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SEDIMENT WAVES ON THE MONTEREY FAN LEVEE: A PRELIMINARY PHYSICAL INTERPRETATION

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ABSTRACT

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Sediment waves on the deep ocean floor occur mostly on the lower continental rise on slopes of 1° or less. Previous studies show that their amplitude and wavelength vary greatly, but little is known about their shape in plan. A detailed survey of a 30-km^2 area of abyssal-depth sediment waves associated with the levee of the Monterey fan valley shows a pattern of sinuous crests and troughs with parallel, well-bedded internal structure. Material in the upper 1 m of sediment consists predominantly of bioturbated, muddy coccolith ooze. A single thin, silty horizon can be correlated between adjoining waves.

On the basis of measured wave dimensions and an estimate of flow velocity we use a simple two-layer model for water movement to infer approximate flow parameters. The sediment waves are considered to be formed most likely by low-velocity (10 cm/s), low-concentration turbidity flows approximately 100—800 m thick. This interpretation emphasizes the role of low-speed, low-concentration turbidity currents in the downslope movement of fine-grained material. This type of transport—deposition regime explains the formation of sediment waves very well except for certain waves occurring on depositional ridges in the deep ocean.

INTRODUCTION

There are many reports of sediment waves on the deep ocean floor, from the continental slope through rise to abyssal-plain environments. Abyssal-depth sediment waves have been variously interpreted as depositional wave forms, fan lobes, slumps, or erosional features. They form on depositional ridges such as the Feni Ridge (Lonsdale and Hollister, 1978) and the Blake Bahama Outer Ridge (Hollister et al., 1976), where a geostrophic bottom-current origin has been inferred. They also occur on the backside (side away from channel floor) of levees bounding deep-sea fan channels (Hamilton, 1967; Damuth, 1975; Hess and Normark, 1976), where they are more probably related to large-scale turbidity currents.

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Table I summarizes much of the recent literature dealing with sediment waves in the deep ocean. Sediment waves occur most commonly on the lower continental rise, where regional slopes vary from about 1° to almost horizontal. Different wave types may be associated with different bottom gradients (cf. the three types of Bouma and Treadwell, 1975), and observed wavelengths are typically from 0.5 to 6 km. The longest wavelengths are found on both the steepest and the gentlest gradients. Amplitude varies widely between 3 and 100 m, with typical values of 10—40 m (Table I); there is an apparent downslope decrease in wave amplitude.

Wave crests, which are continuous for several kilometers (Embley and Langseth, 1977) and possibly for as much as 20 km in one example (Rona, 1969), tend to be aligned transverse to the current direction in the case of sediment waves associated with geostrophic bottom-currents, although parallel (Lonsdale and Hollister, 1978) and oblique (Fox et al., 1968) orientations have been suggested. Upslope migration of wave crests is a common observation, and a migration rate of <1 m/1000 years is suggested by Lonsdale and Hollister (1978) for Feni Ridge examples. In some cases no apparent migration could be observed (Damuth and Hayes, 1977), and in one case down-current migration has been proposed (Ewing et al., 1968).

The sediment type that forms the waves is almost invariably lutite; it may be silt-laminated mud or finer-grained, homogeneous mud. High-resolution seismic reflection profiles suggest that sedimentation is generally more rapid on the shorter upslope limb, where the sediment is probably slightly coarser. The distribution of grain sizes has not been analyzed carefully in most studies, and the topmost layers recovered in gravity cores may not represent the material being carried by wave-forming currents.

Sediment waves have been most often interpreted as depositional bedforms produced either by turbidity currents or by bottom currents (Table I). Arguments for these interpretations are based on the location of these features or the nature of sediment rather than on a physical analysis of the wave forms. Such arguments have been shown to be spurious in distinguishing between fine-grained turbidites and contourites (Stow, 1977, 1979). Slumps or fan lobes may explain some of the more irregular and less persistent wavelike features, but they do not satisfactorily account for the large areas of regular, migrating sediment waves frequently observed.

The present study provides a detailed examination, including bottom samples, of a 30-km^2 area of abyssal-depth sediment waves associated with the levee of a large turbidite fan valley. A preliminary physical interpretation is presented to characterize the flow responsible for formation of these waves.

SETTING

In April 1977 the U.S. Geological Survey research vessel "S.P. Lee" surveyed a large part of the Monterey deep-sea fan. A portion of this survey was devoted to detailed mapping of an area with sediment waves on the northwestern levee of the Monterey fan valley, near the confluence with the

Ascension fan valley (Fig.1). The levee crest adjacent to the study area lies 100—350 m above the valley floors. The western levee of the Ascension valley is contiguous with that of the Monterey valley below their confluence (Normark, 1970), and sediment waves are found on the backside of the levee over a distance of 75 km downchannel and 15 km across the levee. This specific study area was chosen because: (1) it is the central zone of this field of sediment waves, (2) its proximity to land permits the use of an accurate land-based navigation system, and (3) two adjacent deep-tow profiles on either side of the survey provide additional detail on the internal structure and relation between waves (Hess and Normark, 1976).

METHODS

An area approximately 3 km by 10 km was mapped with a trackline spacing of 0.5 km transverse to the trend of sediment waves. Positioning during the survey utilized shore-based C-band radar transponders, with the ship's position determined every 2.5 min, more frequently during turns and coring operations. Accuracy of positions is within about 25—50 m with ranges to the three transponders greater than 100 km. The final computer-calculated navigational plot (Fig.2) represents positions determined with only two of the available transponder range sets.

Shallow-penetration 3.5-kHz and single-channel air-gun reflection profiles were collected for bathymetry and for shallow- and deep-sediment structures. Sediment distribution was examined using six free-fall core samplers that were positioned using the radar-transponder navigation system. Core sites spanned the extent of one wavelength, from crest to adjacent crest of representative sediment waves, in the center of the survey area (Fig.2).

RESULTS

Bathymetry and structure

Water depths for the survey area were taken from the 3.5-kHz reflection profiles. Depth data were corrected using Matthews Tables for areas 43/44 prior to contouring. The average levee gradient in the study area is 1.4%. Wave amplitude varies from 2 to 37 m and averages 25 m. Wavelength ranges from 0.3 to 2.1 km, with 1.7 km as an average. The sediment waves are sinuous, but their overall trend is subparallel to the crest of the Ascension/Monterey levee (Fig.2). Crests and troughs are continuous between adjacent profiles (Fig.3), but only 4 of 12 sediment waves extend across the entire width of the survey, which suggests that few sediment waves extend more than 5 km. Smaller waves coalesce or die out as small terraces on the flanks of larger adjacent waves (Fig.3). Embley and Langseth (1977) correlate similar waves on the South American continental rise over several kilometers. Where the ship track-density of their survey is comparable to that of this study, the sediment waves have sinuosity and wavelengths similar to the

TABLE I

Summary of recent deep-ocean sediment wave studies

Reference	Location of study	Slope tan β	Wave-length L (km)
Ballard (1966)	Western North Atlantic	0.004—0.01	5—7.5
Bouma and Hollister (1973)	Indian Ocean (?)	0.004	2—3
Bouma and Treadwell (1975)	Colombian basin 3 types:	very flat	4.5 → 5.5
		~0.006	0.5 → 3.5
		0.01 → 0.014	6.3 → 7.2
Damuth (1975)	Western equatorial Atlantic: hyperbolic echo types		
	IIB-4 levees	0.009	~1
	rise	0.009	1 → 3
	IIB-5 rise	very gentle slope	3 → 5 (1.5 → 5)
Damuth and Hayes (1977)	Brazilian continental margin Type IIIB	0.003	0.5 → 2.0
Embley and Langseth (1977)	Continental rise off northeastern South America	0.003	1 → 4
Ewing et al. (1968)	Madagascar Basin		4
Ewing et al. (1971)	Argentine basin (very large area)	~flat	5
Fox et al. (1968)	Western North Atlantic (off U.S.)	0.005 → 0.008	4 → 6
Hamilton (1967)	Northeastern Pacific channel	0.003	1
Hess and Normark (1976)	Ascension and Monterey fan valley, western levees	0.013	→1.0
Hollister et al. (1976)	Blake Bahama Outer Ridge		~2
Jacobi et al. (1975)	Moroccan continental rise	0.0033	1 → 2 (0.5 → 5.0)

Amplitude A (m)	Sediment nature	Author's interpretation	Other comments
45—140	?	Slump features	
15—40	?	Bottom currents	
3 → 5	Muddy (?)/ sandy	Fan lobes	Downslope migration?
6 → 20	Muddy (?)/ sandy	Fan lobes? (current bedforms)	Upslope migration (decrease in L downslope)
35 → 65	Muddy (?)/ sandy	Slumping and reworking	(decrease in A downslope)
~10		Deposited by turbidity currents	Upslope migration;
10 → 40	Mud?		Coarser on upslope side;
5 → 25	Silt-laminated muds	Deposited by bottom currents	Longer L on lower slopes
20 → 100	Muds with few silt/sand layers	Some turbidity currents and slumps on upper rise, mostly bottom currents	No apparent migration
10 → 20	Muds with interbedded silt/sand	Two types, one related to turbidity-current overflow and another related to contour currents	Upslope migration; terrigenous sediment is required to develop sediment waves
50	Lutite	Bottom currents (northward flowing)	Thicker sediment downcurrent side (i.e., downcurrent migration) oriented approx. perpendicular to turbidity currents
-50	Lutite	Related to bottom-current deposition from nepheloid layers, but input of sediment into nepheloid layers from Argentine-margin turbidity currents	Apparent "downcurrent" migration
60—100	Clay, silt and sand	Bottom currents	Upslope migration both parallel and oblique to contours
5—10	Mud with interbedded silt/sand		
→40	Mud (and some coarse layers)	Turbidity current overflow	Upslope migration L increases } both up and D decreases } down levee
20—60	Mud	Bottom currents	Upslope migration upcurrent
8 → 10 (up to 80)	Interbedded marls and clays with rare silt-sand layers	Bottom currents hypothesized	Upslope migration; waves trend parallel to contours; L increases downslope

(continued)

TABLE I (*continued*)

Reference	Location of study	Slope tan β	Wave-length L (km)
Johnson and Schneider (1969)	Blake Bahama Outer Ridge		3 → 6
Kolla et al. (1976)	Western Bay of Bengal	0.008	~1—3
Laughton et al. (1972)	Southern Labrador Sea (sediment ridge)	?	~2
Lonsdale and Spiess (1977)	Gardar and Feni Ridges	0.01	1 → 2
Lonsdale and Hollister (1978)	Southeastern flank, Feni ridge	~0.017	2
Nowroozi et al. (1968)	Delgada fan, North-eastern Pacific	?	~1
Rona (1969)	Lower rise off Cape Hatteras		5.6 (3 → 12)
Tucholke (1977) (Tucholke and Houtz, 1976 in DSDP 35 — same study)	Bellingshausen Basin, central continental rise		9—20
			4—7
			~1
Tucholke and Ewing (1974)	Center, Antilles Outer Ridge	~0.005	2—9
This study	Western levee, Monterey fan	0.014	0.3 → 2.1

Monterey fan sediment waves. In general, the sediment waves decrease in amplitude and wavelength toward the levee crest and downslope toward adjacent, flatter fan sediments. Amplitude of the waves across the levee also decreases with distance downchannel (Normark, 1970).

High-resolution 3.5-kHz and single-channel air-gun reflection profiles (Fig.4) show a continuous, parallel, well-bedded internal structure for these sediment waves. Because of vertical exaggeration of the records and over-lapping hyperbolic echoes in the areas between wave crests, it is impossible to resolve unambiguously the structural relation between adjacent waves. Deep-tow profiles (Fig.4) from either side of the survey area (Hess and Normark, 1976) show onlapping internal reflectors between adjacent waves, which indicates upslope migration of these waves. The waves are generally, though not always, asymmetric, with the shorter, steeper limb facing uplevee.

Amplitude A (m)	Sediment nature	Author's interpretation	Other comments
20 → 60		Bottom currents	
5—10	Muds with silt and sand layers	Bottom currents (?)	Upslope migration
50	Mud	Bottom currents (?)	
20 → 40		?	
→30	Mud	Deposited from bottom currents flowing parallel to wave axes	Upslope migration at <1 m/ 1000 yrs
~5	?	Turbidity currents (?)	Upslope migration
43 (10 → 110)	Lutite	Bottom currents	Asymmetric, steeper down-current limbs extend over several km to ~20 km along crests; *L* increases downcurrent
	Muds with silt and sand layers	Turbidity current overflow	
	Muds with silt and sand layers	Bottom currents	
	Muds with silt and sand layers	Bottom currents	
10—20	Muds with rare silt	Bottom currents	
10 → 20 (5 → 40)	Lutite (mostly fine clay in gravity cores)	See text	Upslope migration (not always asymmetric) *L* increases upslope and downslope.

Cores and sediment analysis

Six free-fall cores were collected across two waves in a series (Figs.2 and 3); penetration was 90 to 100 cm in each case. The sediment is predominantly a bioturbated, muddy coccolith ooze containing a coarse fraction (>63 μm) dominated by radiolaria and diatoms, with fewer foraminifers and sponge spicules; there is also a small percentage of mica and iron-stained quartz sand. Correlation between cores is possible on the basis of lithologic color change, the presence of a thin, silty horizon, and systematic variation in the magnetic inclination of the sediments (Fig.5). The thin silt horizon is best developed in those cores from the shorter upslope face and crests of the sediment waves. This conforms with sediment-wave growth and migration in the upslope direction, as suggested by the deep-tow reflection profiles.

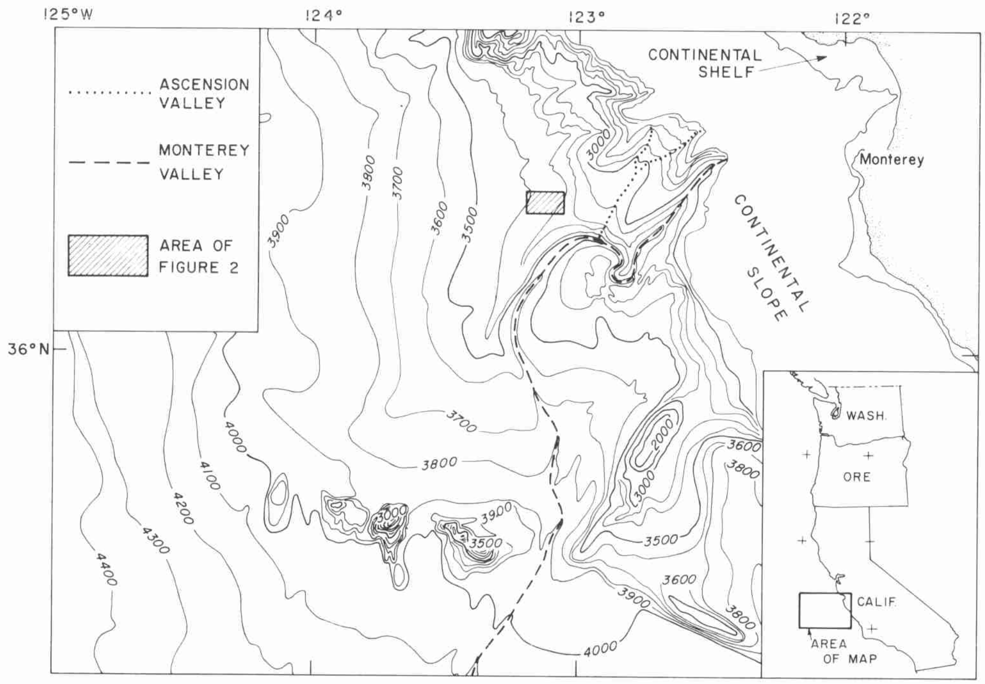

Fig.1. Location map of study area. Dashed pattern denotes location of study area and coverage of map in Fig.2. Dashed line identifies Monterey fan valley.

FLOW CHARACTERISTICS

Little attempt has previously been made to infer flow characteristics from a physical interpretation of sediment waves. While we recognize that the theory is incomplete with regard to density underflows and antidune formation, we believe our data on wave dimensions merit some attempt at derivation of flow parameters. We assume that the sediment waves are formed by turbidity currents overflowing the Monterey fan valley. Our reasons include (1) the restriction of the wave field to the backside of the levee, (2) the occurrence of sediment waves throughout the levee section, and (3) the absence of any significant bottom-water flow in this area. An older, partially buried, fan valley that trends nearly perpendicular to the present Monterey fan valley also exhibits well-developed sediment waves on the backside of the righthand levee; because it is difficult to form perpendicular sets of sediment waves in the same area by normal bottom water flow, we take this as additional support for assuming this type of sediment wave is formed by overflowing turbidity currents.

We must also assume, on the basis of their internal structure and variations in thickness of the cored silt layer, that the Monterey fan sand waves are depositional bedforms of the antidune type, which commonly migrate upslope (although they also appear to move downslope or remain stationary in

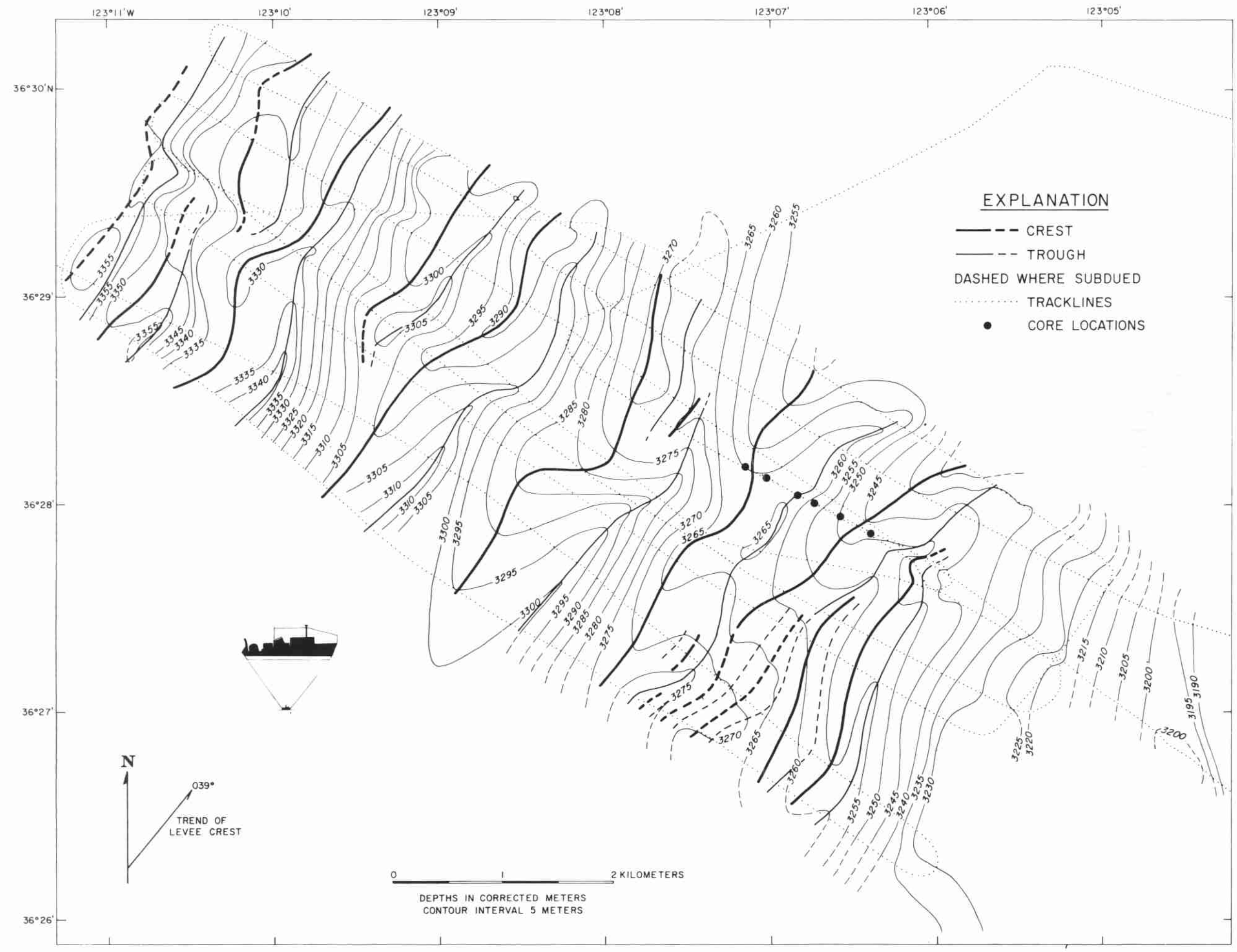

Fig. 2. Detailed bathymetric map of sediment-wave study area constructed from 3.5-kHz profiles taken on the Monterey fan expedition.

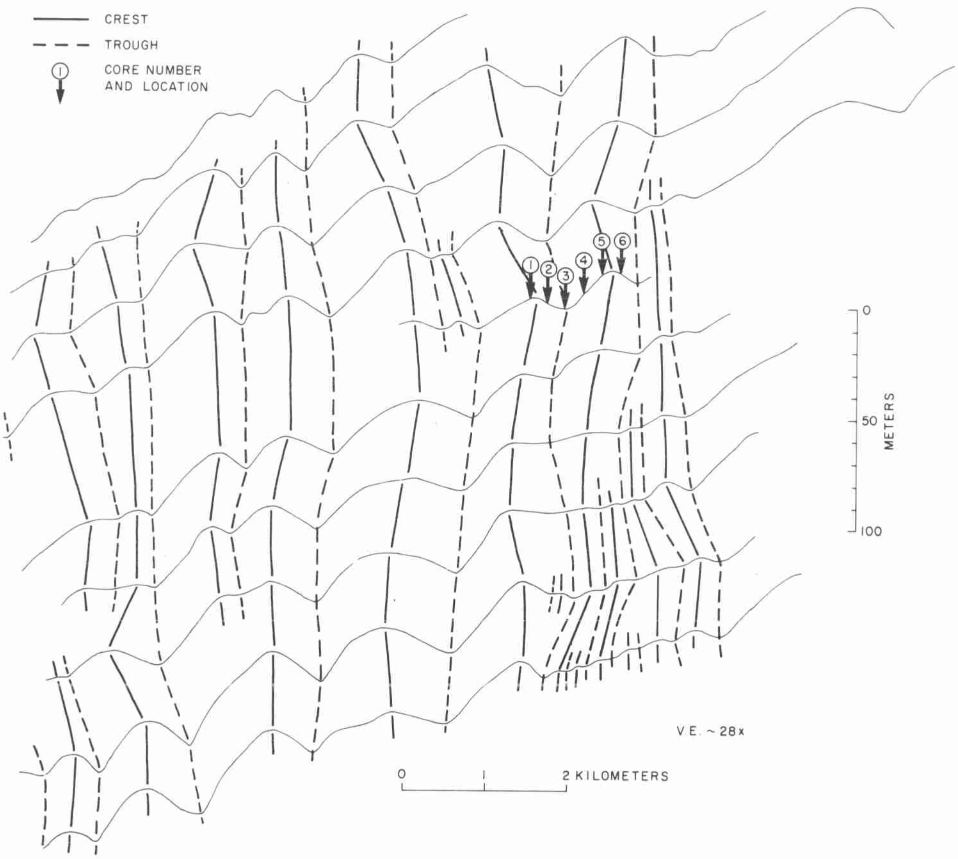

Fig.3. Strike-normal projected profiles across sediment-wave field.

other areas: see Table I). We do not see indications of cross-bedded reflectors on either shipboard or deep-tow high-resolution seismic records from the Monterey fan sediment waves (Fig.4, A to C). Thus, the internal structure of these waves is unlike that commonly described from antidunes in channelized flows. These upslope-migrating levee waves are assumed to be a type of climbing antidune. For channelized flow, antidunes are commonly found in areas of steep slopes and high sediment load (Allen, 1970). The sediment waves on Monterey fan occur in the area of the steepest regional gradient on the fan where the levee slope is as much as three times greater than the adjacent channel floor and longitudinal levee gradients. The sediment waves are not found on or within 3- to 5-km of the levee crest even though much of this area has as steep a gradient as is seen in the wave field. Thus, the Monterey fan antidunes are found in an area of steep slope (for turbidity currents on the fan) and the climbing structure may reflect high sediment load.

Antidunes are fairly well understood theoretically (Reynolds, 1965, 1976; Kennedy, 1969; Engelund and Fredsoe, 1971). Allen (p.81, 1970) has shown

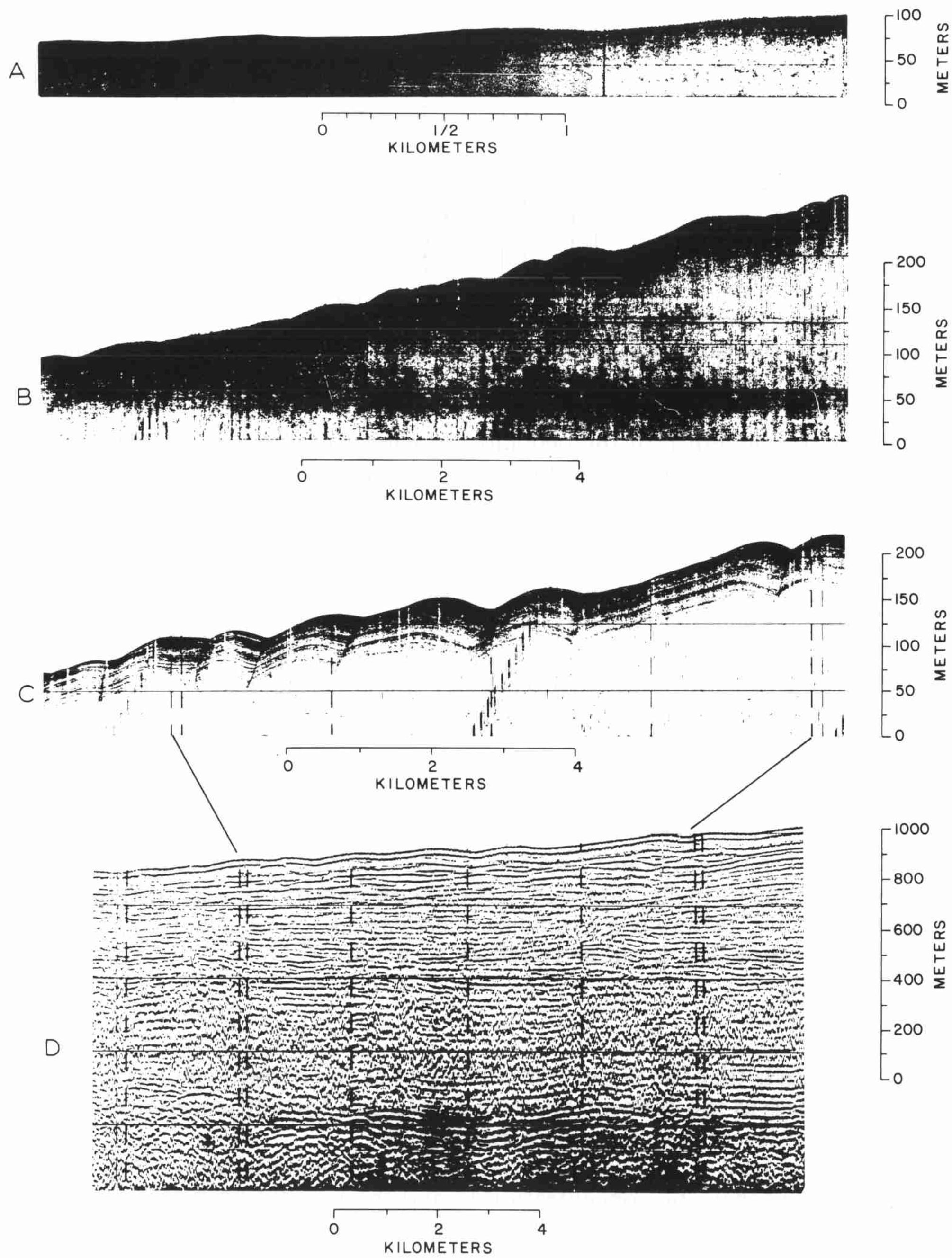

Fig.4. Reflection profiles of sediment waves. A. Deep-tow 4-kHz reflection profile of sediment waves showing onlapping internal reflectors between waves. B. Surface-ship 3.5-kHz profile showing well-bedded, continuous parallel reflectors. C. 3.5-kHz surface profile, with accompanying single-channel air-gun reflection profile (D).

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