Hawkins, J., Parson, L., Allan, J., et al., 1994
Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 135

11. LATE MIOCENE SEDIMENTATION HISTORY OF THE TONGA FOREARC AT SITE 840[1]

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ABSTRACT

Site 840 was drilled in 754.4 m of water during Ocean Drilling Program Leg 135 to provide a better understanding of the geologic history of the Tonga forearc during the Late Cenozoic and to permit investigation of the nature and age of the regional unconformity known as Horizon "A". The cores recovered are the only ones that have been drilled in the marine environment on the southern Tonga Platform. Detailed study of these cores, combined with interpretation of sedimentary structures from Formation MicroScanner (FMS) images indicate two tectonic events of uplift and rotation of the Tonga Platform.

Sedimentologic evidence of a significant seismic reflector interpreted as Horizon "A" was recognized at 500 m below seafloor (mbsf) in the Site 840 cores. This corresponds to an age of 6.3 Ma for this event of uplift of the outer forearc and westward tilting of the Tonga Platform. The second tectonic event identified by this study, at 5.1 Ma, is marked by significant changes in the sedimentation rate, lithology, sedimentary structures and carbonate content of the sediments and by changes in the preservation and abundance of foraminifers. The sediments below 260 mbsf are dominated by late Miocene volcaniclastic turbidites interbedded with thin intervals of heavily bioturbated pelagic marlstones. These sediments were deposited on an east-dipping forearc slope, at or near the foraminiferal lysocline, estimated to be not less than 2000 m during the late Miocene. Significant uplift of the outer forearc and consequent northwest tilting of the southern Tonga Platform occurred at approximately 5.1 Ma. At this time, the southern Tonga Platform assumed its present configuration and shallow bathymetry. Sediments younger than 5.1 Ma accumulated on this shallow-water platform in water depths similar to those found there today.

INTRODUCTION

Site 840 was one of two Tonga forearc sites drilled on ODP Leg 135. It lies in 754.4 m of water and is located approximately 45 km east-northeast of 'Ata Island and about 130 km south-southwest of the islands of Tongatapu and 'Eua (Fig. 1). The site is located in a region informally known as the south central Tonga Platform that forms the crest of the Tonga Ridge south of 21°S. The Tonga Ridge is defined by the 1000-m isobath and extends for more than 1400 km. It is a broad, flat-lying, north-northeast-trending feature between the west-dipping Tonga Trench subduction zone to the east and the active Tofua Arc to the west.

Site 840 was intended to provide information on the sedimentologic and tectonic history of the Tonga arc and forearc throughout the Middle and Late Cenozoic. Specifically, the recovered sediments were intended to document the uplift and subsidence history of the forearc since the Middle Cenozoic. The regional, locally angular unconformity known as Horizon "A" (Herzer and Exon, 1985) was a drilling objective. This feature was identified and mapped based on single and multichannel seismic surveys (Fig. 2) and was estimated to lie between 450 and 500 mbsf at Site 840 (Shipboard Scientific Party, 1992). This unconformity was reasoned to reflect a tectonic event coincident with the initiation of rifting and opening of the Lau (backarc) Basin (Parson, Hawkins, Allan, et al., 1992). It was anticipated that recovery of this interval would permit an investigation of the nature and age of the tectonic event.

One of the significant aspects of the drilling and logging of Site 840 was the unexpected predominance of resedimented material. Before Leg 135, it was anticipated that the rocks and sediments recovered would be shallow-water platform carbonates, possibly even reefal material, interbedded with some volcaniclastics (Parson, Hawkins, Allan, et al., 1992). However, the strata recovered are predominantly gravity flow deposits in the form of volcaniclastic turbidites and debris flows. These are interbedded with thin intervals of pelagic or hemipelagic marlstones. No evidence of a shallow-water carbonate platform at or near Site 840 was recovered.

Strata recovered at Site 840 record the evolution of the Tonga forearc since the late Miocene. In this chapter we present a description of the autochthonous and allochthonous sediments recovered from this site. Our discussion includes an interpretation of the probable depositional environment of these sediments, an evaluation of the tectonic implications of the turbidites, an estimation of the probable paleowater depth, and an assessment of the age and significance of Horizon "A" at this location.

METHODS

Forty thin-sections from various lithologies were prepared and examined. Samples from the most carbonate-rich pelagic and hemipelagic marls, particularly those containing biogenic structures, received special attention. All samples were mounted with an ultraviolet-cure epoxy so that the process could be conducted without heating the samples. This was done to preserve the natural fluorescence of the sediments, particularly the biogenic carbonate fraction. Because carbonate material is more prone to fluoresce than volcaniclastic material, ultraviolet and blue-violet epifluorescent microscopy was used in conjunction with standard petrography to resolve the presence and relative degree of preservation of biogenic carbonate grains (Dravis and Yurewica, 1985). This technique also proved helpful in revealing biogenic structures in thin-section because of the concentration of pelagic carbonate material in infilled burrows. Eighty smear slides were prepared to compare the abundance and preservation of biogenic carbonate grains (microfossils) from within infilled burrows to those within the host sediment.

Because overall core recovery from Site 840 was only 40% (Table 1), Formation MicroScanner (FMS) logging data were used to complement the study of primary sedimentary and biogenic structures in the forearc deposits. These images can be used to resolve individual turbidite units because of the variation in resistivity from the base to the top of the interval (McLeod, this volume).

Processed data from FMS logs acquired from Hole 840B were reformatted for use on a Sun workstation. Schlumberger FMS Image Examiner software was used to identify individual turbidites. Color

[1] Hawkins, J., Parson, L., Allan, J., et al., 1994. *Proc. ODP, Sci. Results,* 135: College Station, TX (Ocean Drilling Program).

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Table 1. Summary of the recovery percentages based on the curated length of core recovered from each of the three holes drilled at Site 840.

		Hole 840A			Hole 840B			Hole 840C			All holes		
Lithologic Unit	Depth (mbsf)	Curated recovery (m)	Cored interval (m)	Recovery (%)	Curated recovery (m)	Cored interval (m)	Recovery (%)	Curated recovery (m)	Cored interval (m)	Recovery (%)	Total recovery (m)	Cored interval (m)	Recovery (%)
Unit I	0–109.98	4.11	4.5	91.3	10.60	109.98	9.6	21.68	38.0	57.1	36.69	109.98	33.1
Unit II	109.98–260.50	—	—	—	11.29	150.52	7.5	37.97	76.0	50.0	49.26	150.52	32.7
Unit III	260.50–597.3	—	—	—	154.33	336.80	45.8	4.01	9.5	42.2	158.34	336.80	47.0
Totals		4.11	4.5	91.3	176.22	597.30	29.5	63.66	123.5	51.5	243.99	597.30	40.8

plots of each core were produced, and the thickness of the turbidites was measured from the interpreted images. Intervals exhibiting a sharp resistivity contrast at the base and increasing resistivity upward were interpreted as a single turbidite. Intervals as thin as 6 cm were resolved in this way. An example of an interpreted FMS image is shown in Figure 3.

SHIPBOARD STUDIES

Site 840

Three holes were drilled at Site 840. In Hole 840A, sediments were cored with the advanced hydraulic piston corer (APC) to 4.5 m below seafloor (mbsf). Hole 840B was cored with the extended core barrel (XCB) to 597.3 mbsf. Hole 840C was spot-cored with the APC to 259.5 mbsf. Core recovery averaged 40.8% overall (Table 1). Three lithologic units were recognized based on the composition and degree of lithification of the sediments and on the sedimentary structures present (Shipboard Scientific Party, 1992); a summary of these descriptions is presented here.

Description of Site 840 Sediments

Unit I

Unit I extends from the sediment/water interface to 109.98 mbsf. Total recovery from the three holes was 36.37 m, representing approximately 33% of the cored stratigraphic section (Table 1). The biostratigraphic ages of the sediments range from Holocene to late Miocene (Shipboard Scientific Party, 1992). Unit I is characterized by comparatively low sedimentation rates, ranging from 5 to 50 mm/k.y. (Shipboard Scientific Party, 1992). The sediments recovered are primarily clayey nannofossil oozes, vitric nannofossil oozes with clay, and vitric silts. Vitric sands, pumiceous gravels and pyroclastic deposits occur in subordinate amounts. The nannofossil oozes are interbedded with and occasionally grade down into vitric silts, vitric sands, and volcanic gravels.

The dominant lithology in the upper part of Unit I is soft, homogeneous, autochthonous pelagic sediment consisting of white to light brownish gray, clayey nannofossil ooze. Isolated pumice clasts (up to 5 cm in diameter) are common and occur throughout the section. Bioturbation is pervasive in the lower part of Unit I but decreases uphole; planar lamination is preserved in the upper 4.5 m of the section (from 0 to 4.5 mbsf). The carbonate content of the pelagic sediments of Unit I ranges from 50% to 86%. Foraminifers are generally well preserved and abundant. Bioclasts include shell fragments and echinoderm spines.

Unit II

Unit II extends from 109.98 to 260.50 mbsf. The total core recovery from both holes was 49.26 m, representing 32.7% of the cored intervals (Table 1). The biostratigraphic age of the sediments recovered is early Pliocene to late Miocene; the estimated sedimentation rate is 820 mm/k.y. (Shipboard Scientific Party, 1992). The lithologic boundary between Units I and II is marked by a sharp transition from structureless nannofossil ooze above the boundary to indurated, light gray to gray, highly bioturbated pelagic and hemipelagic marl and marlstone below the boundary. The percentage of pelagic marl and marlstone decreases downhole as the thickness and abundance of discrete, fining-upward volcaniclastic interbeds representing turbidites increases. This change correlates with a downhole decrease in the concentration of calcium and an increase in the concentration of silica seen on geochemical logs (Pratson et al., this volume).

The redeposited volcaniclastic sediments typically consist of light grayish brown to dark grayish brown vitric sand and sandstone with sharp, occasionally scoured basal contacts. This lithology fines upward into gray to very dark gray or dark greenish gray vitric silt or siltstone. The upper contact of the turbidites with the pelagic marl or marlstone is gradational and often obscured by pervasive bioturbation. The carbonate content of the marls and marlstones ranges from 53% in the upper part of the unit to 41% in the lower part (Shipboard Scientific Party, 1992). Carbonate bioclasts are absent in Unit II; foraminifers are poorly preserved and decrease in abundance downhole (Shipboard Scientific Party, 1992).

Unit III

Unit III is 336.8 m thick, extending from 260.50 mbsf to the bottom of Hole 840B at 597.3 mbsf. Core recovery for this interval is 47% (Table 1). The late Miocene sedimentary sequence recovered ranges in age from 5.3 to 6.6 Ma (Shipboard Scientific Party, 1992). The lithology of this unit is dominated by lithified volcaniclastic turbidites similar to those described in Unit II. The thickness and maximum grain size of the turbidites increases downhole as the carbonate content decreases. Volcaniclastic breccias and conglomerates are more common in Unit III, particularly below 500 mbsf. The carbonate content of the interturbidite pelagic marlstone ranges from a maximum of 50% near the top of the unit to a low of 24% near the base, as clay becomes an increasingly dominant component of these pelagic intervals (Shipboard Scientific Party, 1992).

RESULTS

Thickness of Turbidites

Based on recovered cores and interpretation of the FMS images, turbidites constitute a significant portion of the sediments within Unit II below about 120 mbsf and virtually all of the sediments within Unit III, below 260.5 mbsf (Shipboard Scientific Party, 1992). Although core recovery was approximately 47% in Unit III, high quality FMS images from that interval (Fig. 3) support the shipboard interpretation that the sediments of Unit III are dominated by gravity flow deposits. These beds are marked by a sharp, occasionally scoured basal contact, usually of vitric sandstone or siltstone. This lithology generally fines upward into bioturbated clayey vitric siltstone and then into heavily bioturbated marl. Some of the gravity deposits may contain very coarse sandstone, breccia or conglomerate at the base but vitric sandstone or siltstone is more common.

In the FMS images, the upward change in lithology within a turbidite or debris flow is resolvable because of the change in resistivity interpreted as the response to an upward decrease in porosity in a fining-upward interval. Color plots of the cores within Unit III were used to resolve individual turbidites; the thickness of each turbidite could be measured. Thicknesses were found to range from 6 to 541 cm. The average thickness is approximately 67 cm for the 279 intervals measured. A plot of the thickness of the turbidites vs. depth is shown

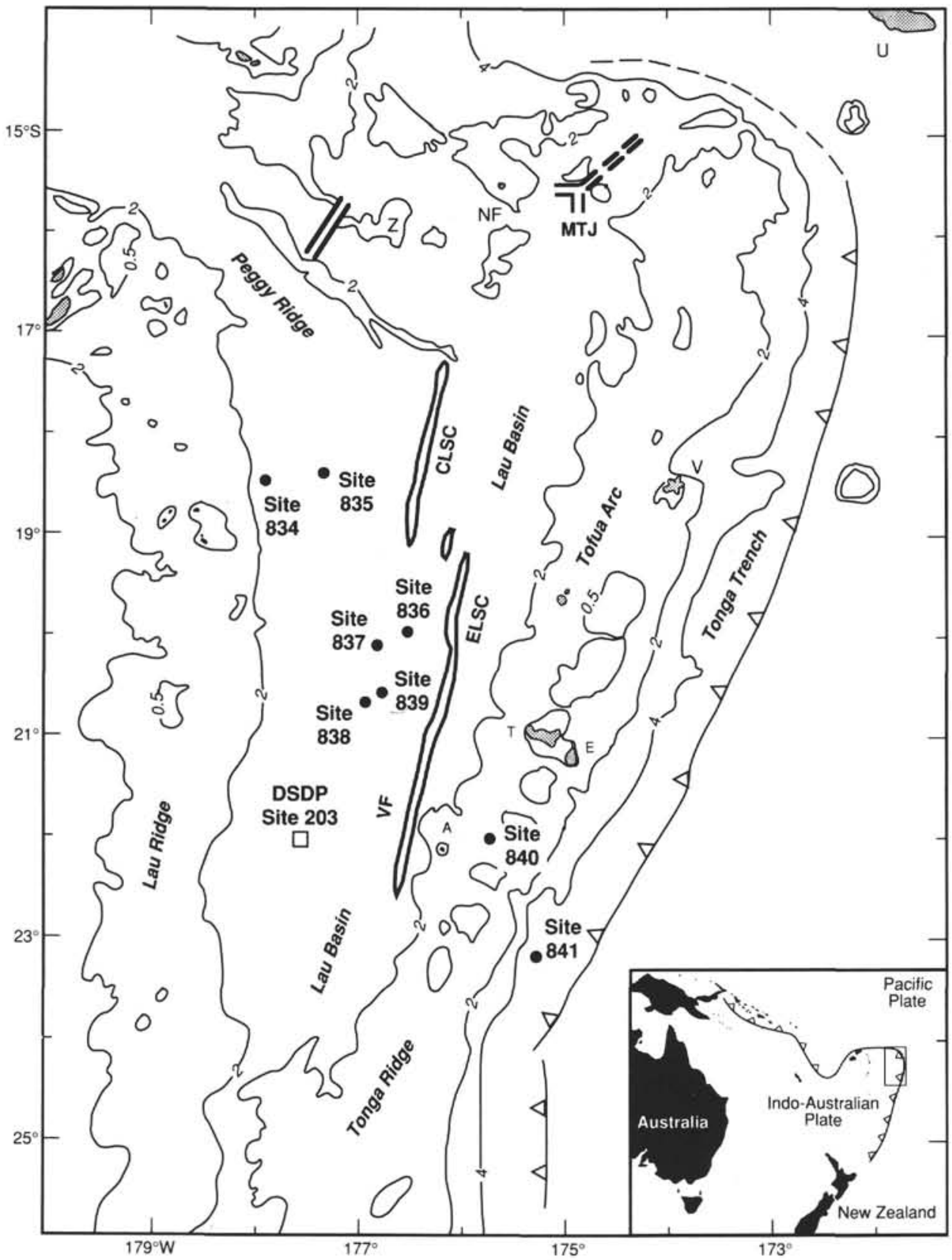

Figure 1. Regional bathymetry of the Lau Basin system and the location of Site 840, as well as other drill sites in the Lau Basin, and major geologic features of the Tonga Trench. Z = Zephyr Shoal; islands include T = Tongatapu, E = 'Eua, V = Vava'u, NF = Niuafo'ou, A = 'Ata, and U = Upolu. Locations of the Central Lau (CLSC) and Eastern Lau (ELSC) spreading centers, Valu Fa (VF) Ridge, and Mangatolu Triple Junction (MTJ) are from von Stackelberg (1990), Parson et al. (1990), Hawkins (1989), and Nilsson et al. (1989). The location of DSDP Site 203 is shown as an open square. Contours in thousands of meters.

in Figure 4. This plot reveals a slight but noticeable uphole decrease in the average thickness of the measured turbidites. No noticeable break occurs in this trend throughout most of Unit III. However, below 500 mbsf, the pattern is slightly more scattered. Shipboard processing and interpretation of FMS dipmeter data revealed a similar trend, suggesting that an additional structural unit could be defined at approximately 500 mbsf (Shipboard Scientific Party, 1992). The results of this study support this interpretation. FMS Image Examiner plots of this interval reveal a marked change in the character of the image and in overall resistivity just below 500 mbsf (Fig. 5). This suggests a significant change in the character of the sediments and probably reflects the level of the seismic Horizon "A" at Site 840.

Microfossil Abundance and Preservation

The carbonate content of all cores recovered from deeper than 120 mbsf is uniformly low, even within the intervals of pelagic or hemipelagic sediment. Based on shipboard analyses (Shipboard Scientific Party, 1992), the carbonate content of these sediments was never found to exceed 60% and was commonly less than 50%. Post cruise processing of geochemical logs from Hole 840C confirm that the carbonate content of the sediments deeper than 120 mbsf is low, ranging from near 0 to less than 60% (Pratson et al., this volume). The low percentage of carbonate deeper than 120 mbsf at Site 840 results from the low abundance and poor preservation of calcareous micro-

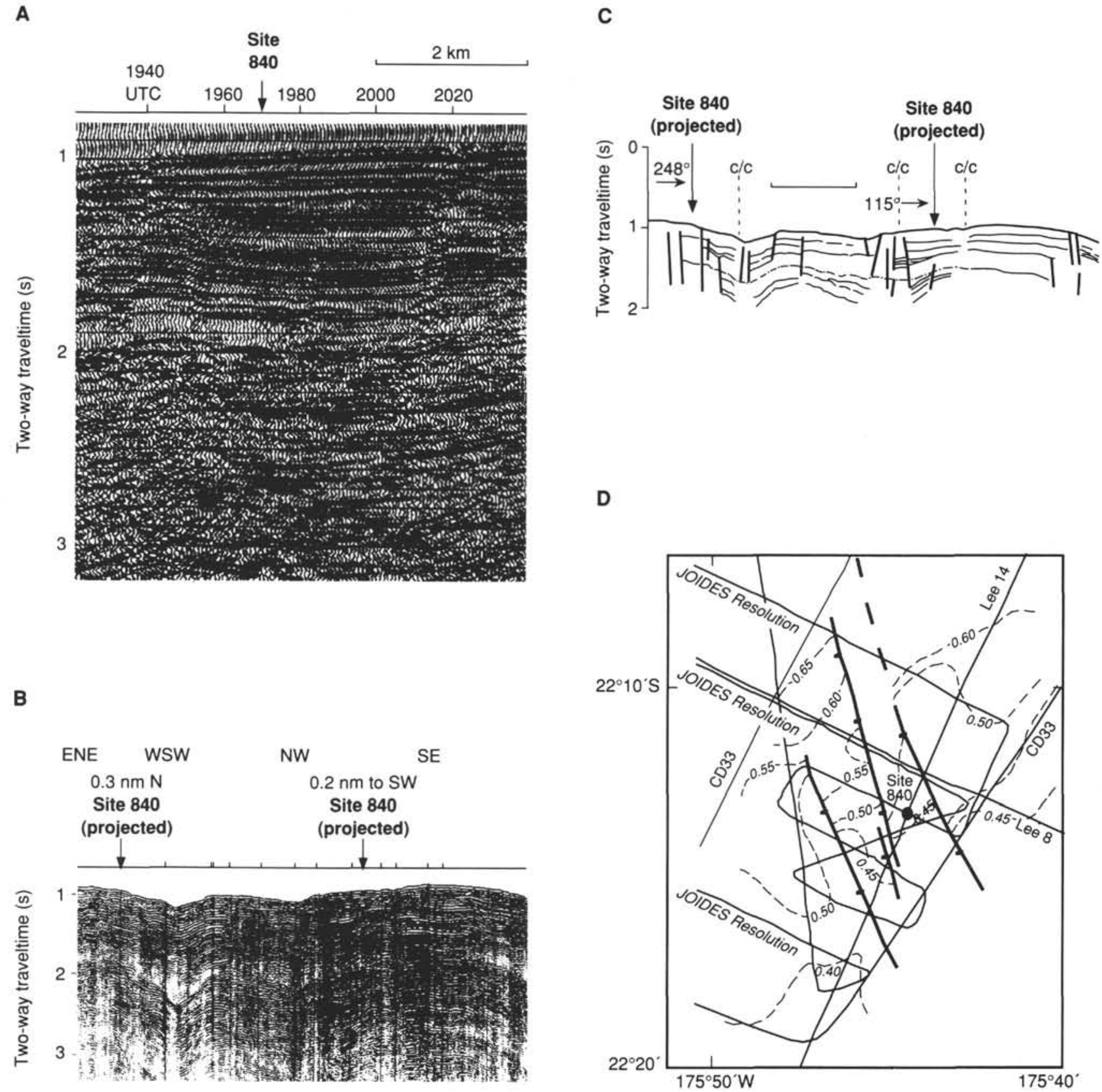

Figure 2. Seismic data for Site 840. **A.** Multichannel seismic reflection profile *S.P. Lee* 14 showing Shotpoint 1970, the location of Site 840. **B.** Single-channel seismic record acquired by *JOIDES Resolution* during the site survey. Site 840 is projected into the section. **C.** Interpreted seismic profile across Site 840. Horizon A is highlighted in dot-dash ornament. **D.** Isopach map of Horizon A in kilometers as derived from single-channel seismic data acquired by *JOIDES Resolution*. Bold lines locate faults, ticks on downthrown-side. Fine dashed lines are isopach contours, solid lines are ship's tracks. From Shipboard Scientific Party, 1992.

fossils, as reported by the shipboard paleontologists (Shipboard Scientific Party, 1992). A plot of the calcareous microfossil abundance derived from the shipboard paleontologic studies is shown in Figure 6. Below 200 mbsf, foraminifers were never reported as abundant. Below 300 mbsf, foraminifers were described as common in only one sample. Smear slides and thin-sections prepared from the Site 840 samples of late Miocene age show a similar pattern. Calcareous microfossils, if present, are predominantly nannofossils. Foraminifers are generally rare or absent, and consist of poorly preserved, broken fragments displaying abundant evidence of dissolution.

Sediments from infilled burrows received special attention in this study because they contain pelagic sediments derived from the seafloor. These sediments provide information about past conditions in the water column and at the sediment/water interface. At Site 840, foraminifer preservation is generally poorer within infilled burrows than in the redeposited volcaniclastic host sediment. Plate 1A shows a typical example of such an infilled burrow in Unit III near 578 mbsf. The dark-colored host sediment is a volcaniclastic siltstone near the top of a turbidite. The burrows between 85 and 94 cm stand out in contrast because of the light-colored pelagic marl infill.

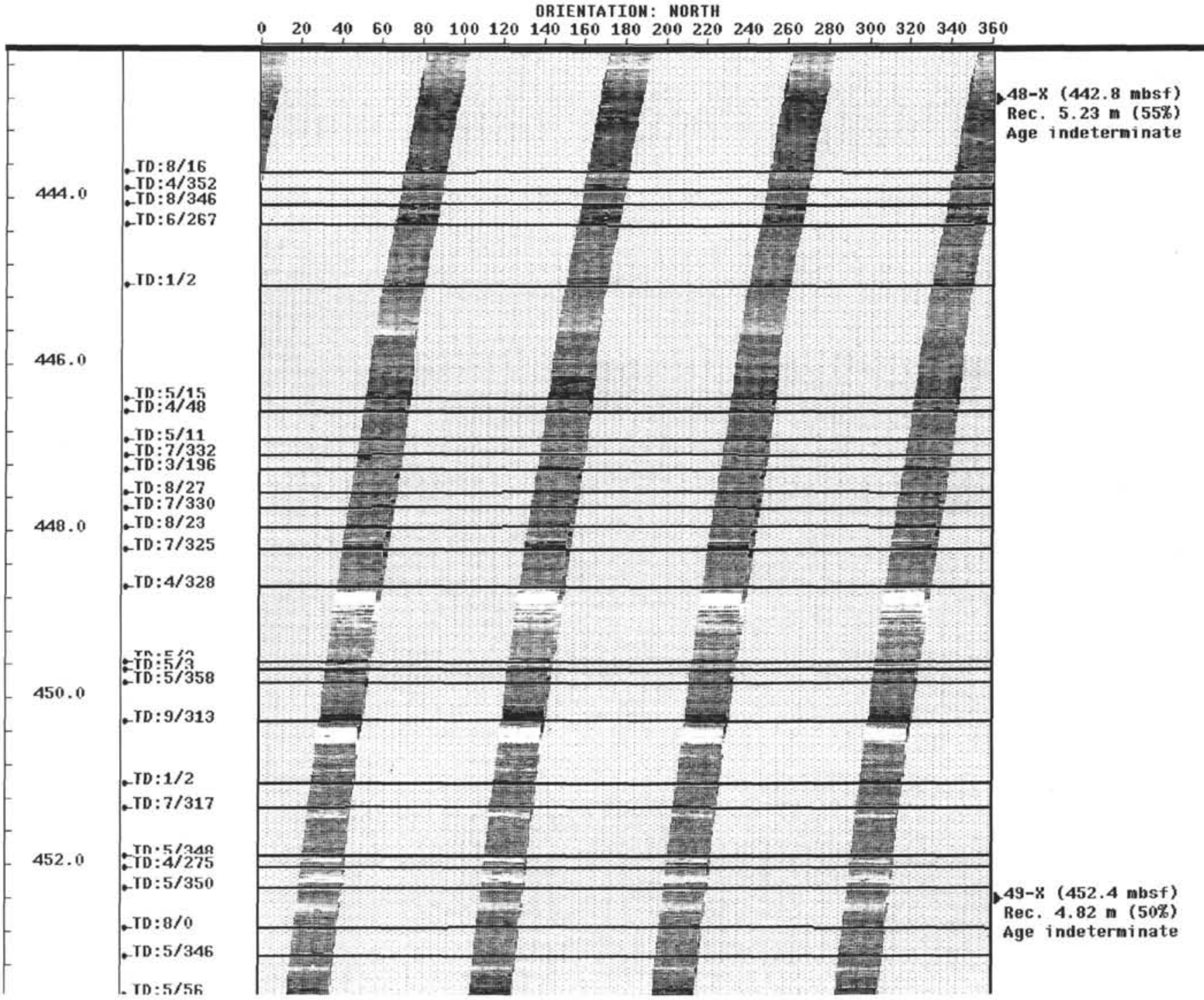

Figure 3. FMS Image Examiner plot of the borehole interval corresponding to Core 135-840B-48X (Unit III, from 442.8 to 452.4 mbsf). The four tracks shown are oriented images of the borehole wall that reflect microresistivity recorded by each of four 16-button pads on the FMS logging tool. In these images, darker shades indicate low resistivity reflecting the coarser, more porous nature of sediment at the base of turbidites. Lighter shades indicate higher resistivity in the less porous material at the tops of turbidites or in clayey pelagic marl between turbidites. The image is dynamically enhanced over the interval shown to increase resolution (Serra, 1989). Solid lines show the position of sine waves calculated by the FMS Image Examiner software through (three or more) points selected by the operator at the base of individual turbidites. The true dip (T/D) of resulting surfaces (the bedding plane at the base of each turbidite) is shown in the second column. Sediments from this unit are dominated by gravity flow deposits.

Plates 1B, 1C, and 1D are representative photomicrographs of infilled burrows from different depths. Plate 1B shows the margin of an unlined infilled burrow in Section 135-840B-56X-3, from Unit II at 523.26 mbsf. Foraminifer molds are clearly seen in the lighter colored sediment of the burrow infill. The host sediment, the upper part of a volcaniclastic turbidite, can be seen in the upper right corner of the photograph. Foraminifers are not abundant in this sediment, but the preservation is slightly better than it is in within the burrow. Plate 1C shows a similar example from Section 135-840B-40X-1, from Unit III at 367.54 mbsf. The burrow infill stands out clearly because of the lithologic contrast between the volcaniclastic host sediment and the marly infill. A few foraminifers are preserved in the host sediment, but none can be clearly identified within the burrow. In contrast, Plate 1D shows an infilled burrow from Section 135-840B-13X-2, from Unit II at 116.79 mbsf. In this sample, foraminifers within the burrow are relatively abundant and well preserved. These observations concur with the trend in the shipboard data on microfossil abundance and preservation.

If the late Miocene sediments were deposited in water depths similar to those found on the southern Tonga Platform today (< 1000 m), as suggested by Chaproniere (1985) and Bukry (1985), they should have contained abundant, well-preserved foraminifers. At Site 840, foraminifers are abundant only in Unit I and the upper 10 m of Unit II, above about 120 mbsf. The low abundance and poor preservation of foraminifers and the absence of foraminifers molds in pelagic sediments below 120 mbsf at Site 840 strongly suggest selective dissolution of foraminifers at or near the sediment/water interface, prior to burial and diagenesis. Foraminifers in redeposited sediments exhibit better preservation because they were protected from this dissolution by rapid downslope transport, followed by rapid burial.

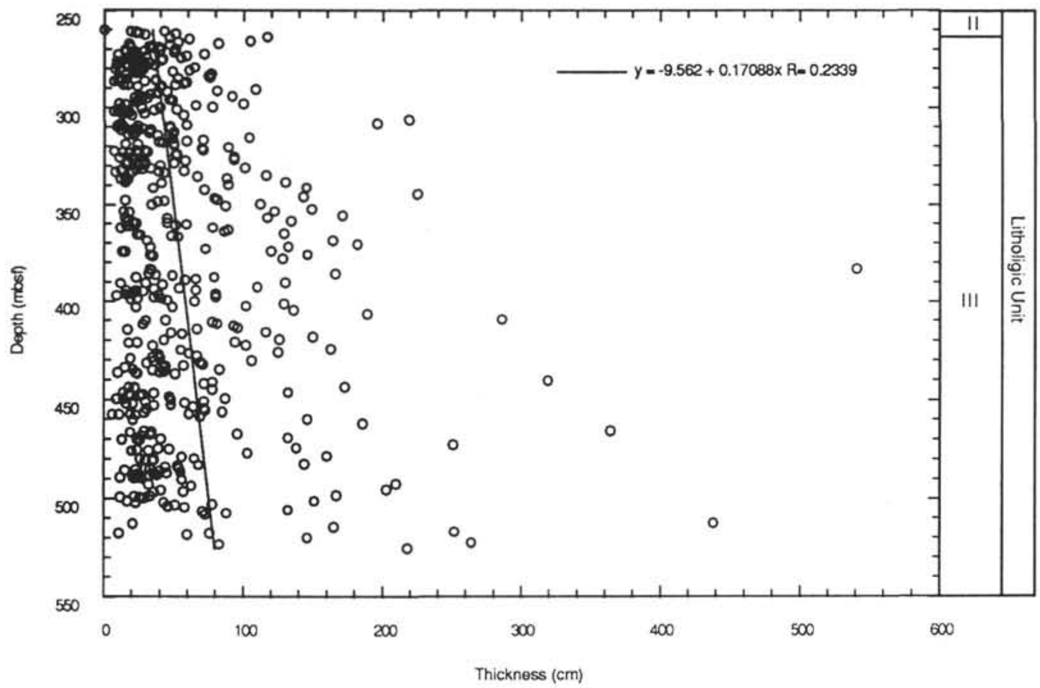

Figure 4. Plot of turbidite thickness vs. depth of individual turbidites identified on FMS images showing a slight increase in turbidite thickness with increasing depth.

Horizon "A"

Detailed study of the Site 840 cores from Units II and III revealed a number of sedimentologic changes that suggest the presence of an unconformity near 500 mbsf which may correspond to the level of Horizon "A" at this site. Below 500 mbsf, the clay content of the pelagic sediments increases and the number of preserved foraminifers and foraminifers molds decreases. This trend correlates with a downhole decrease in carbonate and increase in silica shown on geochemical logs (Pratson et al., this volume).

Detailed examination of the Site 840 cores also revealed that convoluted beds are common in turbidites within Units II and III; however, above 500 mbsf, the thicknesses of these intervals does not exceed 10 cm. Below 500 mbsf, thick intervals (up to 85 cm) of convoluted bedding are common. This transition is not gradational and coincides with an abrupt increase in the maximum grain size of basal turbidite layers and in the thickness of individual turbidite units. The FMS logs were obtained only to 515 mbsf, but the FMS images reflect this change in grain size by a dramatic decrease in resistivity at 503 mbsf (Fig. 3). Few dipmeter readings are available below 503 mbsf, but these reflect an increase in dip angle and a change in dip direction. This trend was noted by the Shipboard Scientific Party (1992).

DISCUSSION

Based on paleontologic evidence from dredged samples, previous investigators have reported that water depths on the Tonga Platform during the late Miocene and late Pliocene–Pleistocene were probably similar to water depths found there today (Chaproniere, 1985; Bukry, 1985). However, interpretation of seismic and bathymetric evidence by Herzer and Exon (1985) show that the Tonga Platform was not subjected to significant erosion until very late in the Miocene. During the Pliocene and Pleistocene, there was widespread planation followed by local intense submarine canyon erosion. This seismic interpretation was used by Dupont and Herzer (1985) to support their contention that the Tonga forearc was in deeper water during the late Miocene than it was during the Pliocene and Pleistocene. They proposed that the profile of the Miocene forearc may have been similar to that of the eastward-dipping Kermadec forearc to the south and suggested that the possibility of redeposition should be considered when evaluating the paleontologic evidence.

This suggestion of sediment redeposition by Dupont and Herzer (1985) is supported by the results from Site 840. The late Miocene sediments are almost exclusively turbidites. This has several significant implications:

1. During deposition of the gravity flow deposits, the dip of the forearc must have been to the east, toward the trench and away from the source of the sediments, the Lau/Tonga Ridge (Shipboard Scientific Party, 1992), not to the northwest as it now is (Fig. 1). Extrapolation of the present shallow, northwest-dipping bathymetry of the Tonga forearc into the late Miocene would require that the late Miocene turbidites consistently ran uphill, from the Lau/Tonga Ridge, onto the Tonga Platform, and accumulated to a thickness of over 500 m in just 1.4 Ma.
2. Therefore, uplift of the outer Tonga forearc and consequent northwest tilting of the southern Tonga Platform must have occurred after the deposition of the late Miocene turbidites. It is reasonable to assume that this event is coincident with the change in sedimentation rate (Fig. 7) dated at about 5.1 Ma by shipboard biostratigraphic and paleomagnetic age determinations (Shipboard Scientific Party, 1992).
3. An east-dipping Tonga forearc with a configuration similar to the Kermadec Ridge to the south would place Site 840 in significantly deeper water during the late Miocene.

The conclusion that Site 840 lay in deeper water during the late Miocene is supported by the poor preservation of foraminifers in Units II and III. Unit I has better preservation and a higher abundance of foraminifers in the pelagic sediments, as would be expected for deposition in water depths similar to those found on the platform today. Because carbonate material may be preserved even below the CCD in turbidites, and shallow-water material may be transported great distances in this way, paleowater depths derived from the carbonate fraction of a gravity deposit can be misleading. A more in-

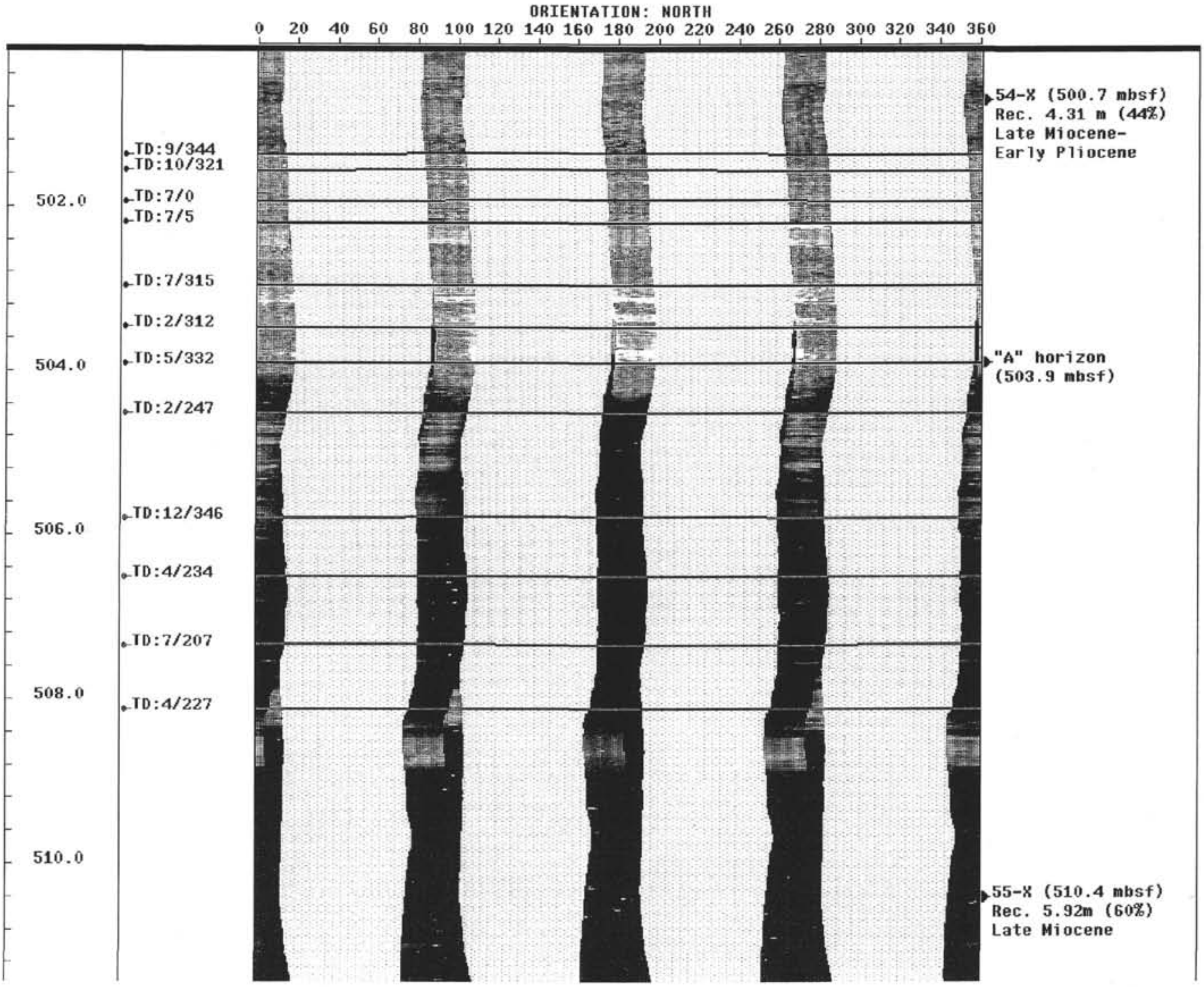

Figure 5. FMS Image Examiner plot of the borehole interval corresponding to Core 135-840B-54X (Unit III, from 500.7 to 510.4 mbsf). The four tracks shown are oriented images where darker shades indicate low resistivity reflecting the coarser, more porous nature of sediment at the base of turbidites and lighter shades indicate higher resistivity in the less porous material at the tops of turbidites or in the clayey pelagic marl between turbidites. The image is dynamically enhanced over the interval shown to increase resolution (Serra, 1989). Solid lines show the position of sine waves calculated by the FMS Image Examiner software through (three or more) points selected by the operator at the base of individual turbidites. The true dip (T/D) of the resulting surfaces (the bedding plane at the base of each turbidite) is shown in the second column. Note the change in the resistivity at 503.9 mbsf. Below this depth, the sediments are interpreted to be much coarser (much lower resistivity). At this depth, the character of the FMS image changes and it is very difficult to identify individual bedding planes or turbidites. The few bedding planes identified may represent the basal planes of coarse debris flows rather than turbidites.

formative evaluation of the depositional environment at the sediment/water interface can be obtained by examination of the biogenic grains within pelagic layers and infilled burrows. The higher degree of dissolution of foraminifers as compared to calcareous nannofossils observed in the pelagic sediments and within burrows in the Site 840 cores suggests that most of the sediments of Unit II and all of the sediments of Unit III were deposited at or near the foraminiferal lysocline. This is supported by the low abundance and poor preservation of foraminifers reported in core-catcher samples examined by the shipboard paleontologists (Shipboard Scientific Party, 1992).

Differences in the rate of dissolution of various calcareous microfossils permit the designation of three types of lysoclines: pteropod, foraminiferal, and coccolith (listed in order of increasing water depth). The foraminiferal lysocline lies between the pteropod and coccolith lysoclines and is defined as the depth at which about 80 wt% of foraminifers are lost by dissolution (Berger, 1976). In the Pacific Ocean, the carbonate lysocline currently lies at approximately 3,600 m (Scholle et al., 1983). The foraminiferal lysocline is probably several hundred meters shallower than that (Berger, 1982). The level of the late Miocene lysocline is not known with certainty, but the position of the CCD has been estimated by van Andel (1975) as being approximately 500–600 m shallower during the Miocene than it is today. A corresponding upward shift of the foraminiferal lysocline would place it near 2800 m during the late Miocene. These figures are somewhat approximate because they represent averages for the entire Pacific. A conservative estimate of the late Miocene paleowater depth of Site 840 would be somewhere between 2000 and 2500 m.

The sediments of Units II and III are interpreted as volcaniclastic turbidites derived from a western volcanic source interbedded with bioturbated pelagic marls. These sediments were deposited on an east-

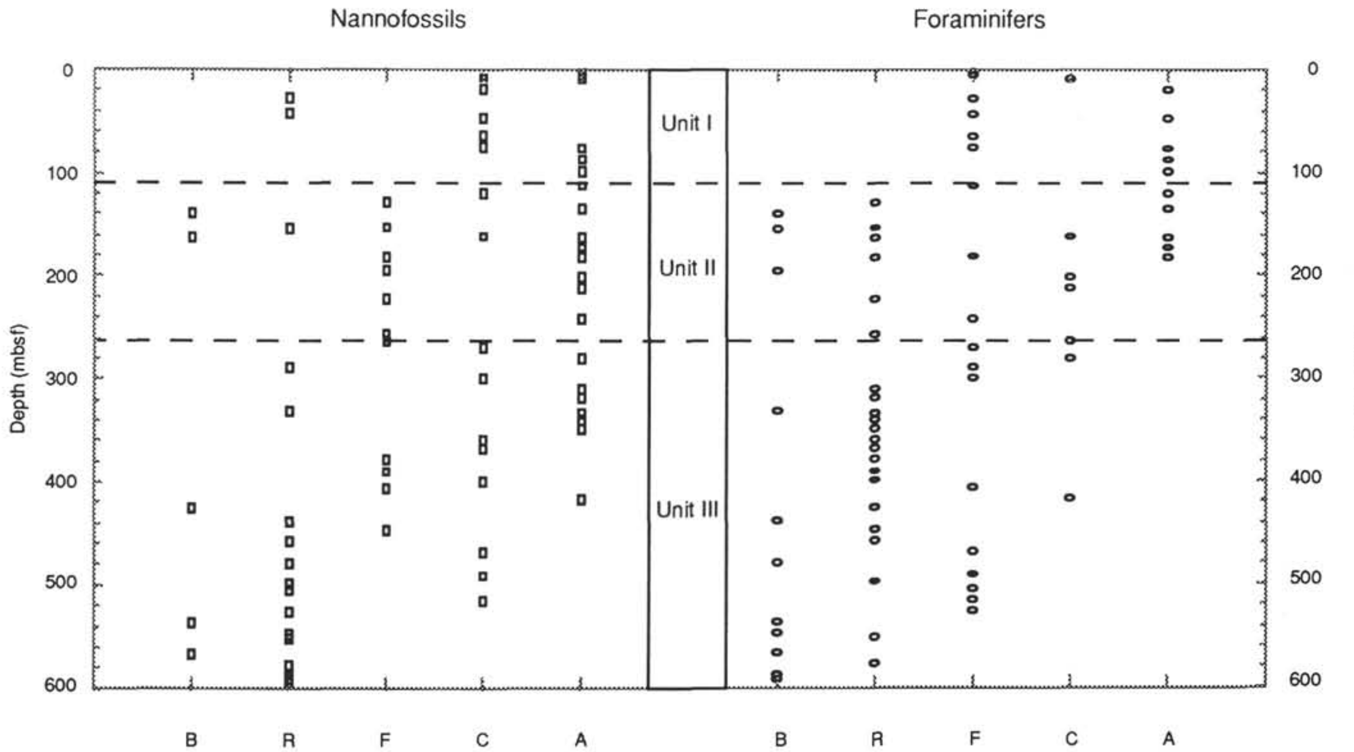

Figure 6. Plot of microfossil abundance vs. depth. The information for this plot was compiled from sample description forms completed by shipboard paleontologists during Leg 135. B = barren, R = rare, F = few, C = common, and A = abundant. The low abundance of foraminifers, particularly in Unit III, suggests dissolution near the sediment/water interface. Nannofossils are slightly more resistant to dissolution than foraminifers, but even these microfossils are not reported as abundant below 120 mbsf. The low abundance of foraminifers, and the relative abundance of nannofossils over foraminifers, strongly suggests sediment deposition at or near the foraminifer lysocline.

dipping forearc slope in at least two thousand meters of water. The bathymetry of the Tonga forearc during deposition of these sediments was very different from what it is today. To permit the accumulation of hundreds of meters of volcaniclastic turbidites in a few thousand meters of water during the late Miocene, uplift of the outer forearc and consequent northwest tilting of the platform could not have occurred earlier than the very latest Miocene or early Pliocene.

Uplift of the Tonga Platform may have been a response to thermal upwelling related to the opening of the Lau Basin (Parson et al., 1990), now dated at 5.6 Ma (Shipboard Scientific Party, 1992). It has also been suggested that the uplift resulted from the addition of low-density crustal material from the Louisville Seamount Chain as it was subducted (Dupont and Herzer, 1985). The results of this study do not provide support for either of these hypotheses. The most recent uplift and tilting of the Tonga Ridge is probably reflected by the change in lithology, increase in carbonate content, and dramatic change in sedimentation rate recorded near the top of Unit II. This suggests that uplift and tilting of the Tonga Ridge occurred at about 5.1 Ma. As shown on Figure 7. The event would then appear to significantly predate (by 3.6 Ma) the subduction of the Louisville Seamount Chain beneath the Tonga Trench near the latitude of Site 840 at about 1.5 Ma (Dupont and Herzer, 1985) and slightly postdate (by just 500 k.y.) the initial opening of the Lau Basin at 5.6 Ma (Shipboard Scientific Party, 1992). Therefore, if the uplift of the outer Tonga forearc resulted from the addition of low-density material, the source of the material is probably not the Louisville Seamount Chain. Although the near coincidence of the tilting and uplift of the Tonga forearc and the opening of the Lau basin suggests that these two events are related, if the uplift resulted from thermal upwelling related to backarc basin spreading, the uplift should be more pronounced near the axis of spreading rather than on the outboard portion of the forearc where it is observed (Dupont and Herzer, 1985). We suggest that neither of the proposed explanations for the uplift of the Tonga Platform are entirely satisfactory and that an alternative explanation should be sought.

ACKNOWLEDGMENTS

We wish to thank the tireless ODP technicians and the SEDCO and CaterMar crews on board the *JOIDES Resolution* during Leg 135. We also would like to express our thanks to all the members of the Leg 135 Shipboard Scientific Party for their hard work both during and after the cruise. In particular, we thank Lindsay Parson, Jim Hawkins, and Jamie Allan for their hard work, leadership, constant encouragement, and unflagging good humor. We have benefited from discussions with Peter Clift, Reidulv Bøe, Sherman Bloomer, George Chaproniere, Hiroshi Nishi, Paula Quinterno, Bryan Tapp, and Dennis Kerr. We thank Chris Mato, John Miller, and the staff of the ODP Gulf Coast Repository in College Station, TX, for their patience, assistance, and hospitality during the time we spent there. Robin Reynolds provided invaluable assistance with the acquisition of FMS data tapes and images. Reformatting of FMS data was provided by the Schlumberger Processing Center in Dallas Texas. Access to FMS Image Examiner software was generously provided by Amoco Production Research in Tulsa, OK and by the Schlumberger office in Midland, TX.

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Date of initial receipt: 18 September 1992
Date of acceptance: 23 July 1993
Ms 135SR-112

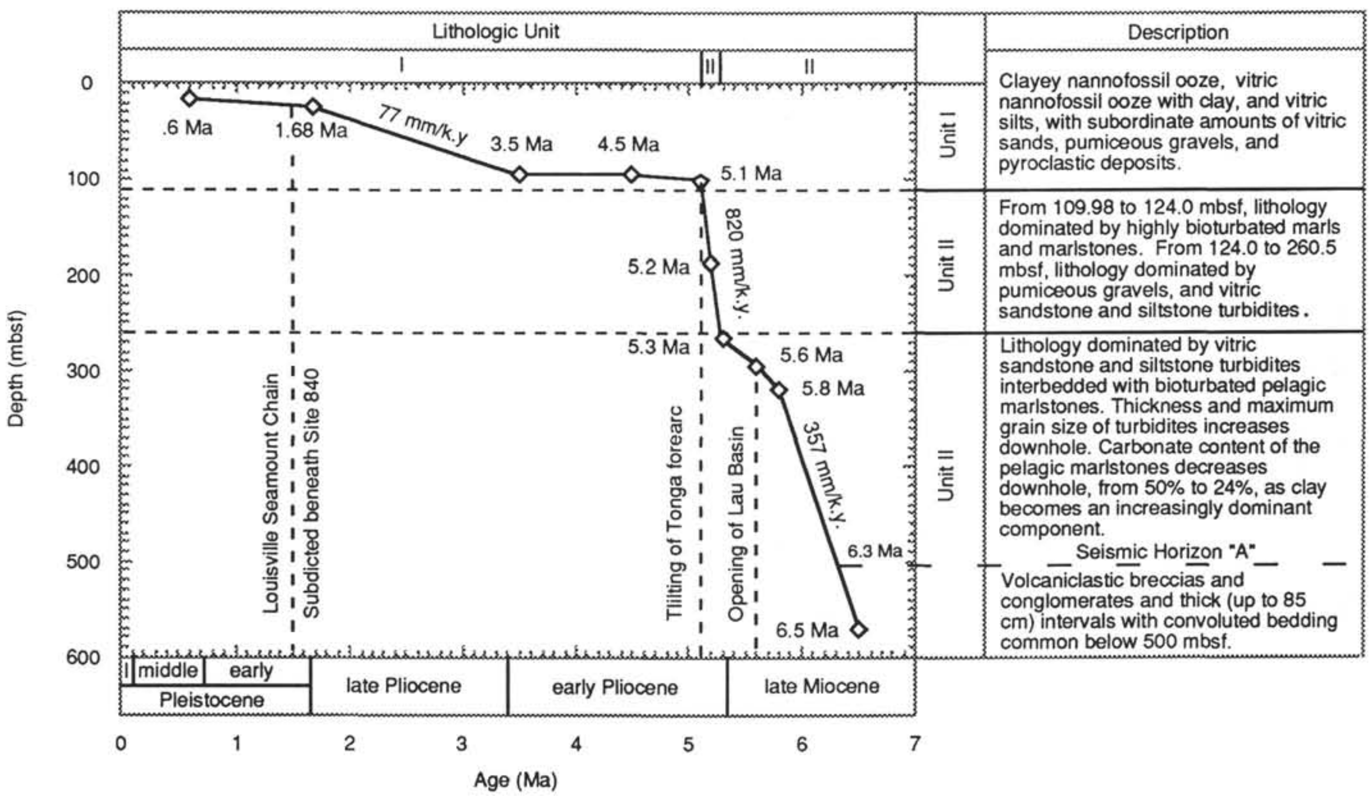

Figure 7. Summary of sedimentation at Site 840 showing approximate age of Horizon "A" at Site 840 (6.3 Ma), timing of the Lau Basin opening (5.6 Ma), approximate age of tilting of the Tonga forearc suggested by this study (5.1 Ma), and subduction of the Louisville Seamount Chain beneath Site 840 (1.5 Ma). The timing for the opening of the Lau Basin and the sedimentation rate curve ages are from shipboard biostratigraphic and paleomagnetic studies (Shipboard Scientific Party, 1992).

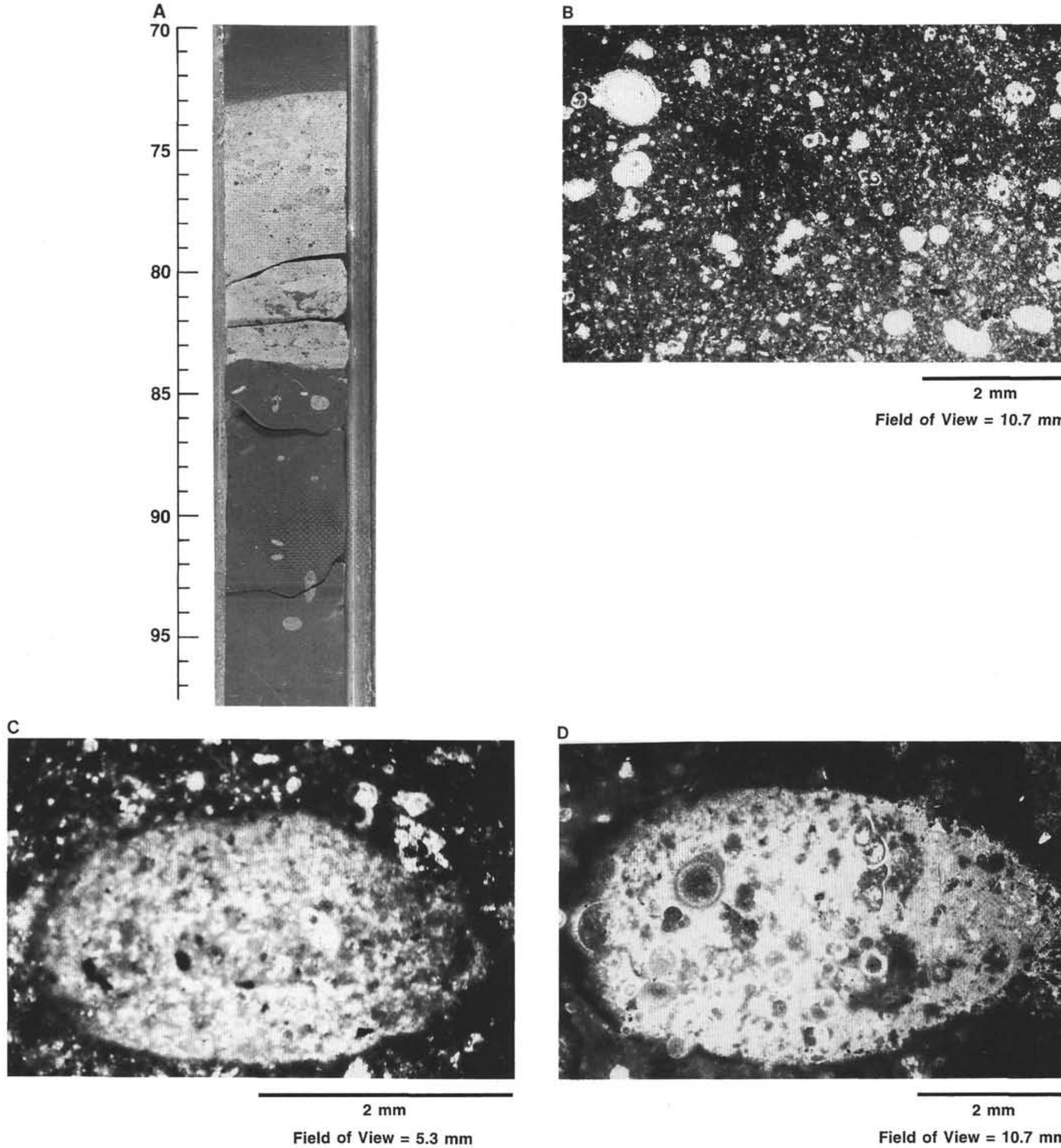

Plate 1. **A.** Core photo of interval 135-840B-62X-1, 70–98 cm (Unit III, 578.70–578.98 mbsf), showing burrows in dark-colored vitric siltstone infilled with light-colored pelagic marl. The sediment surrounding the burrow is redeposited volcaniclastic material that was probably emplaced by a turbidity current. In a depositional environment dominated by gravity deposits, the burrow infill is more likely to have been derived from pelagic sedimentation and, therefore, are more representative of conditions at the sediment/water interface, providing more reliable information regarding paleowater depths. **B.** Thin-section photomicrograph in plane-polarized light (PPL) of an unlined infilled burrow in interval 135-840B-56X-3, 17–21 cm (Unit III, 520.37) mbsf. Foraminifer fragments are rare, but their past presence is indicated by molds. The upper right-hand corner contains a few preserved foraminifers within the fine-grained volcaniclastic host sediment surrounding the burrow. Foraminifer preservation in the host sediment is better than that in the burrow infill derived from the sediment/water interface. **C.** Thin-section photomicrograph in PPL of an unlined infilled burrow in interval 135-840B-40X-1, 104–107 cm (Unit III, 367.54 mbsf). Preserved foraminifers are not found within the burrow fill derived from the sediment/water interface. The host sediment contains foraminifer molds and a few foraminifers showing the effects of dissolution. **D.** Thin-section photomicrograph in PPL of an unlined infilled burrow in interval 135-840B-13X-2, 19–21 cm (Unit II, 116.79 mbsf). Foraminifers within this burrow are relatively abundant and well preserved. Foraminifers are rare in the volcaniclastic host sediment.