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Tectonic controls on sedimentation and diagenesis in the Tonga Trench and forearc, southwest Pacific

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ABSTRACT

Sedimentation in the Tonga forearc is dominated by the redeposition of volcanoclastic sediment from the arc volcanic front by mass flows and turbidity currents onto the adjacent Tonga Platform, the shallowest, flattest part of the forearc region. The greatest sediment thicknesses accumulate in debris aprons close to the volcanic front. Collision of seamounts, notably the Capricorn Seamount and the Louisville Ridge, with the forearc radically shortens and steepens the adjacent modern trench slope, allowing sediment to be redeposited deep into the trench. Rotation, usually arcward, of existing basins on the midslope during collision generates angular unconformities, while synchronous uplift of the outer forearc high results in canyon development and downcutting along the eastern edge of the Tonga Platform. Collision also reactivated major across-strike fault zones on the forearc; the zones are subsequently exploited by canyons depositing sediment into the trench. Collapse and renewed extension of the forearc in the wake of collision result in the development of small perched basins, measuring approximately 5 km by 15 km in the midslope area. This morphology is especially developed at 18°30'S to 20°S, implying a 2–3 m.y. interval for their formation following Louisville Ridge collision. Trenchward of these depocenters sedimentation is slow, resulting in manganese crust formation and localized mass wasting along fault scarps. Over longer periods of time (>5 m.y.) tectonic erosion reestablishes a wide, gently sloping forearc into which canyons incise the shallow Tonga Platform by headwall erosion and collapse.

INTRODUCTION

Sedimentation in deep marine environments is controlled by the interplay of a number of different processes. Variations in eustatic sea level and the generation of topography through tectonic activity are two of the most important influences on the stratigraphic evolution of deep-water basins (Haq et al., 1987; Winsemann and Seyfried, 1991; Underwood et al., 1995). In addition, sediment supply controls the stratigraphy of an evolving basin, and

this parameter can be sensitive to climate, as well as tectonics and eustasy, when sediment is derived from a continental hinterland. In island-arc systems, climate is typically less crucial: instead, sediment supply to forearc basins is more a function of the volume and composition of arc volcanoes, which produce large volumes of tephra and associated volcanoclastic sediments. This is especially true for intraoceanic forearc basins, which are usually far removed from input by continental sources. Apart from the rain of pelagic material, the sediment accumulating in oceanic forearc basins is principally derived either by direct air fall of ash from the active arc volcanoes, or through reworking and redeposition of volcanic ash and other debris as turbidites and mass flows. A smaller amount of sediment may be derived from the erosion of older forearc sediments or from the igneous basement of the forearc. Since volcanism is also influenced by cycles of tectonic activity in the arc (Taylor, 1992; Clift, 1995), it is apparent that sedimentation in these environments is highly dependent on the tectonic evolution of the subduction zone. In this study we present drilling, dredge, and seismic data from the outer Tonga forearc (Fig. 1) to show how sediment generated at the modern arc volcanic front is redeposited in the forearc and how this process is affected by the subduction tectonics, including the collision of seamounts with the trench.

GEOLOGICAL HISTORY OF THE TONGA ARC SYSTEM

The Tonga Arc system represents a classic example of a nonaccretionary convergent margin in an intraoceanic setting. The arc and forearc, collectively called the Tonga Ridge, are divided into a number of structural units across strike (Fig. 2). In the west, the active volcanic arc (Tofua Arc) is between the late Miocene–Recent Lau backarc basin and the Tonga Platform, the westernmost and shallowest part of the forearc region. South of Tongatapu (Fig. 1) the arc is separated from the Tonga Platform to the east by the Tofua Trough, a narrow graben system. Farther north the Tofua Arc is closer to the trench axis and is built upon the sediments of the Tonga Platform (Scholl et al., 1985; Chase, 1985; Tappin, 1994). The Tonga Platform is the widest part of the forearc; it is 60–80 km wide and is composed of a series of volcanoclastic sediments, pelagic chalks, and carbonate debris, and overlies an Eocene volcanic basement. The thickness of these sediments is typically greatest on the western side

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Figure 1. Regional gravity map of the Tonga Arc system contoured at 5 mGal showing the location of the Ocean Drilling Program drill Site (filled circles), dredge localities (filled squares), and seismic lines discussed in this paper (data from Sandwell and Smith, 1995). Dashed lines show the boundaries between northern, central, and southern regions of the forearc.

of the basin, decreasing toward the outer arc high in those places where such a feature is developed (Austin et al., 1989; Tappin et al., 1994a). The outer arc high represents a shallowing of the basement and thus thinning of the sedimentary cover at the trench slope break, a division that is most well developed in the central and southern Tonga Platform. Farther north, where the division is less clear, the sediment thickness across the Tonga Platform remains more constant from west to east. Trenchward of the outer arc high the trench slope drops steadily toward the trench axis

around 24°–21°S, but from 21° to 18°30'S and north of 18°S the slope is marked by the development of narrow terrace features at 4000–6000 m water depth.

Structurally the trench slope is marked by large normal faults, most of which dip toward the trench, but minor arcward-dipping faults are also noted (MacLeod and Lothian, 1994). Along-strike differences in the geometry of the Tonga Platform cause some authors to divide the forearc into a series of tectonic blocks (e.g., Taylor and Bloom, 1977; Austin et al., 1989). Exon et al. (1985) identified a series of four bathymetric and structural highs over a distance of ~160 km south of Tongatapu. Tappin (1994) proposed a broad three-part division of the forearc into a northern area (north of Vava'u), a southern area (south of 'Eua and Tongatapu), and a central region between (Fig. 1).

Subduction in the Tonga area is believed to date from the middle Eocene on the basis of the oldest volcanic strata found in the forearc region. McDougall (1994) dated rhyolitic lavas from Ocean Drilling Program (ODP) Site 841, located on the midtrench slope (Fig. 1), as middle Eocene (44 ± 2 Ma); Acland et al. (1992) dated gabbros from the northern Tonga trench as early-middle Eocene (50 ± 9 Ma) using radiometric techniques. These results are further supported by the middle Eocene age of sediments overlying volcanic rocks at ODP Site 841 (Shipboard Party, 1992), as well as onshore on the island of 'Eua (Ewart and Bryan, 1972; Tappin, 1994), and in boreholes on Tongatapu (Cunningham and Anscombe, 1985). Since that time, subduction and arc volcanism have apparently been continuous, although the arc history has been marked by the rifting of two back-arc basins, the South Fiji Basin during the Oligocene (Weissel and Watts, 1975) and the Lau Basin in the late Miocene (Hawkins, 1974; Parson et al., 1992).

The Tonga forearc is colliding with the Louisville Ridge at around 26°S. The Louisville Ridge parallels the Hawaiian-Emperor chain in the North Pacific and has been shown to be an aseismic, hotspot-related, Upper Cretaceous feature (Lonsdale, 1988; Watts et al., 1988). Due to the obliquity of the Louisville Ridge compared to the convergence direction, the zone of collision is migrating south at approximately 18 cm/yr (Lonsdale, 1986). The effect of the collision on the Tonga Arc and forearc has been a matter of some debate. Ballance et al. (1989) documented the deposition of thick debris flows containing blocks as much as 1 m in diameter on the trench slope; the flows contain reefal limestones and volcanic material, suggesting substantial tectonic erosion and steepening of the trench slope. Tagudin and Scholl (1994) also suggested that a hiatus in volcanism occurs on the adjacent volcanic front during collision. Several authors have proposed that ridge-trench collision causes uplift of the forearc and tectonic erosion (e.g., Dupont and Herzer, 1985; Packham, 1985) as a result of the broader width of the platform and gentle trench slope south of the modern collision zone, compared to the steep narrow forearc north of the collision. MacLeod (1994) showed that the effect of collision at midslope levels, at ODP Site 841, was trenchward oversteepening of the slope, followed by downslope gravitational collapse. Tappin (1994) proposed that transient uplift of the Tonga Platform due to Louisville Ridge collision resulted in the along-strike segmentation of the arc into a number of structural blocks, a conclusion supported by apparent uplift in the Tongatapu region reported by Packham (1985) from subsidence analysis of petroleum well data on the island. In contrast, Clift (1994) argued against major uplift using subsidence data from ODP Site 840, adjacent to the island of 'Ata (Fig. 1), although uncertainties about the water depths at the time of deposition of the sediments allow for as much as 300 m of uplift. Nonetheless, of the three major subdivisions of the Tonga Platform proposed by Tappin (1994), the shallowest is the central section around Tongatapu (Fig. 1), not that adjacent to the modern ridge collision zone. Deformation caused by collision is likely to have been much more intense closer to the trench axis. Cawood (1994) presented chemical data from dredged volcanoclastic sediment close to the point of

Figure 2. Simplified section across the Tonga Arc and forearc showing the principal structural and topographic features discussed in this paper.

Louisville Seamount collision to show that some parts of the chain are accreted to the frontal edge for at least a short period following collision.

Data

The data used in this study are from several sources. The sampling of the sediments of the Tonga forearc was made by coring during ODP Leg 135 (Sites 840 and 841; Parson et al., 1992) and by dredging along the entire length of the forearc during Boomerang Leg 8 of the R/V *Melville* in May–June 1996 (Bloomer et al., 1996). Multichannel seismic lines from several cruises provide a structural framework and have been interpreted and published (e.g., Austin et al., 1989; Exon et al., 1985; Honza et al., 1987; Tappin, 1994). These lines have been supplemented by single channel seismic lines gathered during Boomerang Leg 8 on the R/V *Melville* in May 1996. In addition, swath bathymetric maps and sidescan images collected by SeaBeam 2000 on that cruise are used to examine the morphology of the forearc along the strike of the arc.

SEDIMENT TRANSPORT AND SEDIMENT TRAPS

Sediment eroded from the Tofua Arc, the principal sediment-producing feature in the area, is deposited both downslope into the trench and westward into the Lau Basin. However, volcanoclastic turbidites derived from the Tofua Arc and Lau Ridge (remnant Miocene arc edifice; Cole et al., 1985) are ponded in underfilled grabens within the Lau Basin, close to their sources, and are not redeposited far across the basin (Clift et al., 1995). Similarly, transport to the east is strongly influenced by the structure of the forearc. Much of the arc-derived material accumulates in debris aprons close to the source volcano on the western margin of the Tonga Platform (Fig. 3), resulting in low sedimentation rates in the outer forearc during periods of steady-state subduction. The subbasins that form in the outer forearc are small (5×15 km), but do not fill rapidly; they remain effective sediment traps for substantial time periods (>3 – 5 m.y.), on the basis of the presence of underfilled basins in the northern forearc region that are believed to have been generated not later than during the passage of the Louisville Ridge

through the area. Sedimentation is most rapid within the Tofua Trough, a narrow graben between the Tofua Arc and the Tonga Platform. That the debris aprons shed trenchward from the Tofua Arc show onlapping relations with the underlying Miocene volcanoclastic sediments and nannofossil chinks of the Tonga Platform reflects their young age (<3 Ma) and the arcward tilting of the Tonga Platform in the south during the earliest rifting of the Lau Basin (5–7 Ma; Tappin et al., 1994b).

TECTONIC CONTROLS ON SEDIMENTATION

The structure of the forearc plays a crucial role in determining the location and facies of sediment deposition in the Tonga forearc. The structure, in turn, reflects steady-state subduction and tectonic erosion along the entire forearc; there are rare superimposed changes related to major tectonic events such as arc rifting and seamount collisions. The sedimentary record in the forearc region contains information on the nature of subduction erosion as well as the timing and influence of major tectonic events in the evolution of the Tonga forearc. At ODP Site 841 the turbidite sequences change in a coherent fashion up section. Clift (1994) interpreted influxes of coarser material to reflect tectonic activity on the forearc resulting from events such as the subduction polarity reversal in the New Hebrides Arc following late Oligocene collision of the Ontong Java Plateau with the Vitiaz Trench (ca. 25 Ma; Moberly, 1971). Volcanoclastic sedimentation appears to have been rapid during much of middle Miocene time, wherever it has been sampled—at ODP Site 841, on Tongatapu, and in dated dredge hauls from the trench slope. Volcanism may have been more vigorous during the middle Miocene, following cessation of spreading in the South Fiji Basin at 25 Ma (latest Oligocene; Weissel and Watts, 1975).

Arc Rifting

Rifting of the Lau Basin affected arc volcanism by causing a burst of voluminous magmatism starting at 5.3 Ma, synchronous with the generation of the oldest backarc crust (Parson et al., 1992). The excess volcanism re-

sulted in large amounts of volcanoclastic material being shed onto the forearc but was immediately followed by a volcanic hiatus from 5 to 3 Ma (Clift, 1995). Variations in productivity of the volcanic arc did not have a significant impact on sedimentation at midslope levels in the southern and central zones because large amounts of volcanoclastic sediment were trapped on the Tonga Platform; however, there was a greater effect on the midslope farther north, as well as close to the arc volcanic front everywhere. Drilling at ODP Site 840 revealed the development of thick pumiceous gravels during latest Miocene time on the Tonga Platform, although there is no perceptible change seen in the fine-grained volcanoclastic sediments at ODP Site 841 that were deposited at the same time (Clift, 1994).

Seamount Collisions with the Trench

The Tonga Trench is currently colliding with the Louisville Ridge at 26°S. Ridge-trench collision has had a strong effect on the structure of the

margin and thus on sediment accumulation in the outer forearc. The effect of collision on the Tonga Platform is less pronounced. North of the collision zone the trench axis is extremely deep, reaching 10 850 m in the Horizon Deep, adjacent to which the trench slope has a very high gradient ($\geq 10^\circ$ below 6000 m; Lonsdale, 1986). In contrast, south of the collision zone, where the trench shallows to 6000 m, the forearc is broader, has a more gentle slope (1° – 2°), and descends to only 8000 m (Lonsdale, 1986). The geometry suggests that passage of the Louisville Ridge caused a significant amount of erosion to the outer edge of the forearc, compared to the normal steady-state subduction environment (Ballance et al., 1989). Dredge hauls from the inner trench slope at 8700 and 9163 m adjacent to Horizon Deep recovered structurally shallow volcanic rocks and volcanoclastic turbidites (dredges 83 and 86), suggesting substantial amounts of normal faulting in the wake of the ridge passage. In contrast, farther north, peridotites and gabbros were recovered at such depths (Bloomer and Fisher, 1987; Bloomer et al., 1996). Vallier et al. (1985) reported serpen-

Figure 3. Seismic line 82-11 from U.S. Geological Survey by R/V *Lee* (Scholl and Vallier, 1985) showing the debris apron surrounding a submarine volcano of the Tofua Arc in the southern Tonga Ridge and the onlapping relationship of one volcano to another. Location of line is in Figure 1.

Figure 4. Polished slabs of rock from dredge D89 showing (A) strong normal faulting, and (B) reverse faulting, probably reflecting compression caused by subduction of the Louisville Ridge, followed by extensional collapse.

Figure 5. (A) Swath bathymetric map and (B) sidescan image of the eastern Tonga Platform and trench slope in the central Tonga area (see Fig. 1 for location). Note midslope terrace and well-defined canyon feeding sediments from the Tonga Platform into the relatively unreflective flatter-bottomed basin. Data are from Wright et al. (1996). Faults are interpreted from presence of linear reflective features on the sidescan images.

tinites at 8500 m as far south as 22°S. MacLeod (1994) showed that at ODP Site 841 the rate of trenchward tilting of the mid-slope basin markedly increased in the past 500 k.y., following passage of the Louisville Ridge past this point on the forearc. In addition, MacLeod (1994) demonstrated the presence of both normal and reverse faults throughout much of the cored section at ODP Site 841, a feature also noted on a much smaller scale in dredged sediment samples from all parts of the forearc (Fig. 4). These observations were interpreted by MacLeod (1994) and Ballance et al. (1989) to reflect initial collision with the trench causing compression and uplift in the outer forearc, followed by gravitational collapse and extension as the seamount is fully subducted. The collapse seemingly causes a steepening of the lower trench slope, the excess material being subducted within the graben of the downgoing Pacific plate, much as proposed by Hilde (1983).

In this study we distinguish three basic types of morphology in the Tonga forearc: (1) areas in which steady-state subduction is the dominant tectonic process and that are characterized by broad forearc regions that have gentle trench slopes; (2) areas that have undergone collision in the past 2–3 m.y. and that are characterized by a pronounced tilted fault-block morphology (e.g., south of the Louisville Ridge collision zone at 26°S and the central part south of Vava'u, 18°30' to 20°S; Fig. 1); and (3) areas in which the tectonics of active seamount-trench collision dominate and that are characterized by narrow, steep forearc basins (e.g., between the Louisville Ridge collision zone and 20°S, and the areas adjacent to the Capricorn Seamount).

CANYON SYSTEMS

Due to the obliquity between the trends of the Louisville Ridge and the forearc, the age of the collision increases progressively northward. This means that the northern part of the forearc has had more time to readjust to a regime of steady-state subduction of normal oceanic crust. Sediment eroded from the Tonga Platform, or volcanic detritus that is not trapped close to the arc in the Tofua Trough, is redeposited downslope along submarine canyons that incise the edge of the platform (Fig. 5). Material from depths of 500–1000 m moves down to around 5000 m on the midtrench slope through these canyons. Canyons are well defined south of Vava'u, but they are less well developed on the forearc north of Vava'u and south of the present Louisville Collision Zone. This distribution suggests that these canyons were generated by collision and degrade with time. Canyons incising the Tonga Platform in the central area (e.g., at 19°S) appear to form at the platform edge and erode downslope, similar to canyons mapped in the Izu-Bonin forearc (Klaus and Taylor, 1991). Although our data coverage usually does not extend into the shallow waters close to the arc volcanoes, as in the Izu-Bonin examples, the two sets both show that the deepest erosion is close to the outer arc high, and there is lesser incision downslope toward the trench. This geometry is in accord with an origin caused by uplift of the outer Tonga Platform during Louisville collision and downcutting by erosive sediment flows, resulting in headward erosion. In addition, along-strike variations in the structure of the forearc caused by collision may have a strong influence on canyon formation, as several systems preferentially cut across the strike of the forearc in

Figure 6. (A) Swath bathymetric map and (B) sidescan image of the southern Tonga area (see Fig. 1 for location). Note canyon incising the eastern edge of the Tonga Platform. Data are from Wright et al. (1996). Faults are interpreted from presence of linear reflective features on the sidescan images.

areas of major across-strike faulting (e.g., Fig. 5B). This style contrasts with that developed south of the Louisville Collision Zone, where canyons incise the platform edge and grow arcward by headward erosion from a start at the break of slope (e.g., at 26°S; Fig. 6). In this respect they are similar to canyons noted in accretionary terranes whose formation is linked to fluid flow, sapping, and collapse (e.g., Cascadia; Orange et al., 1994).

Figure 7 shows the area of the forearc immediately adjacent to the colliding Capricorn Seamount. This region contrasts with both the previous areas in having no well developed midslope terraces or basins. The inner trench wall is very steep and is marked by a series of large trench-parallel faults. No large, well developed canyons are noted during this early stage of collision. Only one small canyon is identified in the midslope area.

In all areas examined canyons are of modest length and appear to deliver sediment immediately downslope within channels eroded into the preexisting strata. This situation is different from that documented on the Aleutian forearc, where GLORIA sidescan imaging and reflection seismic surveys demonstrate midslope terraces 20–30 km wide that are fed by well developed leveed canyon systems (Dobson et al., 1991). Along-strike sediment transport can bring sediment from distances of 80–100 km into a basin area. However, as for Tonga, sediment transport to the trench is restricted by structural highs along the edge of the inner trench wall; the highs focus sedimentation in widely spaced (>100 km) areas of major across-strike structures.

BASIN GEOMETRIES

A series of perched basins is found in the central and northern sections of the Tonga Ridge, between Horizon Deep and Capricorn Seamount (20° to 18°45'S) and on a smaller scale at 17°30'S and 16°15'–17°S. These basins typically are 5–8 km wide and 10–15 km long, parallel to the trench. Offsets in the trenchward-dipping faults make the basins discontinuous over greater distances, although individual basins may form close together at slightly different depths on the midslope. Small terraces at around 5000 m provide sediment traps in which redeposited material accumulates. Since the basins are normally underfilled, little overflow of sediment from one basin to another is thought to be likely, although it has been shown that unconfined sediment gravity flows are capable of moving over topographic highs in forearcs (Underwood, 1991). In addition, local small canyons feed sediment from higher to lower basins; the flow is typically oblique, not perpendicular, to the trench axis.

Figure 5A shows a bathymetric chart of the forearc in the central Tonga region: a flat, basinal area is fed by a canyon incising the upper trench slope. The upper trench slope is shown by high backscattering on the sidescan sonar image (Fig. 5B), suggesting a rough texture. The texture is probably caused by the erosion and outcrops of older Miocene Tonga Platform units. In contrast, the midslope basin is highlighted in light tones, indicating low backscattering caused by the acoustically absorbent qualities of the newly

Figure 7. (A) Swath bathymetric map and (B) sidescan image of the trench slope in the northern Tonga area (see Fig. 1 for location). Note lack of mid-slope terrace and chaotic strongly reflective sidescan image, caused by strong faulting on the slope. Data are from Wright et al. (1996).

deposited fine-grained sediments. On the trenchward side of the basin, outcrops of reflective lithified sediments and volcanic rocks represent the uplifted crest of the footwall of the next, big, trenchward-dipping normal fault block, or the plane of a fault scarp. By identifying linear regions that have steep slopes, it is possible to tentatively map major fault lineaments. It can be seen that downslope sedimentation from this basin is related to faults crosscutting the dominant margin-parallel structure. Seismic surveys through this and other similar basins (Fig. 8) show a common pattern of a faulted margin on the arcward flank and an unconformable onlapping pattern on the trenchward side. Sediment thicknesses may be in excess of 600 m in the center of the basins. In the basin shown in Figure 8, seismically reflective sediments overlying basement are seen to be dissected by faulting and overlain by deposits prograding away from the relatively uplifted footwall block. The entire sequence is overlain by a flat-lying postextensional drape. Intrabasinal disconformities are common features and may reflect either motion on the basin-bounding faults, or more regional tectonic events. In the northern Tonga forearc, where Louisville collision occurred earlier, seismic surveys reveal angular disconformities within the stratigraphy of many of the subbasins, and these disconformities may be related to ridge collision (Fig. 9). Unfortunately, the lack of well control does not permit a definitive tie to be made to this event, nor does the density of seismic data allow us to show that these unconformities are younger farther south. However, structural data from ODP Site 841 (MacLeod, 1994) confirm that that drill site has recently undergone rapid trenchward tilting in the wake of collision with the Louisville Ridge, following an extended period of more gentle trenchward rotation. Thus, it is likely that subsequent sedimentation will result in an angular unconformity or disconformity as a result of collision.

SEDIMENTARY FACIES

The presence of canyons and the dredging and coring of rocks from the mid-slope together provide strong evidence that sedimentation in the mid-slope terrace basins is dominantly achieved through the action of turbidity currents. Products of fine-grained, low-density flows and thicker, coarser high-density flows have been dredged and cored from the mid-slope. Figure 10 shows the generalized stratigraphy cored at ODP Site 841, which provides our best overall record of sedimentation on the outer forearc. Sandstones that have distinct bases and show normal grading, current ripple lamination, and parallel lamination indicative of upper-flow-regime deposition, are common in both core and dredge samples (Fig. 11C; Allen, 1994). All divisions of the Bouma (1962) sequence have been identified, although the complete sequence is only recognized in the thickest beds (>60 cm). There is evidence of water escape in the form of flame structures in <5% of the recovered units, but slumped, soft-sediment-deformed sandstone is more commonly seen in the thicker turbidites (Fig. 11D). Such features are most common in the high density turbidite layers, which are associated with mass flow conglomerates at ODP Site 841 (Fig. 11B; Shipboard Party, 1992). The conglomerates are typi-

Figure 8. Single channel seismic line through a perched basin in the North Tonga Arc, away from areas of collision (see Fig. 1 for location). Note the steep slope on the trenchward side of the basin, formed by normal faulting and the development of a series of stratigraphic packages related to different phases of local extension.

Figure 9. Single channel seismic line through a perched basin in the northern Tonga forearc. Note the strong intrabasinal disconformity between sequences 3 and 4, interpreted to have been generated during passage of the Louisville Ridge, which resulted in rapid and pronounced tilting of the basin fill. Sequence 1 is a preextensional sequence, while 2 and 3 represent two phases of faulting and sedimentation prior to the major rotation associated with sequence 4.

cally structureless and poorly sorted; larger volcanic clasts are supported within a muddier matrix of volcanic sandy mudstone. Grading is rare; the clasts are dominated by lava and pumice material, although there are small amounts of reworked mudstone, typically angular to subangular.

Coring at ODP Site 841 shows a strong temporal variability in the facies developed. Detailed sedimentary logs derived from core and downhole geophysical logging data (Clift, 1994) show that as late Miocene time progressed, the sediments deposited in this perched basin became finer grained and thin bedded. In the lowermost part of the section cored from the hanging wall of the major normal fault that cuts this section (Fig. 10), the sediments are dominantly massive conglomerates, stratified into beds, usually 4–6 m thick, between which are smaller amounts of hemipelagic mudstone

and thin sandstone turbidites (Fig. 12A). Up section, the proportion of conglomerate decreases markedly, and sandstone turbidites that have fining-upward silty tops predominate. The proportion of hemipelagic material increases, as does the average thickness of the individual beds, which approaches 2 m at the top of the logged section (Fig. 12B). This suggests an overall change from a proximal to distal turbidite facies association.

Where a prominent midslope terrace is developed, sedimentation on the trench inner wall is very limited because of the ponding of material higher. Low sedimentation rates are evidenced by the common development of manganese crusts on material dredged from fault scarps during Boomerang Leg 8. At the foot of fault scarps, and other steep slopes, localized scree breccias (i.e., clast supported; Fig. 13A) and debris flows (matrix supported) were

Figure 10. Schematic simplified lithological and stratigraphic log of the section drilled at Ocean Drilling Program Site 841.

dredged from the entire length of the Tonga Trench. The scree deposits contain clasts that are typically derived from a single source, presumably that material exposed in the fault scarp, although some debris flows are polymict. Structurally, the debris-flow deposits are massive; the matrix is sandy mudstone containing angular, poorly sorted blocks (Fig. 13B). Bioturbation of the *Chondrites*, *Planolites*, and, more rarely, *Zoophycos* ichnospecies disrupts the muddier sediments. Some dredged samples have manganese layers that developed between successive mass-flow deposits (Fig. 13B), the sedimentation of which must have been widely separated in time. Manganese crusts normally grow at rates of 0.5–4.0 mm/m.y. (Cronan, 1980); therefore, 3–5 mm crusts observed on the Tonga samples imply growth periods of 10^6 – 10^7 yr. Koski et al. (1985) noted that manganese crusts on the Tonga Platform have a chemistry typical of a hydrogenous, rather than hydrothermal, origin.

They also attributed crust development to slow sedimentation rates and a current swept environment.

In the northern Tonga forearc the lack of an outer arc high and the location of the Tofua Arc centrally within the Tonga Platform (Tappin, 1994) mean that there is no effective barrier to the redeposition of arc and platform detritus on the trench slope. Small basins, similar to those south of Vava'u, are developed at intervals, but their discontinuous nature makes them ineffective sediment traps. Volcaniclastic mass-flow deposits and platformal, foraminifer-rich limestone blocks as much as 1 m across dredged from the trench slope (e.g., at ODP Site 109 in 4357 m water depth; Fig. 1) indicate that mass wasting can occur easily in the northern Tonga forearc. Late Pliocene to Pleistocene limestones contain the planktonic foraminifers *Globigerinoides fistulosus*, *Sphaeroidinella dehiscentes* s.s., and *Globorotalia truncatulinoides* (R. Norris, 1996, personal commun.). Sample 109-1-3 also contains *Globorotalia tosaensis*. The limestones lack early and middle Pliocene markers like *Sphaeroidinellopsis* sp., *Dentoglobobulimina altispira*, and *Globorotalia multicamerata*, which have last appearances at 3.12, 3.09, and 3.09 Ma respectively (Berggren et al., 1995). Biochronology gives the ranges of the other species such as *G. fistulosus* (3.33–1.6 Ma), *G. truncatulinoides* (2.58–0.0 Ma), *G. tosaensis* (3.55–1.0 or 0.65 Ma), and *S. dehiscentes* s.s. (3.25–0.0 Ma). Sample 109-1-4 shows significant calcite corrosion and contains only dissolution-resistant forms, suggesting prolonged exposure below the lysocline. None of the samples contains shallow-water benthic foraminifers, consistent with the subphotic water depths on the Tonga Platform away from the arc volcanoes in the immediate vicinity of the northern part of the platform.

In addition to coherent limestone blocks, volcaniclastic deposits were recovered in northern Tonga. These are typically poorly sorted, clast-supported, angular pumiceous breccias indicative of an origin as a scree deposit. The presence of these gravels at great depths in the trench contrasts with their absence from the section at ODP Site 841, or from dredge samples farther south, despite continuous sedimentation across this interval there. In addition, dredges have recovered substantial quantities of turbidite sandstones and pebbly sandstones, some showing pervasive hydrothermal alteration. In less altered sediments the clasts are principally dominated by acidic and intermediate volcanic debris alteration is approximately uniform and minor. Reddened, highly altered volcanic-rock fragments are rare. These characteristics indicate that sediments are composed principally of fresh volcanic detritus derived directly from the arc, and that erosion of older volcaniclastic sediments or exposed chemically degraded lavas is volumetrically minor.

Microscopic Analysis

Two substantially different types of sediment are recognized in thin section. Figure 14 (A and B) shows examples of sandstones that contain components that were reworked from older sediments on the Tonga Platform. Shallow-water algal and rarer coralline fragments, as well as whole and broken benthic and planktonic foraminifers, show evidence for redeposition from the platform. Figure 14B shows rounded clasts of different types of arc-derived lavas; the clasts reflect the origin of this sediment as the product of several erosional events at several different eruptive sites, and conceivably more than one arc volcano, if along-strike transport is significant. Erosion of the rounded volcanic clasts was probably subaerial; the rounding was caused gradually by current or wave reworking, usually in shallow water. Figure 14C shows a markedly different sediment in which all the clasts are clearly volcanic and of one type. This type of sediment may be either a primary air-fall ash layer or a reworked ash: in either case, the source of the sediment was a single eruptive event. This type of sediment is most common in the debris aprons around the Tofua Arc volcanoes, but was also found in dredges and cores on the trench slope.

Figure 11. Representative examples of the sediment facies dredged or cored in the Tonga Trench. (A) Middle Eocene shallow-water calcareous volcanic sand, Ocean Drilling Program Site 841 (core 135-841B-46R). (B) Mass flow conglomerate of volcanic fragments, dredge 104-4-17. (C) Parallel laminated turbiditic volcanic sandstone, dredge 89-1-15. (D) Hemipelagic mudstones with contorted slump folding, dredge 113-4-3.

Diagenesis

Diagenetic alteration affects the sediments of the forearc to varying degrees; the general trend is greater alteration with increasing age. However, fluid flow associated with the large normal faults that dissect the forearc can result in local preferential alteration of the volcanic glass (Schöps and Herzig, 1994). Alteration is especially prevalent within the more porous and usually coarser layers in turbidites, which are altered to a light color, giving the rock a striped appearance. Microscopic examination of sediments with this type of alteration reveal Fe-stained, but otherwise fresh, volcanic shards in dark layers, interbedded with gray-greenish, strongly altered sediment in which the individual glass shards have lost all their orig-

inal morphology and degraded to chlorite and smectites, including nontronite. This alteration was also reported in the lower Miocene strata at ODP Site 841, on the footwall of a major trench-parallel, trenchward-dipping normal fault zone (MacLeod, 1994). The flow of hot (80–150 °C), chemically reactive fluids was interpreted to reflect seawater flow within the forearc rather than initial dewatering of the subduction slab, on the basis of pore-water compositions and the presence of thaumasite (MacLeod, 1994; Schöps and Herzig, 1994). The available sampling and geophysical data for the Tonga forearc support a model of enhanced fluid flow along faults and through porous sedimentary and volcanic units (Schöps and Herzig, 1994; Bloomer et al., 1996), rather than in the form of serpentinite mud diapirism, as recorded in the Mariana forearc (Fryer et al., 1985,

Figure 12. Sedimentary logs showing (A) a sequence of turbidites and mass flow conglomerates from the late Miocene, providing evidence of high-density current deposition and mass wasting from the arc at that time, and (B) more distal turbidite section from the late Miocene, dominated by thin, fine-grained turbidite sandstones and siltstones. 1—conglomerate, 2—sandstone, 3—siltstone, 4—mudstone, 5—dolerite. Parallel lines indicate parallel laminations after Clift (1994). Black zones in recovery column indicate percent actually recovered by coring.

Figure 13. Modern sediments from the lower Tonga Trench. (A) Muddy breccia of gabbro clasts reworked from exposed fault scarps, dredge 114-4-14. (B) Mass flow conglomerate of volcanic sandstone clasts, covered by manganese coating. Pencil tip for scale.

1990). Fluid flow has caused cementation of the sediments where there is no or little depositional matrix. Micritic ooze forms the most common matrix (Fig. 14C), although clay is also found in some fine-grained turbidites. Quartz, zeolites, and sparry calcite are all recognized as cements in dredge and core samples, reflecting the different temperatures and chemistries of the precipitating fluids. The recovery of minerals precipitated at 80–150 °C in rocks exposed at the surface does not require structural exhumation of the forearc, because fluid temperatures can remain hot until they are close to the sea bed. However, the exposure of arc gabbros and peridotites in the inner trench wall (Bloomer and Fisher, 1987), together with the association of alteration and normal faults in drill cores, suggests that this process is operative in the outer forearc and could expose older, altered sediments that would otherwise be covered by more recent deposits.

DISCUSSION

The dredge and core data presented here are strong evidence that sedimentation in the Tonga forearc is controlled by structural development, which in turn is strongly affected by the collision of seamounts with the trench. Collisional events disrupt the normal pattern of basal tectonic erosion, subsidence, and accumulation of volcanoclastic debris from the arc. Other tectonic events that affect the arc (e.g., arc rifting) influence the sediment supply but do not greatly change the structure of the outer forearc, which appears to be in continuous extension when not in collision (Shipboard Party, 1992; MacLeod, 1994). It is likely that these same processes have affected sediment accumulation since subduction reached a steady-state condition soon after initiation in Eocene time. Evidence for the collision of seamounts that are now subducted is difficult to identify, but a collision may have occurred and contributed to the marked Oligocene-Miocene unconformity (17–35 Ma) that is recognized at ODP Site 841 and on 'Eua (Cunningham and Anscombe, 1985). Several factors suggest that this stratigraphic gap may have been caused by collision of a seamount at 17 Ma. Although MacLeod (1994) recorded a steady increase in the trenchward tilt of the sediments down section at ODP Site 841, he also noted that the sedi-

ments immediately under the unconformity have shallower dips than those above. This suggests that these sediments had undergone progressive trenchward tilting before and after the hiatus, but were backtilted toward the arc during the hiatus, before the renewal of sedimentation and trenchward tilting. Such tilting is predicted by the seamount-trench collision model of Ballance et al. (1989). In addition, paleo-water-depth indications from the preservation of foraminifers and nannofossils in the sediment show that deposition took place at 35 Ma below the carbonate compensation depth (CCD) beneath the unconformity, but was above the CCD when sedimentation resumed at 17 Ma (Clift, 1994). Although the level of the CCD in the Pacific is seen to shallow over that time period (van Andel, 1975), such a trend could indicate some shallowing of the site at the end of the unconformity period. Taken together the erosional unconformity, backtilting and possible uplift point toward the collision of a seamount with the trench adjacent to ODP Site 841 just before the deposition of the oldest sediments overlying the unconformity (i.e., 17 Ma). This process is the most elegant explanation for all these features being together in a subduction setting.

CONCLUSIONS

We conclude that sedimentation and diagenesis on the Tonga forearc is strongly controlled by tectonic activity related to steady-state subduction and basal tectonic erosion of the overriding plate. The long-term subsidence of the forearc is punctuated by occasional compressional and uplift events resulting from seamount collisions that form major angular unconformities within basins on the midslope terrace and cause downcutting by canyons along the trenchward edge of the Tonga Platform. Collisional deformation also steepens the trench slope and allows sediment normally ponded in small half-graben basins to be shed deep into the trench. Across-arc structural lineaments developed or reactivated during collision are exploited by canyon systems that aid the redeposition of sediments to deep levels of the trench slope. The outer forearc appears to recover from seamount collision by ongoing basal tectonic erosion broadening the forearc by extension, initially forming major perched basins on rotated fault blocks (within 2–3 m.y.); then

Figure 14. Representative thin-section photomicrographs of sediments dredged from Tonga forearc. (A) Dredge 89-1-7, poorly sorted sandstone with degraded volcanic clasts, large clinopyroxene and smaller minor orthopyroxene crystals, foraminifers, and algal debris. (B) Dredge 89-1-7, well-rounded phyrlic arc lava clast in sandstone. (C) Dredge 113-4-8, primary air-fall ash showing slightly altered vesicular glass shards in micritic matrix.

a more gentle slope is formed, characterized by canyons progressing arcward by headwall erosion and collapse (after > 5 m.y.). Eustatic influences on forearc sedimentation appear to be minor.

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