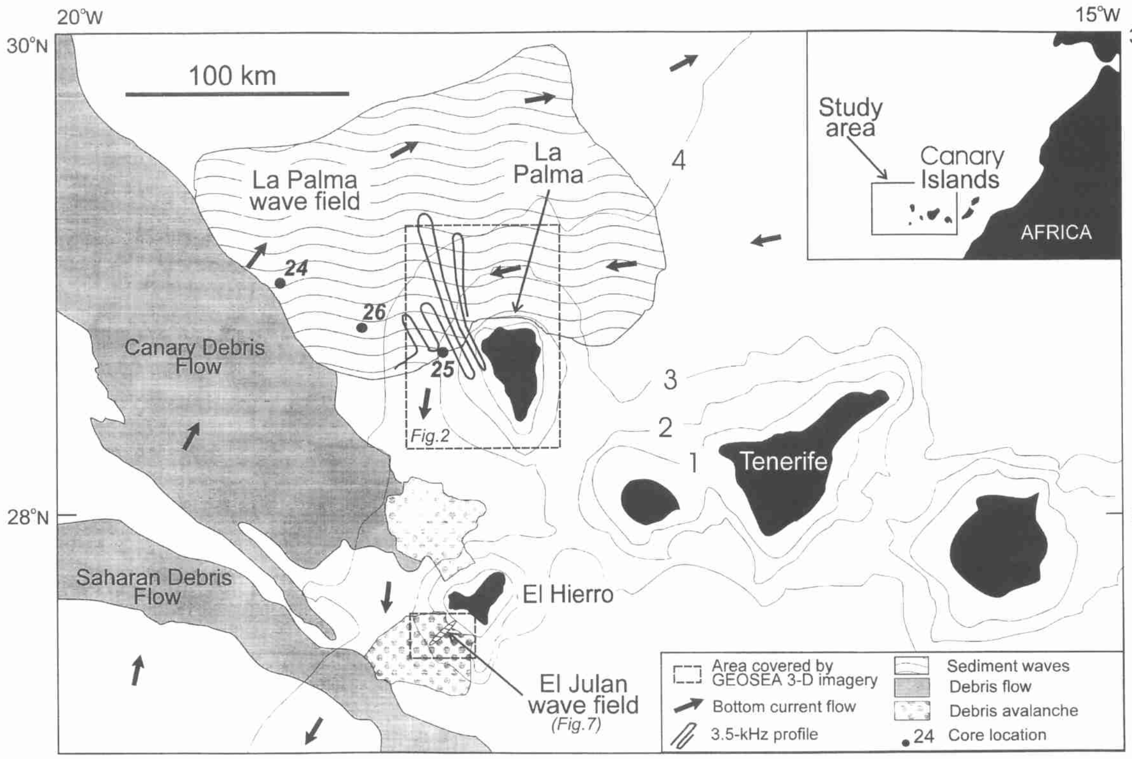

Fig. 1. Location map showing the regional setting and bathymetry of the sediment wave fields around the western Canary Islands. Boxes indicate the location of the GEOSEA images shown in Figs. 2 and 7. Bathymetric contours in kilometres.

Single-channel seismic reflection profiles have revealed that sediment wave sequences on levees may reach 400 m in thickness (Carter et al., 1990). Sediments are dominantly fine-grained, although some waves are composed of numerous thin-bedded sand/silt turbidites. A study of channel–levee overbank waves on the Amazon Fan revealed that on the upslope (upstream) flanks of the waves, turbidite beds were thicker and more numerous than on the downslope (downstream) flank (Shipboard Scientific Party, 1995). Previous hydrodynamic interpretations of turbidity current waves suggest they form as giant antidunes beneath low-velocity, low-concentration turbidity currents (Normark et al., 1980).

This study describes two sediment wave fields on the submarine slopes of the Canary Islands (Fig. 1), using a high-quality dataset obtained during RRS *Charles Darwin* cruise 108. Examination of the wave distribution and morphology, combined with detailed sedimentological analysis, has allowed the wave-forming processes to be interpreted.

2. Methodology

Many previous studies of turbidity current sediment waves have been restricted by a lack of core data and 3-D imagery. This limits the opportunity to interpret the wave-forming process with any certainty. The present study comprises TOBI and GEOSEA 3-D data collected during RRS *Charles Darwin* cruise 108, which took place in the autumn of 1997. In addition, a GLORIA mosaic and three sediment cores collected during earlier cruises have also been incorporated into this study (Masson et al., 1992). The six main types of data have been grouped as follows.

2.1. Multibeam bathymetry

The La Palma and El Julan sediment wave fields have been imaged by the Simrad EM12 multibeam echo-sounder. These bathymetric data have been processed with GEOSEA modelling software, which produces high-resolution 3-D images of the seafloor (Figs. 2, 3 and 7).

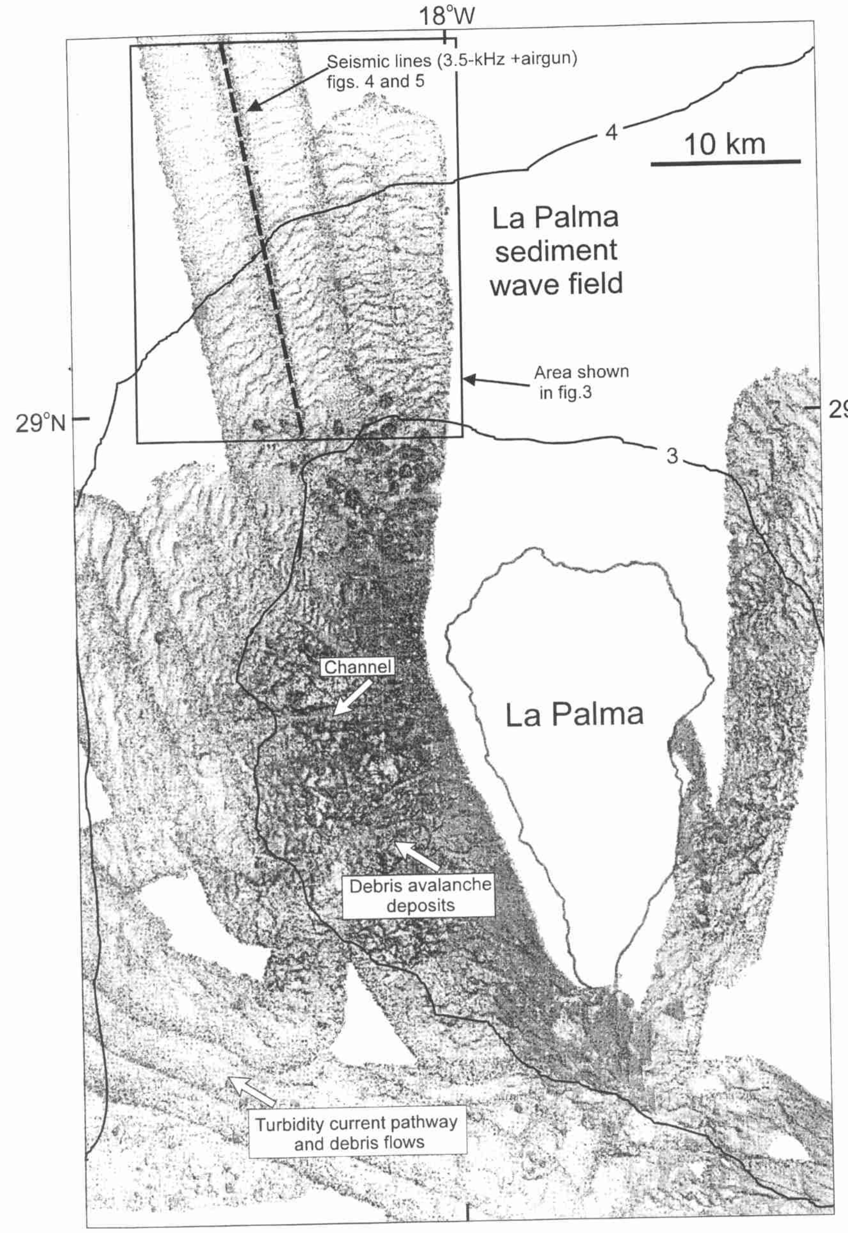

Fig. 2. GEOSEA 3-D image (plan view) of the La Palma sediment wave field. Note that wave crests are aligned roughly parallel to the bathymetric contours, and that the waves are not present on the southern flanks of La Palma. Bathymetric contours in kilometres. Box locates Fig. 3. Dashed line shows location of 3.5-kHz profile in Fig. 4 and airgun seismic profile in Fig. 5. Vertical exaggeration = ×10. Illumination is from the north.

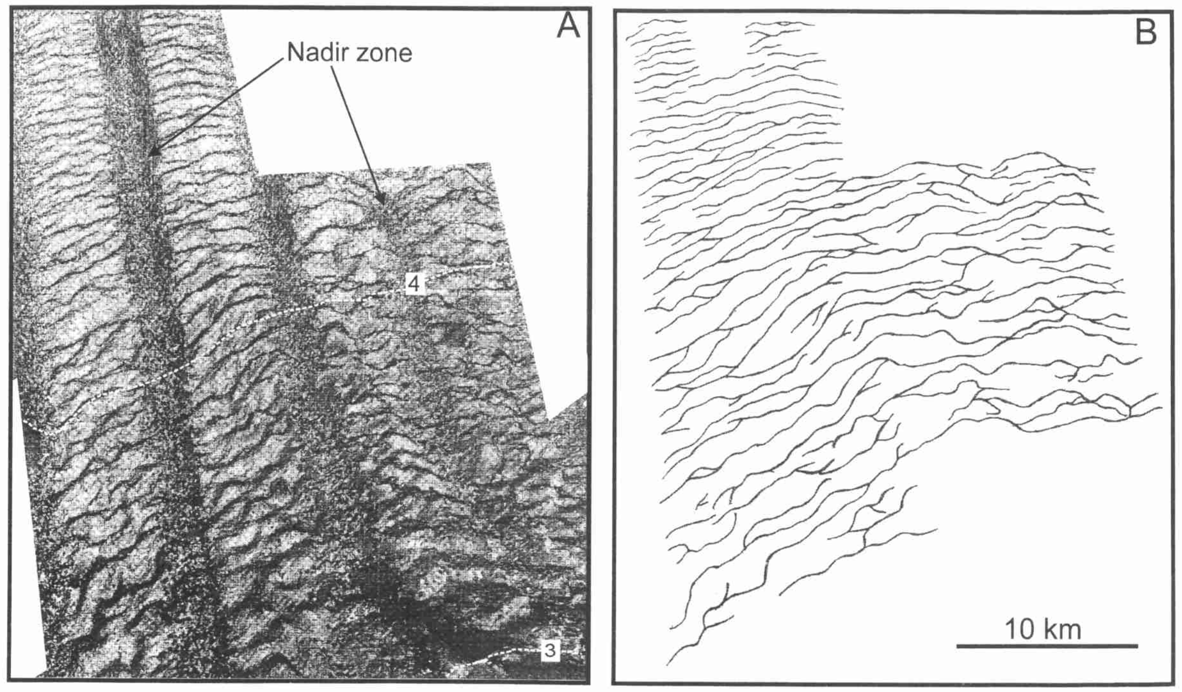

Fig. 3. (A) Enlarged GEOSEA 3-D image (oblique plan view) of the La Palma sediment waves. (B) Tracing of the wave crests shown in A. Note the common bifurcation and clear sinuosity of the crestlines, and the change in crestline orientation in response to the curve of the bathymetric contours. Bathymetric contours in kilometres. Vertical exaggeration = ×50. Illumination is from the north.

2.2. 3.5 kHz-Profiles

Most of the quantitative data from the La Palma wave field was obtained from a series of 3.5-kHz profiles that run perpendicular to the wave crests (Figs. 1 and 4). These data provided information on wavelength, wave height, thicknesses and migration direction. A review of the 3.5-kHz echo-character definitions applied to the Northwest African margin is presented in Wynn et al. (in press).

2.3. Airgun seismic profiles

A series of single-channel seismic profiles, made with a single 300 in.^{3} airgun, were collected across the La Palma wave field. The profiles used in this study were taken roughly perpendicular to the regional bathymetric gradient and the wave crestlines (Figs. 1 and 5).

2.4. GLORIA sonographs

GLORIA is a 6.5-kHz long-range side-scan sonar, with a swath width of up to 10 × water depth. It has surveyed a large section of the La Palma wave field. A modified version of the GLORIA interpretation scheme given by Kidd et al. (1985) is presented by Masson et al. (1992) and Wynn et al. (in press).

2.5. TOBI imagery

TOBI is a high-resolution side-scan sonar, with a swath width of about 6 km (Murton et al., 1992). TOBI has surveyed the entire El Julan wave field (Fig. 8), and resultant measurements of seafloor backscatter were particularly useful for studying grain-size variations across the wave crests.

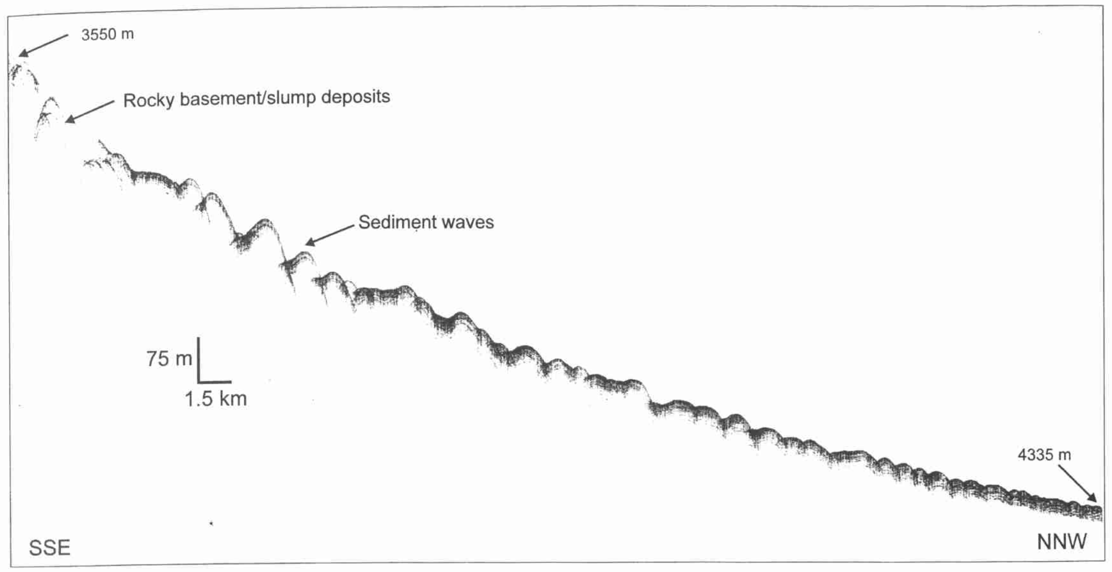

Fig. 4. Profile of 3.5-kHz through the La Palma sediment wave field. Wave dimensions clearly decrease downslope, while the penetration depth increases. Most of the waves have thicker beds on their upslope faces, and are clearly migrating upslope. Location of profile shown in Fig. 2.

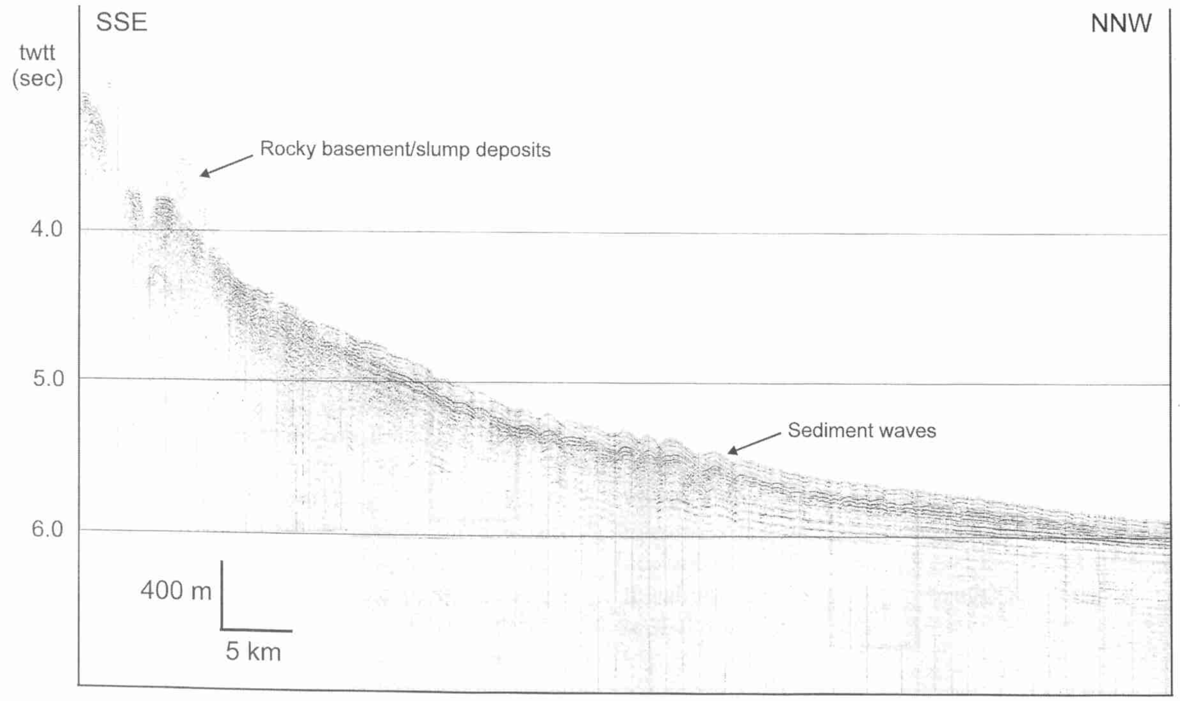

Fig. 5. Airgun seismic profile through the La Palma sediment wave field. Note the sharp contrast in seismic expression between the rocky island flanks (top left) and the sediment wave field. Location of profile shown in Fig. 2.

2.6. Sediment cores

Three short (maximum length 2.05 m) kasten cores were recovered from the southern margin of the La Palma wave field (Figs. 1 and 6). These cores confirm earlier interpretations of sediment facies, based on 3.5-kHz data, and have been a key factor in determining the wave-forming process.

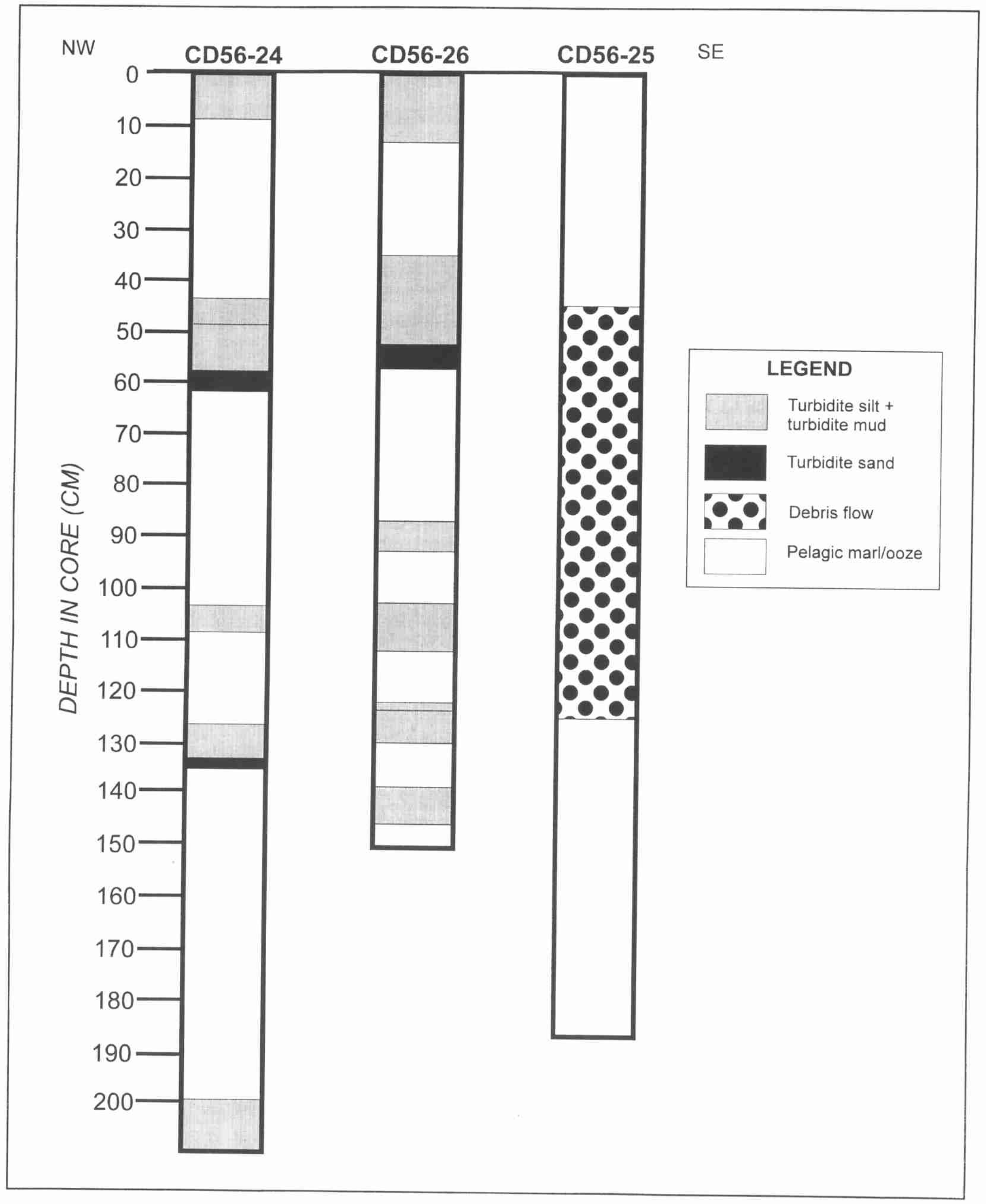

Fig. 6. Sedimentary logs of three short kasten cores recovered from the southern margin of the La Palma sediment wave field. Core locations shown in Fig. 1.

3. The La Palma sediment wave field

3.1. Distribution and morphology

The La Palma wave field lies upon the northern slopes of La Palma at a water depth of 3600–4500 m, and covers approximately 20,000 km^2 (Fig. 1). The waves extend upslope to the boundary between the rocky island flanks and the slope sediments, and downslope onto the continental rise. To the west, the wave field is bordered by the Canary Debris Flow, which is believed to post-date the sediment waves (Masson et al., 1992). Sediment waves are not present on the southern flanks of La Palma, probably due to the dominance of mass movements in this area (Fig. 2).

The sediment waves display wave heights of < 5–70 m (averaging 21 m), and wavelengths of 0.4–2.4 km (averaging 1.2 km). Wave crests are aligned parallel or subparallel to the regional slope, and are laterally continuous for up to 40 km. The crestline morphology is often complex, with common bifurcation and a clear sinuosity, although the crests become less sinuous and more regular downslope (Fig. 3). In profile, most of the waves display an asymmetrical morphology, with a steeper downslope flank. The waves also show a progressive downslope decrease in dimensions (Fig. 4). On airgun seismic profiles the wave morphology is still clearly visible to a depth of at least 200 m (assuming a sediment velocity of 1600 m/s), and the wave crests and troughs consistently shift downslope with increased penetration depth, indicating upslope migration throughout deposition of the sequence (Fig. 5).

3.2. Sediments

Three short kasten cores have been recovered from the study area, in water depths ranging from 3364–4377 m (Figs. 1 and 6).

Core CD56-25 is 185 cm long and was taken from an area of hummocky topography at a water depth of 3364 m, just within the upper limit of the wave field. This core contains two bioturbated silty clay units, and an 80 cm thick volcaniclastic debris flow. The debris flow is poorly developed, and appears to be a 'grain-flow' deposit. It contains clasts of sediment similar to those seen in the underlying and overlying beds, as well as volcanic debris and shell fragments. It is not seen in other cores recovered from the area and is therefore interpreted as a small-scale failure on the island flanks.

Core CD56-26 is 148 cm long and was taken from an area of migrating sediment waves in a water depth of 4103 m. This core contains seven volcaniclastic turbidites, interbedded with bioturbated pelagic marls and oozes. The turbidites are up to 20 cm thick, and generally consist of normally graded, fine-grained silts and muds. One turbidite has a thin (5 cm) sandy base. Parallel and cross lamination is present in some of the silty units.

Core CD56-24 is 205 cm long and was recovered from the southeastern margin of the wave field at a water depth of 4377 m. This core contains six volcaniclastic turbidites up to 12 cm thick, interbedded with bioturbated pelagic marls and oozes. These turbidites also consist of normally graded silts and muds, although the turbidite at 60 cm displays an erosive sandy base, overlain by cross and parallel laminated silts.

Analysis of 3.5-kHz profiles reveals that the average penetration depth of the sediment waves increases from 12 m at 3700 m, to 28 m at 4300 m (Fig. 4), which suggests that the overall grain size of the wave sediments decreases downslope. In addition, sediment waves in the upper part of the field show a marked variation in penetration across the wave crest. In the upper wave field, the penetration depth on the upslope flanks is 25 m, as opposed to 10 m on the downslope flanks. This variation is less marked in the lower part of the wave field, with the upslope flanks having a penetration depth of 28 m, as opposed to 26 m on the downslope flanks. This variation suggests that the waves are finer-grained on their thicker upslope flanks, particularly in the upper part of the wave field.

GLORIA images of the wave field show a 'tiger-stripe' pattern of variable backscatter across the waves (Masson et al., 1992). The low backscatter lineations are interpreted as being the finer-grained upslope flank of the waves, and the high backscatter lineations are interpreted as being the coarser downslope flanks.

3.3. Discussion of wave-forming processes

It is important to initially establish whether or not the waves are primary depositional bedforms, or compressional features resulting from mass movements. The waves in the La Palma field are (a) asymmetrical, being made up of beds that are thicker on the upslope flank and thinner, or even absent, on the downslope flank, (b) have troughs that show clear evidence of upslope displacement through time, and (c) show a progressive downslope decrease in wave dimensions (Figs. 4 and 5). These features indicate that the waves have migrated upslope through time and are primary depositional bedforms. They are clearly not compressional features associated with gravitational mass movements (e.g., Hill et al., 1982; Mulder and Cochonat, 1996). These waves have therefore been formed beneath along slope bottom currents or downslope turbidity currents.

The La Palma wave field lies within a zone of northeastward-flowing Antarctic Bottom Water (AABW), and it is possible that this current has been responsible for forming and maintaining the waves (Fig. 1). Jacobi and Hayes (1992) and Masson et al. (1992) have previously described the sediment waves in this area, and both favour a bottom current origin. However, the AABW flow is fairly weak at the present-day. Current meter studies undertaken in the vicinity of the Canary Islands have recorded bottom currents flowing to the northeast at velocities of <5 cm s^{-1} (Lonsdale, 1982; Saunders, 1988). In addition, bottom photographs taken from the slope and rise northeast of the Canary Islands show a tranquil seafloor, with no evidence of significant bottom current activity (Jacobi et al., 1975; Embley, 1976). Generally, sediment waves maintained by bottom currents are thought to occur under velocities of 9–50 cm s^{-1} (e.g., Flood, 1988), therefore, the present-day bottom current regime in the area is probably not sufficient to maintain the waves. However, AABW was believed to have been stronger during glacial periods (Sarntheim et al., 1982), therefore, it is possible that bottom currents may have had a more significant role in wave development in the past.

It is also difficult to relate the crestline orientation to a bottom current origin, as recent models of mudwave dynamics (Blumsack and Weatherley, 1989; Blumsack, 1993), derived from the lee-wave model of Flood (1988), suggest that sediment waves growing in the northern hemisphere will generally propagate at an angle clockwise to the prevailing bottom current direction, and will migrate upcurrent and to the right of the current flow direction. In the La Palma wave field the wave crests are aligned roughly parallel to the bottom current flow, with an upslope migration. There is no evidence that wave migration has an *upcurrent* component, and overall, it is difficult to relate the distribution of the sediment wave crestlines to current models of bottom current waves.

Finally, the upper part of the wave field lies within a zone of mixing between the northeast flowing AABW and the southwest flowing North Atlantic Deep Water (Sarntheim et al., 1982). Zones of mixing between two opposing major water masses are commonly zones of ''no motion'' and are therefore unlikely to generate significant bottom currents (L. Carter, personal communication). In addition, there is no change in the wave migration direction and crestline orientation across this zone of mixing, which also suggests that bottom currents are having little effect on sediment wave processes.

It seems unlikely from these observations and arguments that bottom currents are responsible for forming and maintaining the La Palma wave field. They are certainly not being maintained by the present-day current regime, although the possibility that increased AABW flow in the past had a greater influence on wave formation cannot be dismissed.

An alternative explanation is that the waves have been formed by downslope turbidity currents. Evidence of turbidity current flow across the wave field is shown by the presence of numerous fine-grained volcaniclastic turbidites in cores taken from the southern edge of the field (Fig. 6). In addition, the wave crests are aligned roughly parallel to the regional slope (and are therefore perpendicular to downslope flows), and the waves migrate upslope. These features are all compatible with a turbidity current origin for the waves (e.g., Damuth, 1979; Normark et al., 1980; Carter et al., 1990; Piper and Savoye, 1993; Nakajima et al., 1998). The progressive downslope decrease in wave dimensions can be attributed to a reduction in turbidity current velocity as the slope gradient decreases. Further evidence for recent turbidity current activity in the area is given by Urgeles et al. (in press). They describe the channels on the western flanks of La Palma, which occur adjacent to debris avalanche lobes (Fig. 2). Several of the channels contain scattered debris avalanche blocks, and haloes of fine-grained sediment in the lee of the blocks are interpreted as being deposited by turbidity currents.

Within the La Palma wave field channels are absent, and the wave field is generally out of range of turbidity current overspills from the channel systems to the north and south (Masson, 1994; Urgeles et al., in press). We therefore interpret the waves as being formed by unconfined turbidity currents originating on the island flanks. These flows are initially constrained within feeder canyons, but rapidly become unconfined downslope and therefore spread out over an extensive area. The lateral extent of the La Palma wave field suggests that turbidity currents are sourced from several input points along the island flanks, rather than from a single canyon. The bifurcation and clear sinuosity of the wave crests may be a function of different turbidity currents from different input points interacting. This is backed up by the core data, which show a marked heterogeneity in sediment deposition across the wave field.

Howe (1996) attempted to apply the lee-wave model of Flood (1988) to turbidity current sediment waves in the Rockall Trough area. However, the lee-wave model is dependent upon a weakly stratified water column and a steady, continuous current flow. This model is therefore not wholly appropriate to sediment waves that form beneath an episodic, dense turbid underflow (McCave and Carter, 1997). Instead, we propose that the sediment waves described in this study form as antidunes which develop beneath a flow with a Froude number close to one. Normark et al. (1980) used measured wave dimensions and an estimate of flow velocity to construct a simple two-layer model applicable to unconfined turbidity currents flowing over sediment waves on the Monterey Fan levee. This two-layer model accounts for the excess density of a turbulent sediment/water mix flowing beneath stationary seawater. Normark et al. (1980) assumed a flow velocity of 10 cm/s^{-1} (equivalent to deposition of silt-sized material) and used a wavelength value of 0.5–5 km in the following equation, derived from the antidune model of Allen (1970):

$$C \cong \frac{2\pi}{1.6g}\frac{U^2}{L} = (4\times10^{-3})\frac{U^2}{L}$$

The concentration C is dimensionless, velocity U is expressed in cm/s, g is acceleration of gravity (980 cm/s^2), and wavelength L in cm. The specific gravity of suspended sediment in the flow is assumed to be 2.6.

For the Monterey Fan waves, this produces an estimated flow concentration between 8×10^{-7} and 8×10^{-6}. A concentration of 8×10^{-6} is approximately equivalent to 20 mg/l, assuming a sediment density of 2.6 g/cm^3.

This procedure can be repeated for the La Palma sediment waves. For the upper part of the wave field, comparison with other turbidity current data suggests that a flow velocity of 100 cm/s^{-1} is reasonable (e.g., Bowen et al., 1984). For the lower part of the wave field, a flow velocity of 10 cm/s^{-1} is assumed (e.g., Normark et al., 1980; Stow and Bowen, 1980). The wavelength value averages 2.4 km for the upper wave field, and 0.4 km for the lower wave field. These values produce a sediment concentration of 1.7×10^{-4} (427 mg/l) for a turbidity current crossing the upper wave field, decreasing to 1×10^{-5} (26 mg/l) as it reaches the lower wave field.

Normark et al. (1980) then combined the antidune model with the results of Ellison and Turner (1959) which showed that flow in the centre of a turbidity current approaches $Fr\cong1$. They formulated the following equation to calculate the depth of flow:

$$L \cong 2\pi h(Fr\cong1)$$

so that the depth of flow h is approximately one-sixth of the wavelength.

The maximum wavelength of the La Palma sediment waves is 2.4 km in the upper wave field, giving an estimated flow thickness of 400 m. The minimum wavelength of 0.4 km in the lower wave field gives a flow thickness of 60 m. This compares to Normark et al.'s estimated flow thickness of 80–800 m for the Monterey Fan waves.

To summarise, on the basis of this simple two-layer model, we can estimate the flow conditions of turbidity currents passing over the La Palma wave field. At the top of the wave field, turbidity currents flowed at 100 cm/s^{-1}, had a thickness of 400 m, and a sediment concentration of 427 mg/l. The flow velocity decreased to around 10 cm/s^{-1} at the bottom of the wave field, and the flow thickness and sediment concentration decreased to 60 m and 26 mg/l, respectively. It should, however, be remembered that this antidune model has a number of limitations. For example, there are obvious problems with applying a model derived in laboratory flumes and fluvial systems to kilometre-scale bedforms in the deep ocean. In addition, antidunes are generally recognised as being short-lived, unstable bedforms and are rarely described from the geological record (Allen, 1982). It is therefore difficult to understand how extensive sediment wave fields can build up over millions of years by this process. We therefore need to obtain a greater understanding of the processes that generate and maintain turbidity current sediment waves if we are to use predictive models with any certainty.

4. The El Julan sediment wave field

4.1. Distribution and morphology

The El Julan wave field lies within a low relief turbidity current channel, some 8 km long and 2 km wide, on the southwest flank of El Hierro. The wave

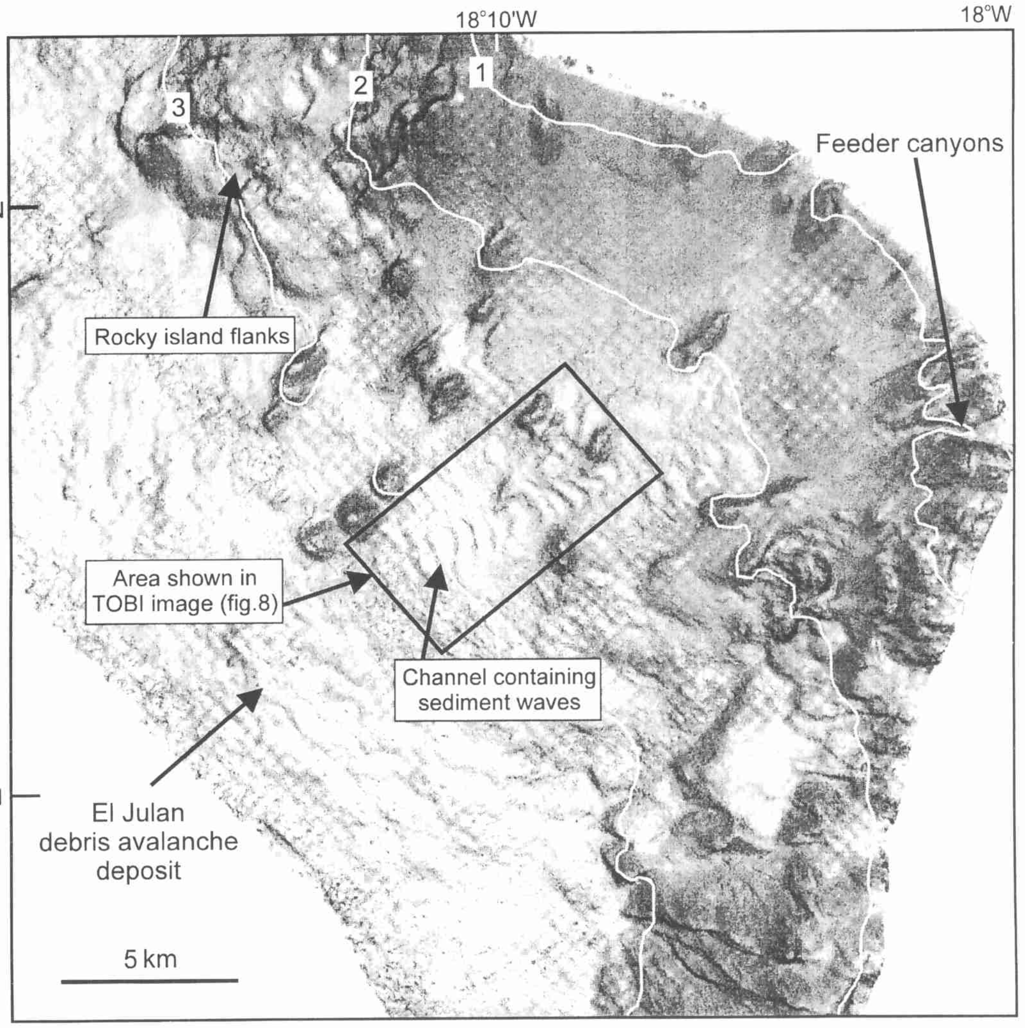

Fig. 7. GEOSEA 3-D image (plan view) of the El Julan sediment wave field within the scar of the El Julan debris avalanche. Box indicates location of TOBI image in Fig. 8. Bathymetric contours in kilometres. Vertical exaggeration = ×10. Illumination is from the northeast.

field covers 14 km^2, and lies at a water depth of 2400–3000 m (Figs. 1 and 7). The waves are confined to the floor of the channel, and no waves are visible on the adjacent slopes.

There are 10 sediment waves within the channel, with wavelengths of 0.4–1.2 km (averaging 0.8 km), and wave heights of around 6 m. The wave crests are aligned parallel to the bathymetric contours and are

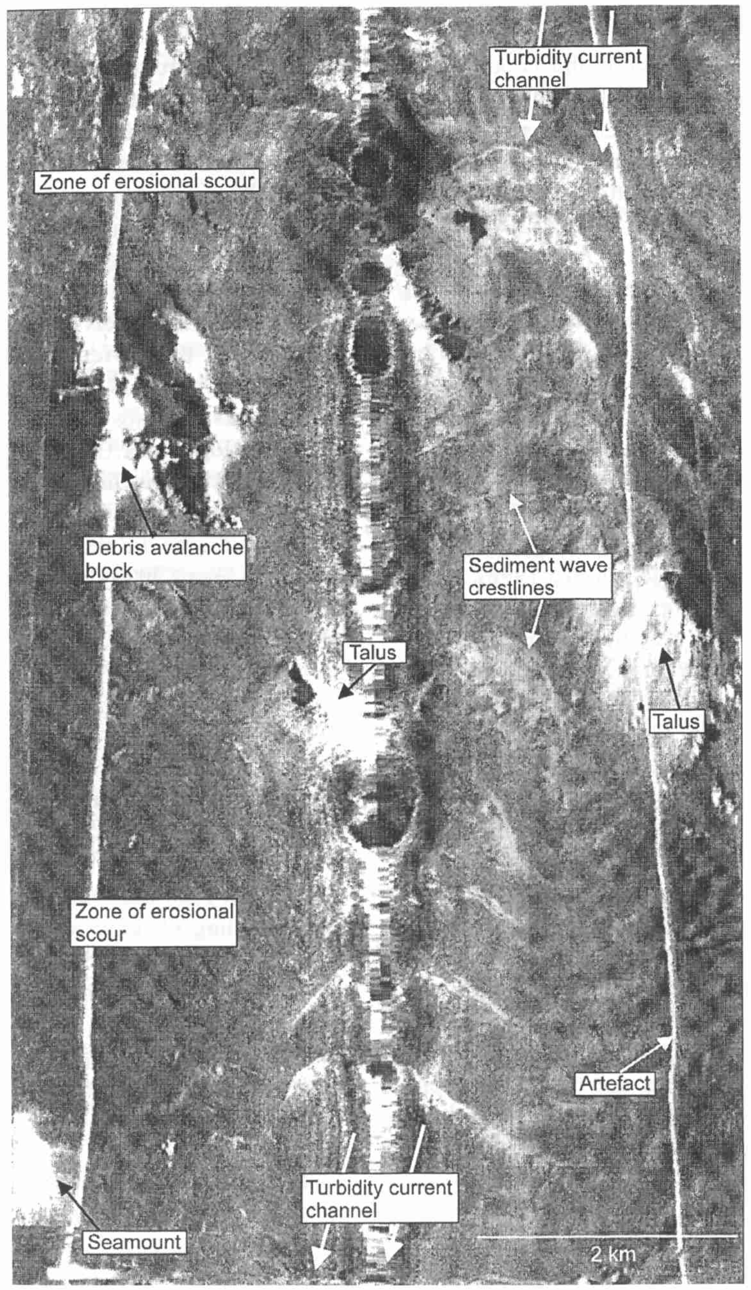

Fig. 8. TOBI image of the El Julan sediment wave field. High backscatter areas are pale, low backscatter areas are dark. Note the high backscatter streaks on the lee faces of the waves. For location, see Fig. 7.

therefore perpendicular to downslope flows, although they show a roughly crescentic outline with the 'arms' pointing downslope (Figs. 7 and 8). There is no downslope variation in wavelength.

4.2. Sediments

Unfortunately, the lack of core and good-quality profile data through the wave field limits any interpretation of sediment type. Backscatter patterns on the TOBI image, however, provide some indication of the grain-size distribution across the wave (Fig. 8). There appears to be a series of high backscatter streaks on the downslope flanks of the waves, which are interpreted to be coarse sediments. These contrast with the low backscatter areas on the upslope flanks and in the wave troughs, which are interpreted to be fine-grained sediments.

4.3. Discussion of wave-forming processes

Sediment waves within channels have previously been assigned to a turbidity current origin (e.g., Normark and Piper, 1991; Kidd et al., 1998). Most of these channel floor waves have wavelengths of < 300 m, wave heights of < 6 m, and are composed of gravel or sand. For example, gravel waves in channels on the Var Fan (Malinverno et al., 1988) and in the Corinth Graben, Greece (Piper and Kontopoulos, 1990) display wavelengths of 35–100 m and wave heights of 1.5–6 m. Coarse sand/conglomerate waves in channels on the Laurentian Fan (Piper et al., 1988) and in the Stromboli Canyon (Kidd et al., 1998) have similar dimensions, with wavelengths reaching 300 m and wave heights up to 4 m. The location of the El Julan wave field within a channel also points towards a turbidity current origin for the waves. However, the El Julan waves are different from the above examples in that they display wavelengths up to 1.2 km, and this makes them substantially longer than previously published examples of sediment waves in channels.

The El Julan channel lies within a debris avalanche scar, and is downslope of a series of feeder canyons (Fig. 7). It seems likely that the waves are composed of sediments that have been transported through these canyons and deposited on the channel floor as sediment waves. It is interesting to note that sediment waves are not present on the slopes adjacent to the channel. This is probably due to a lack of available sediment being transported to these areas.

The waves have high backscatter streaks on their downslope flanks running perpendicular to the wave crest (Fig. 8). High backscatter streaks running perpendicular to the crests of sediment waves have also been recorded from the floor of the Stromboli Canyon (Kidd et al., 1998). These have been interpreted as streaks of coarse sediment, and it seems likely that this interpretation can also be applied to the El Julan waves. These features are probably a result of increased flow velocities across the wave crest, leading to deposition of coarser sediment, and/or winnowing of sediments on the downslope flank. This is compatible with models of antidune formation, which suggest that the current velocity decreases as the flow travels up and over the upslope flank, and increases as it passes over the wave crest and across the downslope flank (Allen, 1982).

The curved crestlines of the waves are concave downslope, which means that the wave crests are furthest upslope in the middle of the channel. It therefore seems likely that the waves are migrating upslope, and are migrating most rapidly in the centre of the channel where the flow velocity is highest.

5. Conclusions

This study describes two sediment wave fields that have been formed by turbidity currents in the western Canary Islands. An extensive 2-D and 3-D dataset has been utilised and this, combined with an understanding of regional processes, has enabled us to interpret the process of wave formation with confidence. In particular, the application of high-resolution GEOSEA and TOBI imagery has given us new insights into the crestline morphology and sediment distribution across the waves.

The La Palma wave field was formed by unconfined turbidity currents originating on the flanks of La Palma. An attempt at modelling the flow characteristics suggests that this wave field formed beneath flows similar to those that form sediment waves on channel–levee backslopes.

The El Julan wave field was formed by channelised turbidity currents originating on the flanks of El Hierro. These waves are migrating upslope, and migration is most rapid in the centre of the channel where flow velocity is highest. The backscatter pattern across the waves suggests that the flow velocity increases on the downslope flanks of the waves, leading to deposition of coarse sediment streaks.

Future work should be directed towards obtaining a greater understanding of the flow conditions that initiate and maintain the waves. In particular some attempt should be made to formulate a new model for turbidity current wave formation.

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