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19. SEISMIC SEDIMENTOLOGIC INTERPRETATION OF A CARBONATE SLOPE, NORTH MARGIN OF LITTLE BAHAMA BANK[1]

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ABSTRACT

Analyses of seismic profiles and descriptions of sediments from ODP Leg 101 cores were combined to investigate the evolution of the northern margin of Little Bahama Bank, which has been prograding northward since the early Miocene. Modern depositional systems on the midslope and lower slope are found to be uncharacteristic of interpreted ancient sedimentary environments. Large slump masses covered much of the lower slope during the middle Miocene, possibly triggered by a regional tectonic event. Throughout the late Miocene and most of the Pliocene, a channel and levee system meandered across the sediment apron of the lower slope. The modern lower slope contains no meandering channels, although gullies incised in the midslope funnel sediments to the base-of-slope apron, actively promoting sediment bypass on an accretionary margin. These changes in sedimentation pattern on the lower slope indicate increasing strength of ocean-bottom contour-following currents from the Pliocene. Pliocene to Holocene gravitational creep has produced large-scale rotational movement of unlithified sediments and a major detachment surface along the base of the middle Miocene slump masses. These creep lobes extend far into the lower slope, where sediments are contorted by propagation of, and movement along, multiple minor detachment surfaces.

INTRODUCTION

The northern margin of Little Bahama Bank (Fig. 1) was selected for studying the evolution of an accretionary carbonate slope (Schlager and Ginsburg, 1981) during the first internationally staffed cruise of the *JOIDES Resolution*, ODP Leg 101 (Leg 101 Shipboard Scientific Party, 1985a, 1985b; Austin, Schlager, et al., 1986). This area was the focus of a regional seismic site survey prior to the drilling of three sites (Sites 627, 628, and 630) (Austin et al., this volume). This paper utilizes the multichannel seismic reflection profiles, acquired as part of the 243-nmi geophysical site survey conducted during ODP Leg 101 drilling in April 1984, to present an interpretation of Neogene gravity-flow deposits on part of the northern slope of Little Bahama Bank. Spacing of the 24-trace, 12-fold water-gun reflection profiles averaged 1 to 2 nmi over the middle, gullied part of the slope, and 3 or more nmi farther seaward (Fig. 2). Interpretation of these lines plus integration of sedimentologic and seismic data was carried out at the University of Newcastle upon Tyne.

Before ODP Leg 101 drilling, depths to seismic sequence boundaries were interpreted from the seismic profiles, using calculated seismic interval velocities from published data, later modified by data from site surveys (Sheridan et al., 1981; Van Buren and Mullins, 1983; Austin, Schlager, et al., 1986; Ladd and Sheridan, 1987; Austin et al., this volume). In this study, slight modifications to the interval velocity times used during Leg 101 were calculated by correlating the thicknesses and depths of sedimentologic units from Holes 627B and 628A with the seismic data (Table 1). Core information also led to slight reinterpretation of some boundaries of the seismic units; as a result, the seismic stratigraphic units in this paper differ slightly from those in Austin, Schlager, et al. (1986) (Table 2). As these differences are minor and to avoid confusion, we decided to retain the nomenclature used therein. One difficulty encountered was determination of the C/D sequence boundary throughout the area. It was impossible to detail this boundary accurately in all seismic profiles, and thus we decided to combine the two sequences in this study. Interval velocity times are higher for these units because of substantial lithification, in contrast to the unlithified overlying sediments (Austin, Schlager, et al., 1986).

Seismic nomenclature in this paper follows that of Mitchum (1977) and Mitchum et al. (1977). When integrating seismic and sedimentologic data it is important to realize the difference in scale of resolution. Seismic sedimentologic features are recognizable to a resolution of better than 10 m, whereas core analysis details units to a finer precision on the scale of meters (e.g., Table 2, Hole 628A, Unit IA). Nevertheless, seismic analysis does permit recognition of large-scale features that would not otherwise be detected from core description alone.

In this paper we attempt to (1) integrate sedimentologic features apparent from seismic analysis with those from core descriptions and (2) present a summary of the different sedimentologic processes active during the evolution of the northern slope of Little Bahama Bank from the Miocene to the present.

SEISMIC/SEDIMENTOLOGIC FEATURES

In this section we detail the major seismic features through the stages of slope evolution, starting with the modern slope configuration. We also document the three-dimensional geometry of the larger sedimentologic features (channel sequences, ancient slump masses, and active gravitational creep), which cannot be determined from core description and log analysis.

Present-day Slope Configuration

Gullies are present on the southern part of the slope included in the seismic coverage, where slope angles are between 2° and 4°. These gullies are clearly visible in some seismic transverse slope lines (lines LBB 2, 3, and 4) and downslope traverses (lines LBB 7, 8, and 18) where the bases of the gullies are commonly represented by a series of amorphous reflectors. Gully widths range from 0.5 through 2.8 km, with relief of 40 through 150 m. A plot of the present-day gullies constructed from seismic and bathymetric coverage of the area (Fig. 2) shows a pattern of nonlinear, slightly sinuous gullies extending across the slope (Fig. 3). The gullies lose amplitude downslope between 750 and 900 m water depth and commonly widen in this direction. They

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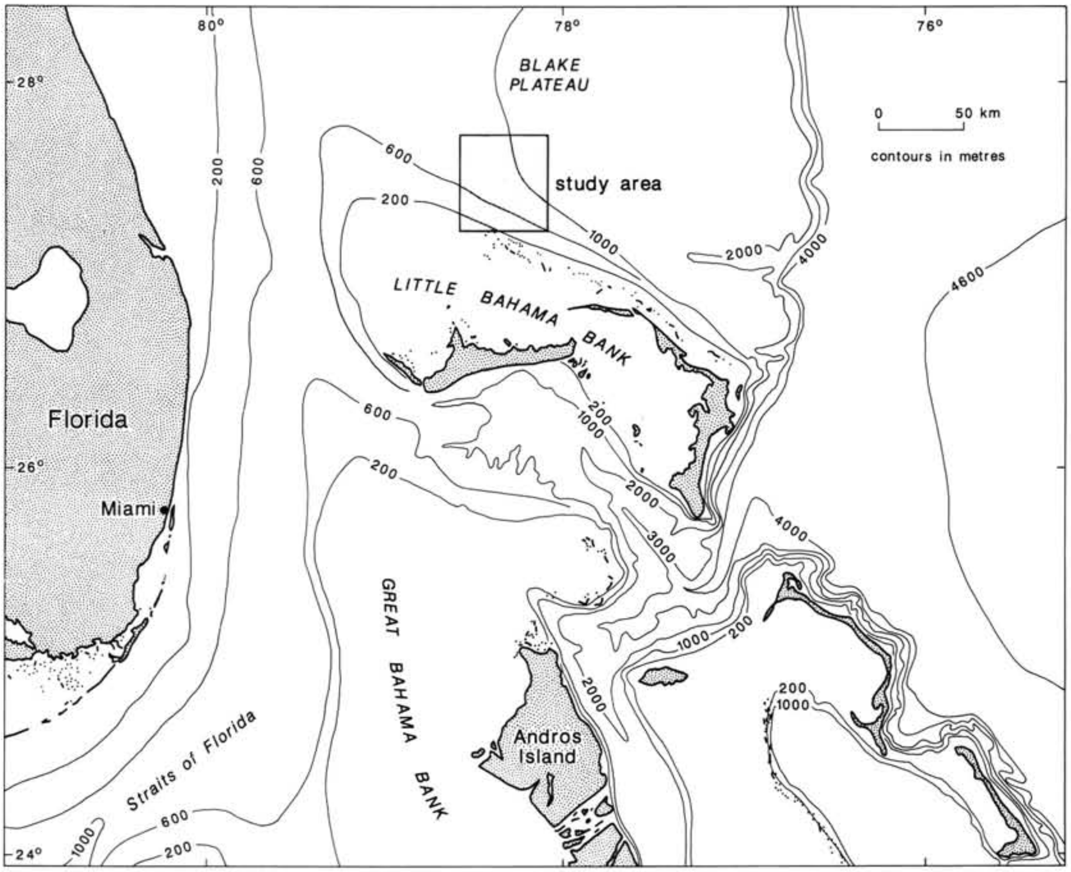

Figure 1. Map of the northern Bahamas, showing study area on the northern flank of Little Bahama Bank.

die out with gradual loss of relief at about 900 m water depth, where slope angles are 1.5° to 0.5°. This change in slope configuration can be used to define a change from the midslope to the lower slope (Fig. 3) (cf. Mullins et al., 1984; Mullins and Cook, 1986). Sediment is supplied to the lower slope by these gullies, which act as closely spaced point sources, producing a sediment apron of a series of overlapping sediment fans (Fig. 3). The shelf component of these sediments, therefore, effectively bypasses the upper slope and midslope. However, in addition to the shelf-derived sediments, a considerable proportion of the sediment present on the midslope and lower slope is derived from fallout of planktonic fauna and flora. One further noticeable feature of the present-day slope is the lack of gravitational sediment movement within large surficial slump masses; available seismic and bathymetric data indicate the slope profile to be smooth, both between gullies and on the lower slope sediment apron.

The gullies have steep lateral margins, some with V-shaped cross sections on the upper midslope, and most are U-shaped downslope. They reach their maximum relief in the center of the midslope, where their U-shaped morphology is clearly visible on the seismic profiles (Fig. 4). Relief is considerably less in the upper, V-shaped gullies (Fig. 2). Two gullies do not extend above 650 m on the upper midslope. Also apparent on the seismic profiles are listric failure traces, a result of inward collapse through gully margin failure, which is, in part, responsible for their U-shaped configuration (Figs. 3 and 4). Although the sediment surface is commonly cemented on the midslope (Austin, Schlager, et al., 1986), a few meters beneath the surface the sediment is predominantly uncemented ooze and carbonate turbidites, enabling such collapse to take place readily. Collapse is concentrated in the center of the midslope (Fig. 3), where gully margins are steepest and, together with the effects of cross-slope currents, may cause a minor amount of gully migration across the slope. The collapsed sediments are redistributed down the gullies to the lower slope. The V-shaped cross section of some gullies upslope also indicates that, in common with most siliciclastic shelf margins, gullies migrate upslope through time. Here, however, their upward migration may be restricted by more pervasive cementation within sediments of the upper midslope (Austin, Schlager, et al., 1986).

Ancient Channel and Levee System

Within seismic unit B is a series of disrupted and/or discontinuous reflectors, with both small-scale onlap and offlap, well displayed on seismic lines LBB 3 (Fig. 4; cross-slope) and LBB 8 (Fig. 5; downslope). These reflectors define an ancient system of meandering channels and corresponding levees, with channels up to 5 km wide and relief approaching 90 m. These channels were, therefore, both of lower amplitude and broader than the present-day surficial gullies that they underlie. The channel and levee system does not appear to extend below the modern midslope area, although deposition at that time was presumably on the lower slope. In cross section these channels have an onlapping fill (Fig. 4), but in longitudinal section (Fig. 5) the fill progrades downslope. Levees and overbank deposits are also apparent (Fig. 4), indicating downslope channelized flow. Some of these channels incise an erosion surface present within seismic unit B (see below). There is no feature comparable to this channel and levee system on the present-day lower slope, although in siliciclastic systems meandering channels have been

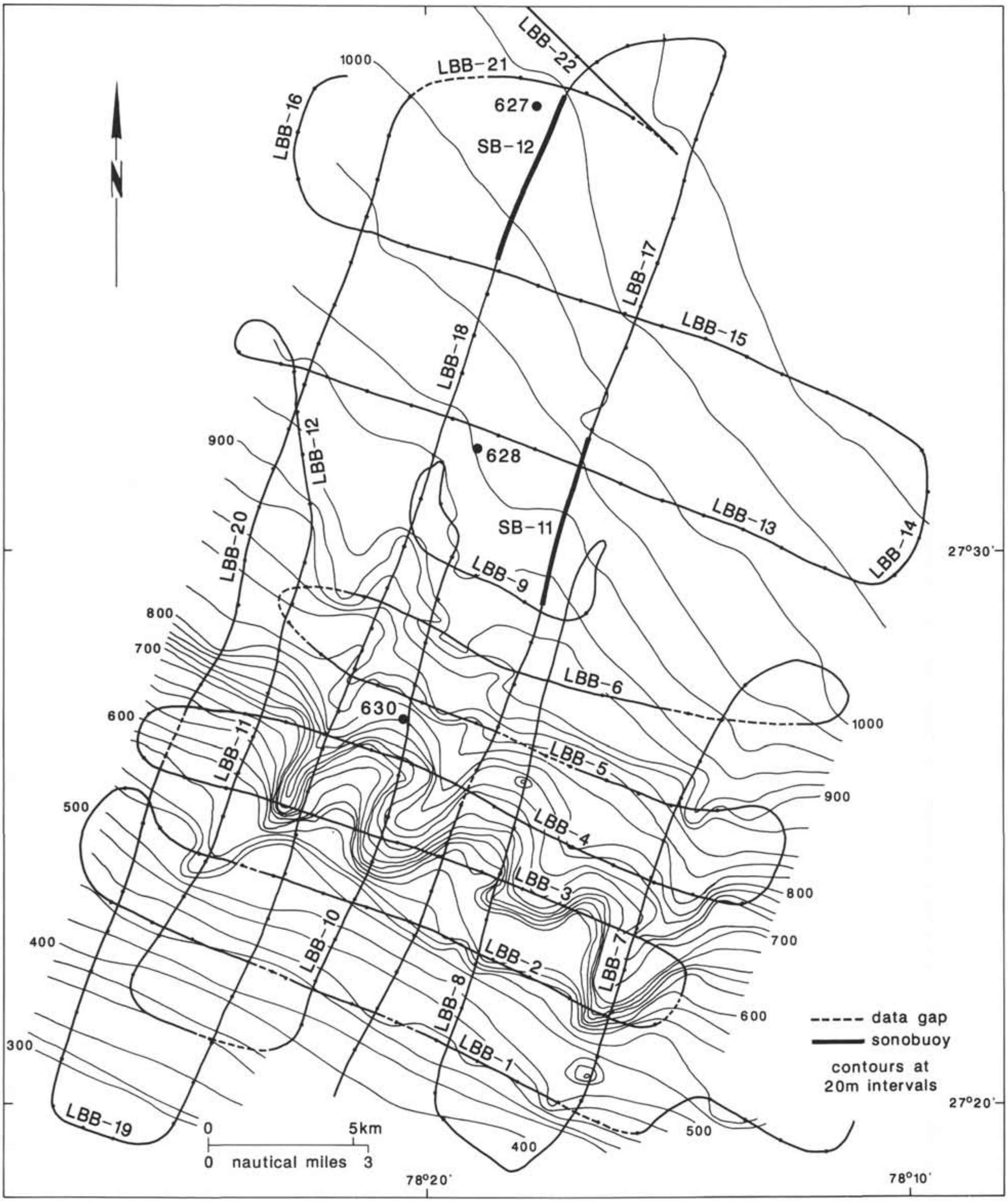

Figure 2. Bathymetric map of Little Bahama Bank showing traces of multichannel seismic profiles run during the site survey. Leg 101 sites are also marked.

recognized on submarine fans (Walker, 1978, 1980; Colacicchi and Baldanza, 1986). Unlike a single siliciclastic submarine fan with a point sediment source, here the lower slope was composed of a series of overlapping sediment fans forming a base-of-slope apron (e.g., Mullins and Cook, 1986); the carbonate margin thus provided a line source of sediment. Deposition was therefore in a slope environment different from those existing today. This ancient channel and levee system does, however, have some influence on modern slope configuration, as some of the modern gullies appear to be stacked above the uppermost major channels (Fig. 4), possibly as a result of differential compaction within the underlying channels.

Table 1. Interval velocities used for seismic units.

Seismic unit	Interval velocity (km/s^{-1}) Leg 101 data	 This paper
A	1.70–1.75	1.55–1.60
B	1.70–1.75	1.51–1.93
C	1.75–2.15	2.53–2.64
D	2.15–2.26	

Erosion Surface Within Seismic Unit B

Within the ancient channel and levee system an erosion surface subdivides seismic unit B, and can be traced northward to the present lower slope (Figs. 5 and 6). This erosion surface is best developed in the western part of the area and is easily traceable in seismic lines LBB 20, 11, 18, and 10. It is still present, although less distinct, in seismic lines LBB 17 and 8. Correlation with biostratigraphic units determined aboard ship from Sites 627 and 628, plus evidence from changes in sedimentation rate (Austin, Schlager, et al., 1986), establishes the age of this erosion surface as earliest Pliocene, where it corresponds to a possible biostratigraphic break (Watkins et al., 1986; Watkins, pers. comm.).

Seismic analysis has also indicated a sediment thickening in seismic units A and B in the northeastern part of the site survey coverage (visible on lines LBB 13, 14, and 15), although we admit that seismic coverage there is sparse. A potential cause of the erosion surface and the subsequent sediment thickening could be movement along Walker's Cay Fault (Fig. 7A), which is known to have been active in the Cenozoic (Mullins and Van Buren, 1981). Walker's Cay Fault is visible on seismic profiles LBB 5, 6, 13, and 15, with a minor splay on LBB 18 (Fig. 6), but throughout the area it has only a minimal effect on sediments younger than middle Miocene. It appears unlikely, therefore, that movement on this fault can account for both the erosion surface, which can be traced east of Walker's Cay Fault, and the sediment thickening. We propose here that the erosion surface represents a regional tilting of 1° or less toward the northeast during the earliest Pliocene, accounting for both the lesser prominence of the erosion surface in the east and the sediment thickening within the overlying units present in the northeast. The thickened sediments here are the probable lateral expression of a major depocenter farther east, marked by a regional gravity minimum (Klitgord et al., 1984; Austin et al., this volume)).

Ancient Surficial Slumps

Slumps, the result of large-scale surficial downslope sediment collapse and subsequent movement, have been identified by the presence of upper surface hummocky clinoforms and internal chaotic and discontinuous reflectors (e.g., Figs. 5 and 6). The resolvable thickness of surficial slumps from the seismic lines is less than 10 m; thinner, unresolvable, slumps may also be present. Figure 7A shows the lateral extent of the resolvable surficial slumps and demonstrates that, although there are some slumps within the upper seismic units, most are concentrated within seismic intervals C and D. Biostratigraphic correlation indicates these slumps to be of middle Miocene age. These slumps overlap each other and underlie much of the present-day lower midslope to upper lower slope; their depositional position must have been considerably more distal, possibly at the oceanic margin of the toe of slope. The slumps range in length downslope from a few to 15 km (discounting the possible continuation of S10 to S13, Fig. 7A) and are as much as 5 km wide. Thicknesses of the middle Miocene slump masses are shown in Figure 7B; larger slumps commonly reach thicknesses in excess of 80 m, with each slump having a planar base (Fig. 6).

Mapping the individual slumps and constructing their isopachs have enabled calculation of the areas, volumes, and masses of individual flows (Table 3). These volumes are considerably greater than those elsewhere in the Bahamas recorded by other authors and calculated from core data. Bornhold and Pilkey (1971) report carbonate turbidites of volumes of 10^8 m^3 from the Columbus Basin in the Bahamas, Crevello (1978) and Crevello and Schlager (1980) document carbonate gravity deposits of 10^7 m^3 from Tongue of the Ocean, whereas Schlager and Chermak (1979) present common maximum volumes of 10^7 to 10^8 m^3 within Bahamian basins and further state that flows in excess of 10^8 m^3 may indicate bank margin failure. Slump volumes calculated in this study range from 10^9 through 10^{12} m^3 (Table 3), several orders of magnitude higher. One reason for this discrepancy lies in the fact that these other authors are concerned with intrabasinal sediment deposition, contrasting with the open-ocean situation of Little Bahama Bank. A further difference is that their calculations are from sediment analysis, commonly involving finer distinction of units than seismic analysis. Whatever the causes of these differences, we emphasize that even the smaller slumps resolved within the uppermost seismic unit on Little Bahama Bank (S14 and S15) are considerably larger than the gravity deposits hitherto documented.

Detachment Surfaces

Seismic profiles through the lower slope show detachment surfaces climbing from seismic units C/D, and in some cases to unit A (Fig. 6; Austin, Schlager, et al., 1986). These surfaces climb through relatively unconsolidated and unlithified sediments, and most are at or above the level of the major surficial slumps. Movement directions commonly indicate that the sedi-

Table 2. Sedimentologic/seismic correlations between this interpretation and that used by Austin, Schlager, et al. (1986).

Hole 630A Sedimentologic unit	 Site survey seismic unit	 This paper	Hole 628A Sedimentologic unit	 Site survey seismic unit	 This paper	Hole 627B Sedimentologic unit	 Site survey seismic unit	 This paper
I 146	A ?52	A ?95	IA 5	A 52	A 48		A 47/48	A 41
II 250+	B 267–284	B 255	IB 48			IA 108	B 109/119	B 108
			IC 111	B 120	B 111			
			1D 137	C 138	C 137	IB 144	C 146/164	C 180
						IC 181	or	
							to 180 m	
			II 272	D 294	D 295	II 248	D 208/227	D 220
			III 298+			III 325	E 325	E 325

— — — — — Correlatable horizon on seismic profiles.
Thickness of sedimentologic units is in meters.

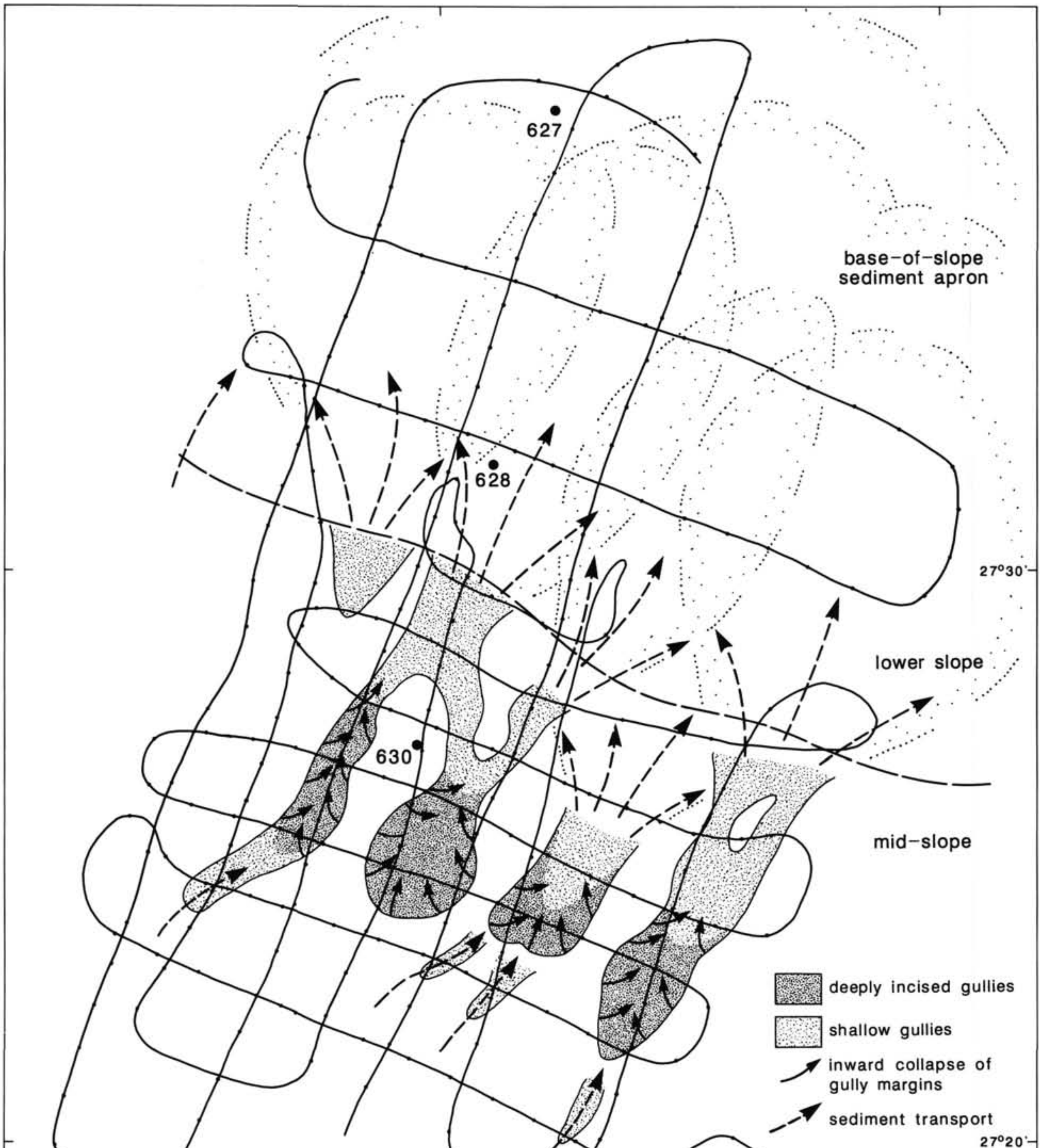

Figure 3. Modern slope configuration. Gullies are deeply incised into the midslope but lose relief both upslope and toward the lower slope. A base-of-slope sediment apron is present on the lower slope.

ments overlying each detachment surface have moved downslope, producing minor repetition of sequences, not discernible by biostratigraphy. In other areas (e.g., parts of LBB 20 and LBB 17) the movement sense is upslope.

Plotting these movement directions within seismic units B and C/D has shown a series of large lobes of downslope creep (Fig. 8), the margins of which, in places, climb through Pliocene sediments to within seismic unit A and, less commonly, to the present-day seafloor (Fig. 6). The scale of these lobes is such that they continue well beyond the present seismic coverage, extending up to 30 km basinward from the top of the lower slope (Fig. 8). Although each detachment surface represents only a small amount of downslope movement, major downslope sediment creep within each large lobe has occurred and probably

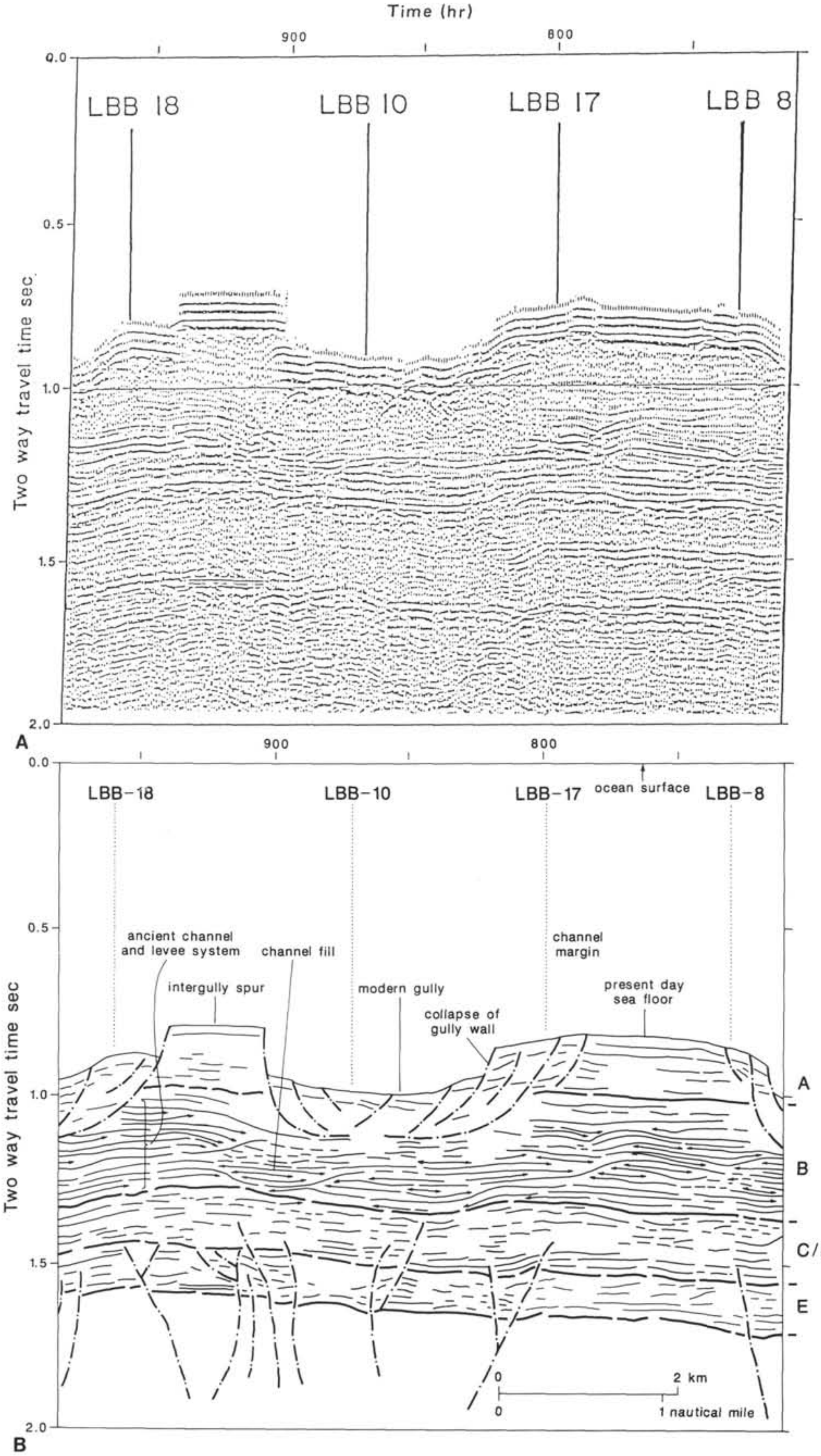

Figure 4. A. Part of seismic profile LBB 3, uninterpreted. B. Interpretation of seismic profile LBB 3, showing major seismic units, modern gullies, and collapse of gully margins plus upper Miocene through Pliocene channel and levee system. West is to the left of the figure.

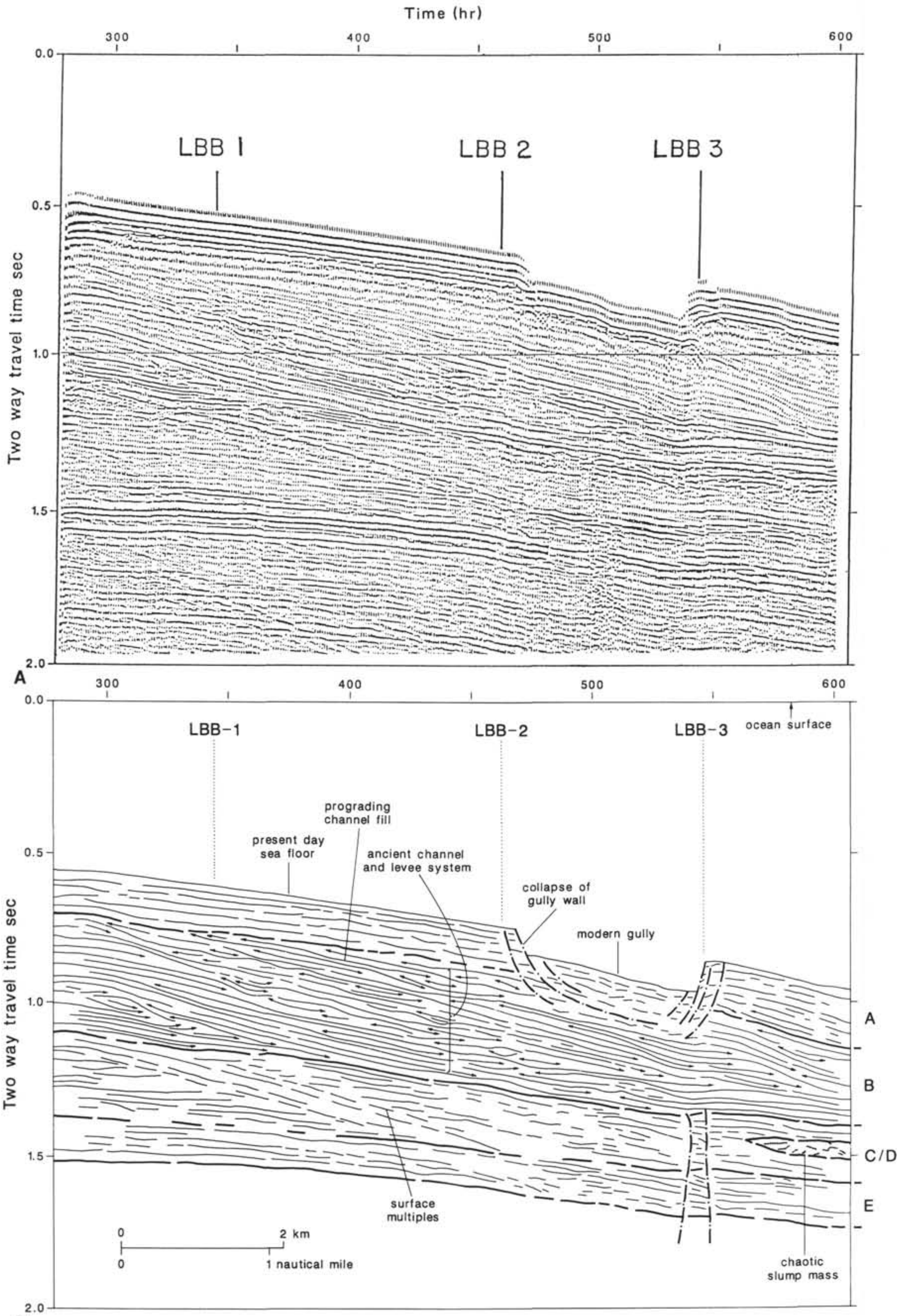

Figure 5. A. Part of seismic profile LBB 8, uninterpreted. B. Interpretation of seismic profile LBB 8, with longitudinal section through channel and levee system showing prograding channel fill. Modern gully has listric failure collapse of margins. North is in the downslope direction.

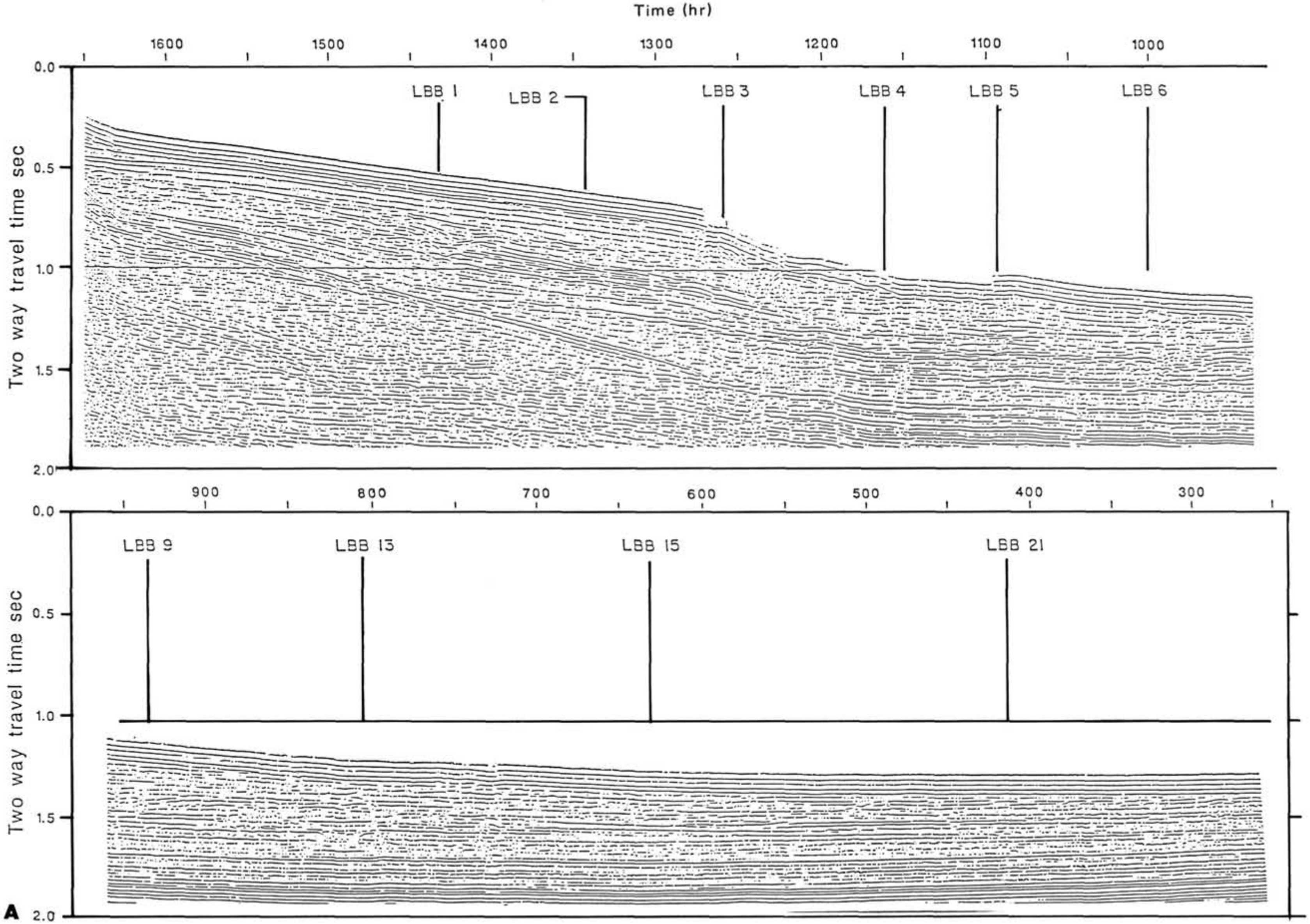

Figure 6. A. Seismic profile LBB 18, uninterpreted. B. Interpretation of longitudinal seismic profile LBB 18. In addition to the features of the preceding figures, the erosion surface within seismic unit B is shown to extend from the midslope to the lower slope. One large chaotic slump mass (S8) is defined within seismic units C/D. Large-scale rotational creep is demonstrated by climbing minor detachment surfaces; décollement took place at the base of the large slump mass. The fault reaching the present seafloor between LBB 13 and LBB 15 is interpreted as a splay from the Walker's Cay fault system (see also Austin et al., this volume). North is in the downslope direction.

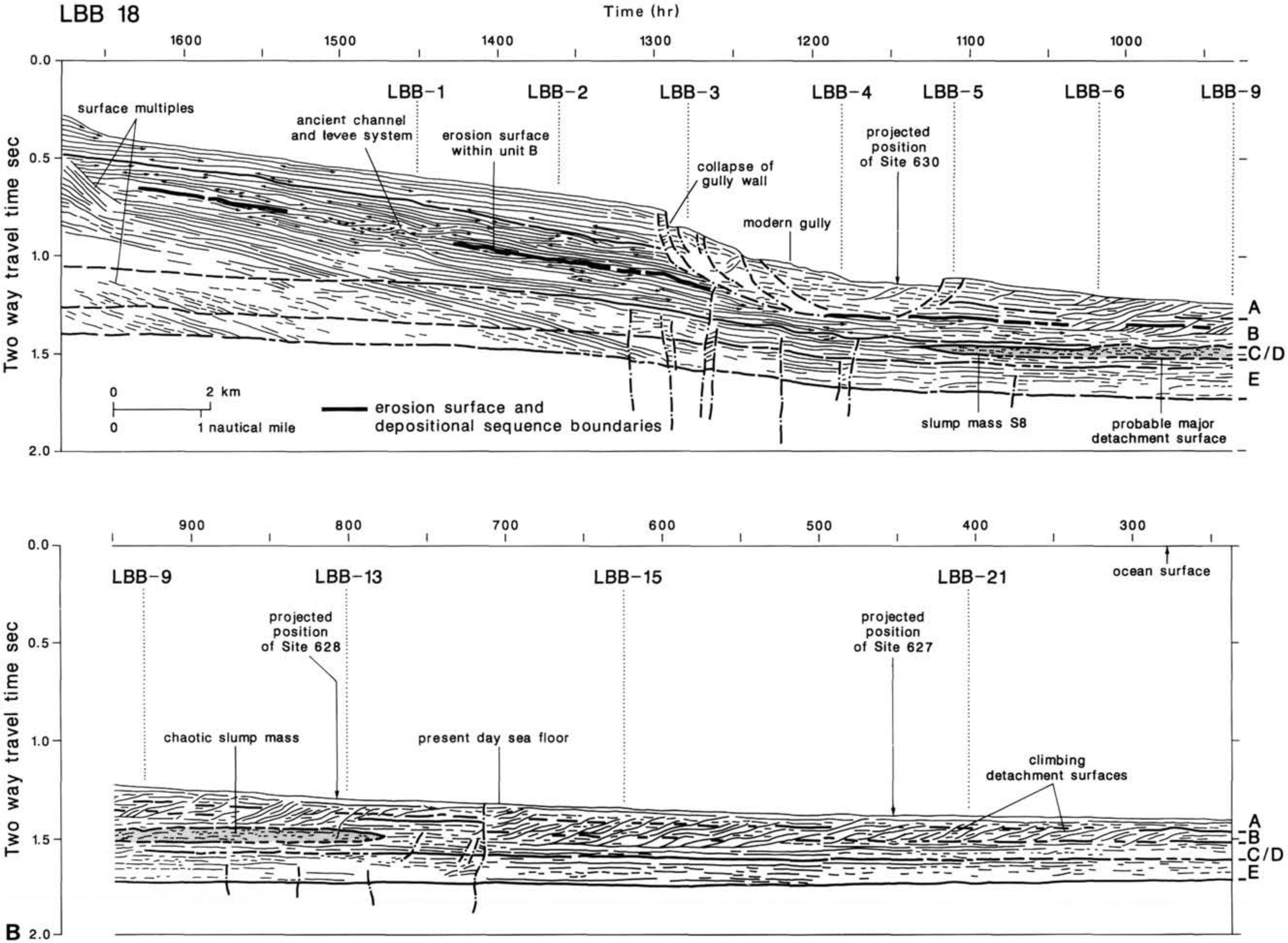

Figure 6 (continued).

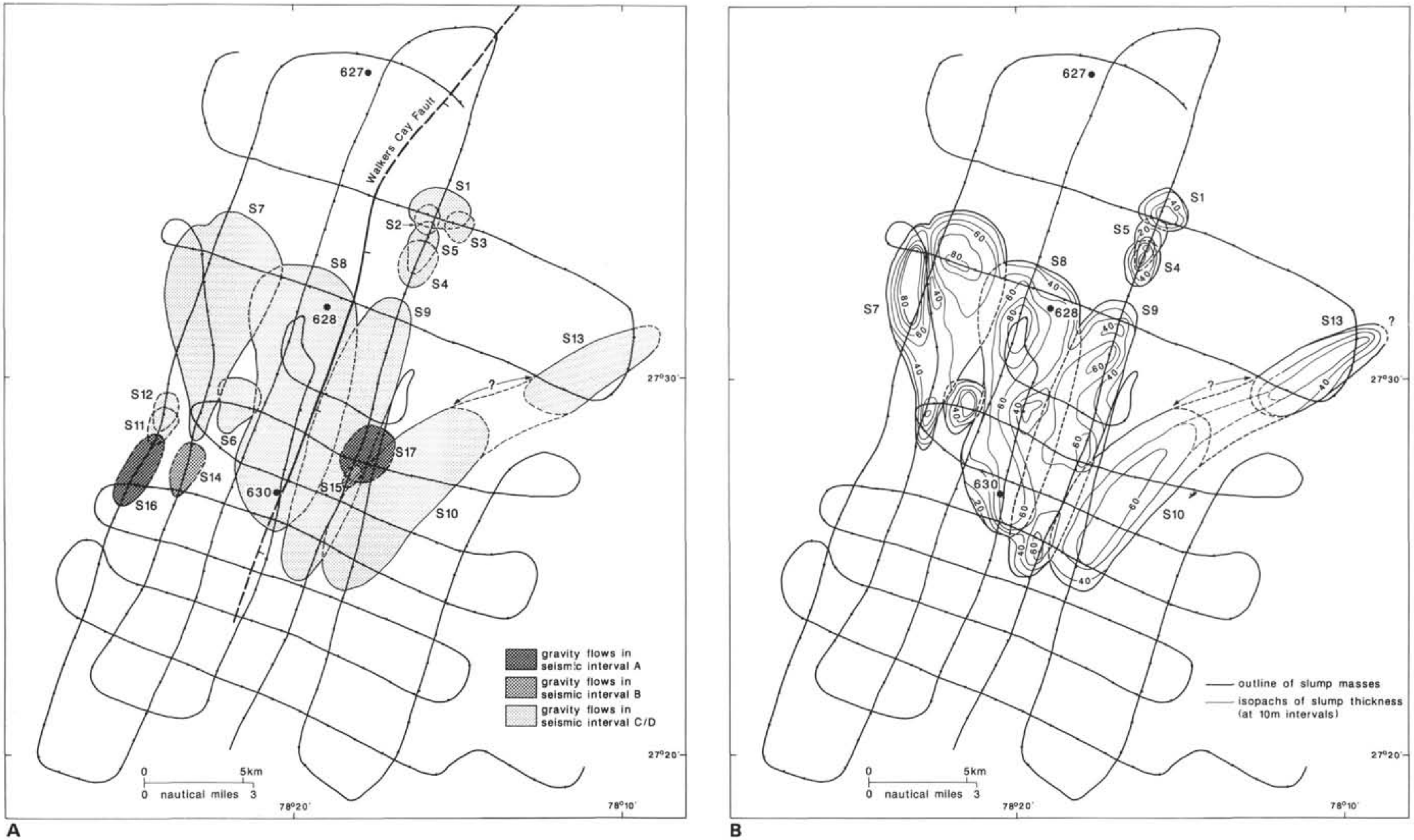

Figure 7. A. Areal extent of slump mass gravity flows within the different seismic units. Walker's Cay Fault runs across slump masses and has no determinable effect on their configuration. B. Thickness variations of the large middle Miocene slump masses.

Table 3. Areal extent, volume, and mass of the slump masses delineated from seismic profiles.

Seismic unit	Gravity flow	Area (km^2)	Volume (m^3)	Mass (tonnes)
A	S17	3.55	2.6×10^{11}	4.7×10^{11}
	S16	2.85	8.3×10^{11}	1.5×10^{12}
B	S15	0.42	6.8×10^{9}	1.3×10^{10}
	S14	1.84	9.9×10^{10}	1.9×10^{11}
C/D	[a](S13 + S10)	35.83	3.6×10^{12}	6.6×10^{12}
	S13	9.43	8.1×10^{11}	1.5×10^{12}
	S12	1.12	4.4×10^{10}	8.0×10^{10}
	S11	1.07	6.6×10^{10}	1.2×10^{11}
	S10	22.06	2.4×10^{12}	4.5×10^{12}
	S9	24.82	1.9×10^{12}	3.2×10^{12}
	S8	34.54	3.5×10^{12}	6.1×10^{12}
	S7	23.81	2.0×10^{12}	3.7×10^{12}
	S6	2.39	1.7×10^{11}	3.1×10^{11}
	S5	1.97	7.4×10^{10}	1.3×10^{11}
	S4	2.11	1.1×10^{11}	2.1×10^{11}
	S3	1.14	4.3×10^{10}	7.2×10^{10}
	S2	0.77	1.1×10^{10}	1.9×10^{10}
	S1	3.00	8.7×10^{10}	1.7×10^{11}

[a] Calculation based on S13 + S10 representing one gravity flow.

still is occurring. The numerous small detachment surfaces and the different sediment depths at which they occur suggest that this process has continued for some time. The upper limit of this downslope creep is in the upper midslope (Fig. 6); rotation must therefore commence in this area. It is in this part of the slope that the gullies have their greatest relief (Fig. 2), and the slow rotational sediment creep may form a surficial scar which, in turn, initiates gully formation. We place the area of scar formation between seismic profiles LBB 2 and 3, where the gullies become deeply incised into the slope (Fig. 2). Active gullying has destroyed direct evidence of these scars apart from the upper ends of two gullies, those crossed by LBB 10 and lying between LBB 8 and 7 (Figs. 2 and 3). These gullies do not continue upslope into a gully with a V-shaped cross section, and we interpret their upper extremities to be the surface expression of the rotational sediment creep, producing active listric fault scarps. Longitudinal seismic profiles show that many listric failure lines associated with gully margin collapse are deep-seated (Fig. 6) and may extend downslope into the plane of a major detachment surface.

All the minor detachment surfaces climb from the same level within seismic intervals C/D, the subplanar base of the major slump masses (Fig. 6). This is also the approximate level of the change from the predominantly unlithified sediment package to partial lithification within the underlying sediments. The base of the major slump masses, therefore, appears to represent a major detachment surface that has been continuously utilized by the process of downslope creep. The underlying pre-Miocene chalk within seismic unit E at Site 627 contains neither major nor minor detachment surfaces.

SEDIMENTOLOGIC CONSTRAINTS

Sediments recovered from ODP Sites 627, 628, and 630 on northern Little Bahama Bank indicate a northward progradation of the bank margin since the beginning of the Miocene (Leg 101 Shipboard Scientific Party, 1985a, 1985b; Austin, Schlager, et al., 1986). Discontinuities between sedimentologic units are in part coincident with the boundaries of seismic sequences (Table 2). Figure 9 shows the major correlatable seismic and sedimentologic units and summarizes their sedimentology. Units A and B thin downslope toward the upper part of the lower slope, beyond which they maintain a near-constant thickness (Figs. 6 and 9).

Correlation of units C and D is, however, more problematical. The seismic interpretation presented here questions the correlation of sedimentologic units presented by Austin, Schlager, et al. (1986), as seismic correlation indicates equivalence of the base of lithologic Units IC (Hole 628A) and IA (Hole 627B) (Fig. 9). Austin et al. (this volume) comment on the irregularity of thickness of units in seismic unit D, noting that at Site 627 this unit was latest Oligocene to early Miocene in age, whereas at Site 628 seismic unit D ranges from latest Eocene to late Oligocene in age and is considerably thicker (Leg 101 Shipboard Scientific Party, 1985b). We have been unable to correlate the C/D boundary throughout the seismic coverage and therefore cannot comment further on these thickness variations across the area. Nevertheless, the combination of biostratigraphic, sedimentologic, and seismic evidence supports the contention that there is no lateral equivalent of lithologic Unit IB, Site 627, at Site 628 (Fig. 9) and thus that this unit bypassed the distal lower slope during the middle Miocene, a period when the large slump masses (Fig. 7) were formed. Deposition in the Miocene resulted in a thicker series of sediments at Site 627 than at Site 628, and deposition continued for a longer time (late early Miocene to middle Miocene, as opposed to middle Miocene only) (Leg 101 Shipboard Party, 1985b). It appears, therefore, that bypassing took place during this time, perhaps a consequence of slump formation, although the depositional environment was considerably more distal than the area of the present-day slope studied by Leg 101.

DISCUSSION

Evidence presented in this paper has several implications for carbonate slope evolution within the Little Bahama Bank area. One of the major distinctions between modern and ancient slope configurations is the current absence of large-scale surficial slumps, although small-scale slumps not resolvable on the seismic profiles may be present. The only modern slumping resolvable is the gully wall collapse. The largely unlithified nature of the sediments from the lower midslope oceanward is inconsistent both with the lack of slumping and with the relatively high sedimentation rates on the midslope to lower slope (14 to 33 m/m.y at Sites 627 and 628, respectively; Austin, Schlager, et al., 1986). Surficial slumping may take place, but slumped sediments may be winnowed and redistributed by ocean-bottom contour-following currents, originating from the Antilles Current. A further pertinent factor here is the lack of large surface expression where minor detachment surfaces climb to the sediment/water interface (Fig. 6), also a possible consequence of sediment redistribution by ocean bottom currents. If this is so, these currents are presumably stronger today than during earlier (Miocene) stages of slope evolution. Mullins et al. (1984) correlate the decrease in cementation downslope with a concurrent slackening of contour-following bottom currents. We maintain that the currents active on the present-day lower slope are sufficiently strong to redistribute uncemented sediments, but we agree that their decrease in strength from the midslope through to the lower slope may be one factor preventing lithification at these depths.

The modern slumps associated with gully wall collapse result in down-gully redistribution of the slumped sediments and the formation of extensive depositional sediment lobes on the lower slope (cf. Mullins et al., 1984; Colacicchi and Baldanza, 1986). Such sediments probably compose the Holocene/upper Pleistocene debris flows present near the top of Holes 628A and 627B (Fig. 9), the contained clasts of which may be the cemented upper few meters of sediment from former intergully areas of the midslope. Unlithified sediments involved in gully wall collapse are probably redistributed by density flows.

The ancient channel and levee system (seismic unit B, upper Miocene through Pliocene) was deposited on the lower slope, where slope angles are calculated to have been 1° through 2° in water depths on the order of 1000 m (Table 4), similar to those

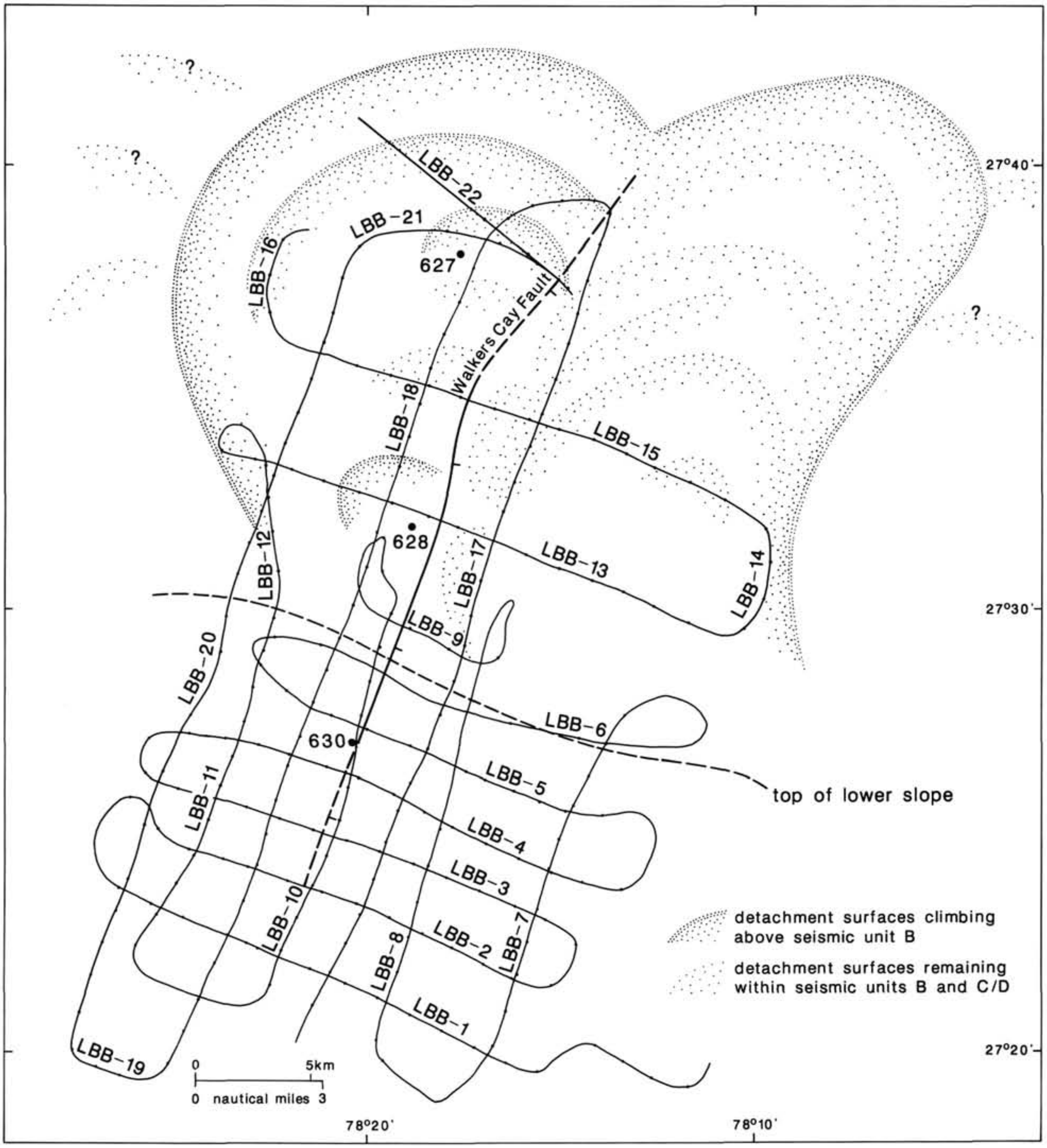

Figure 8. Distribution of creep lobes on the lower slope, showing position of groups of minor detachment surfaces that climb upward through the unlithified sediments. Extrapolated creep lobes extend well downslope of the seismic coverage.

of the lower slope today. Site 630 recovered ooze and thin turbidites from throughout this interval (Fig. 9), comparable to those deposited on the lower slope throughout seismic unit A. An increase in strength of ocean-bottom contour-following currents could account for the change in sedimentation patterns on the lower slope from the Miocene to the present. The channel and levee system was deposited during a period of little ocean current movement, but, as current strengths increased over time, lateral sediment transport inhibited channel and levee formation, resulting in a smoother configuration to the base-of-slope sediment apron. This hypothesis obviates the need to link these differences in slope sediment deposition to sea-level changes, which themselves show considerable variation during deposition of seismic units A and B (Vail et al., 1977; Haq et al., 1987), although major channel downcutting episodes may reflect low sea-level stands. The hypothesis also implies that changes in current strength took place at the commencement of, or at least during, seismic unit A, latest Pliocene to Pleistocene in age.

Haq et al. (1987) show no major period of lowstand in the lowermost Pliocene. Thus the erosion surface detailed within seismic unit B may not be a result of sea-level fall and subsequent slope erosion; this supports our suggestion of regional

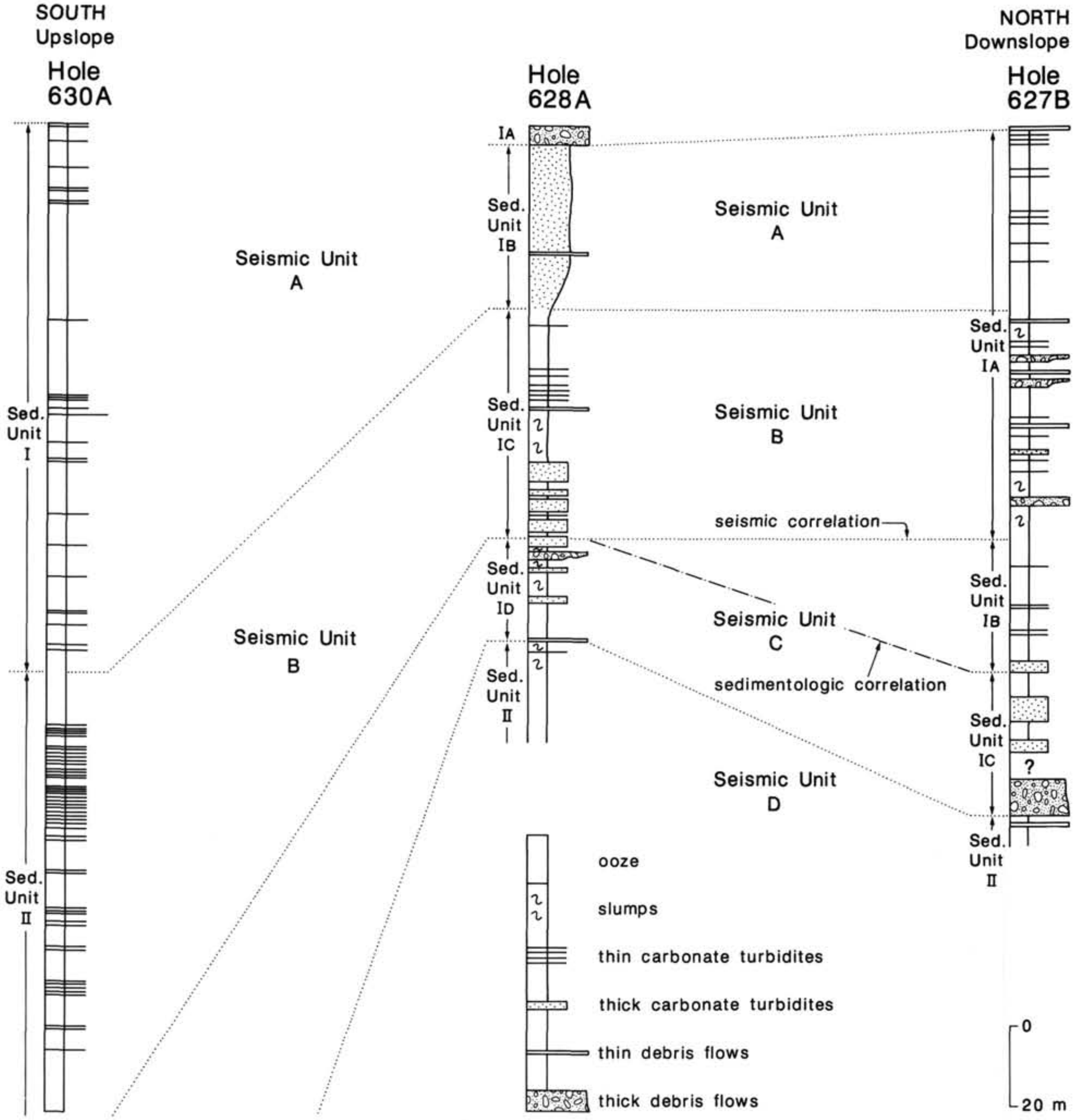

Figure 9. Correlation of seismic and sedimentologic units between Sites 627, 628, and 630. Site logs summarize the sedimentologic components recovered.

tilting at this time. We have already presented evidence indicating that this tilting appears not to be from reactivation of Walker's Cay Fault, and we propose that it may be a result of regional flexure along postulated deep-seated basement faults (Sheridan, 1974; Sheridan et al., 1981; Klitgord et al., 1984). Elimination of this post-Miocene tilt results in a Miocene paleoslope that faced approximately north-northeast, almost exactly paralleling the downslope seismic profiles, themselves run at an angle of a few degrees to the dip of the present-day slope, which faces more toward the northeast (Fig. 2). Restoration of the paleoslope demonstrates that many of the large slump masses (Fig. 7) moved directly downslope, the major exceptions being S10 and S13.

Large slump masses north of Little Bahama Bank are coeval with middle Miocene debris flows sampled at Site 626 (Leg 101 Scientific Party, 1985a, 1985b; Austin, Schlager, et al., 1986), debris flows in the Blake-Bahama Basin (Benson, Sheridan, et al., 1978; Sheridan, Gradstein, et al., 1983) and, possibly, catastrophic collapse of part of the west Florida margin (Mullins et al., 1986). The occurrence of coeval large debris flows and slump masses over this large area rules out their simple initiation through gravitational instability caused by high rates of sediment accumulation (Bliefnick et al., 1983); a more regional control is preferred. Although a high sea-level stand took place during the middle Miocene (Vail et al., 1977; Haq et al., 1987), with consequent high slope sedimentation rates from highstand shedding (Boardman and Neumann, 1984; Boardman et al., 1986; Austin et al., this volume), this is unlikely to have been the sole control of these regional sediment gravity deposits. Triggering of collapse by subsequent sea-level fall (Mullins et al., 1986) may have resulted in some local collapse, but we concur with Austin et al. (this volume) and Fulthorpe and Melillo (this volume) that a tectonic event is the most plausible cause of this regional phenomenon.

The base of the large slump masses is coincident with the décollement horizon for the rotational downslope movement of the creep lobes. Therefore, the chaotic nature of these slump masses may in part be a result of movement along this detachment surface. However, beds younger than the slumps onlap the slump margins (Figs. 5 and 6), showing that not all the slump features visible on the seismic profiles are a result of this later detachment. Nevertheless, some of the contorted sediments seen in cores above the level of the major slump masses from Sites 627 and 628 (Fig. 6) probably result from propagation of minor detachment surfaces through these sediments, rather than being evidence of surficial sediment slumping. Minor biostratigraphic repetition would provide firm evidence of this, but with only small movement along each of the minor detachment surfaces there is little likelihood of sufficiently intensive sampling coupled with amply precise biostratigraphic resolution. Disruption by the minor detachment surfaces of alternating lithified and nonlithified carbonate beds could produce sediments similar in appearance to debris flows; indeed some of the "debris flows" at Sites 627 and 628 may have this origin. Detailed study of both clasts and matrix is necessary to determine if some, or all, of these are true debris flows, or if some were produced by detachment surface propagation through the sediments.

The volume of material that moved slowly downslope by creep along the detachment surfaces is very large. Creep lobe propagation requires the build-up of sufficient overburden and hence enough pressure to initiate movement along a plane of weakness, the detachment surface. Most sediments above the major detachment surface are unlithified, but lithification increases toward the base of the creep lobes. Creep movement along the major detachment surface may utilize a lithified or partially lithified zone within the sediment column, particularly as sediments below this level show increasing degrees of lithification. In the landward direction, pervasive lithification within upper midslope and upper slope sediments forms the upward limit of sediment creep, and listric failure scars initiate gully formation across the slope between seismic profiles LBB 2 and 3. Lithification may also restrict the depth of propagation of the major detachment surfaces and hence the total vertical dimension of the creep masses.

The above discussion has several consequences for theories of carbonate slope development. One major objective of ODP Leg 101 was studying carbonate slope evolution, using Little Bahama Bank as an example of an accretionary slope. Evidence presented by Austin, Schlager, et al. (1986) and in this chapter demonstrates that some bypassing is occurring on the present surfaces of Little Bahama Bank and has occurred while the slope has been prograding northward. Initial paleoslope reconstructions show an increase in slope angle with time, according with slope steepening as progradation proceeds and the slope evolves (Schlager and Ginsburg, 1981; Schlager and Camber, 1986). These reconstructions also indicated that surficial sediment deposition occurred at very low slope angles (Table 4). Our evidence has demonstrated that sedimentation was active across the lower slope, particularly in distal parts of the lower slope, during slope evolution throughout the Neogene and that sedimentation took place both by surficial movement (slumps, debris flows, and density currents) and by large-scale within-sediment creep, not hitherto documented from a carbonate slope. Excluding the large middle Miocene surficial slumps, which are an exceptional event in the slope's history, the sedimentary features developed during the evolution of Little Bahama Bank do not closely accord with Schlager and Ginsburg's (1981) original model, but are more similar to some siliciclastic fan models (e.g., Walker, 1978, 1980; Colacicchi and Baldanza, 1986). We consider the lack of lithification in the lower midslope and lower slope to be one of the major reasons for this similarity.

Table 4. Slope angles and water depths of the present-day slope, channel and levee system, and slump horizon.

Location	Slope angle	Water depth range
Present slope (mid-slope)	2°–4°	200–900 m
Present slope (lower slope)	1°–2°	900–1300 m +
Channel and levee system (proximal apron)	1.5°–2°	?? ? > 900 m
Slump horizon (distal apron??)	<0.5°	?? ? > 1000 m

CONCLUSIONS

Study of the evolution of Little Bahama Bank using seismic profiles and sedimentological analysis has yielded four major conclusions:

1. The modern slope is not an adequate analog for the ancient slope sedimentary environments deposited during northward progradation of Little Bahama Bank. Although our evidence was restricted to the midslope and lower slope, facies associations in Miocene and younger sediments are not repeated today, and processes acting during different stages of slope evolution are more varied than those of the present day.
2. The combination of seismic and sedimentologic evidence demonstrates that surficial downslope sediment movement (slumps, debris flows, turbidites, and so on) has continued throughout the history of the slope, but that bypassing has been an integral part of sediment deposition, even during very early stages of slope evolution.
3. Creep within the unlithified sediment pile produces large-scale gravitational sediment movement in the form of creep lobes. We have demonstrated that this movement is taking place today, but the many complexes of multiple minor detachment surfaces indicate that downslope creep has been proceeding for a considerable period of time, probably since the late Pliocene. The extent of the creep lobes, both upslope and within the sediment pile, is determined by the amount of lithification, with predominantly unlithified sediments within the lobes.
4. Ocean-bottom contour currents have increased from the Pliocene to the present day. Ocean-bottom currents during deposition of the upper Miocene–lower Pliocene channel and levee system were slight, whereas modern ocean-bottom contour currents are actively redistributing loose sediment across both the midslope and the lower slope.

Little Bahama Bank has evolved from an oceanic plateau through three main stages: first, a low-angle accretionary slope, notable for the presence of large slump masses on the distal slope; second, a lower slope, where the sediment apron at the base of slope was modified by a migrating channel and levee system; and third, the modern slope, where sediment is supplied to the lower slope sediment apron both by gullies and by planktonic fallout. The bank has had a varied history, a reflection of integration of many different processes, including sea-level stand, sediment input, tectonic events, cementation (or the lack thereof), presence or absence of ocean-bottom currents, slope angle, stage in slope evolution, and, as with other carbonate slopes, aspect and nature of the shallow margin.

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