27. STRUCTURAL FEATURES IN CORES FROM THE SLOPE LANDWARD OF THE JAPAN TRENCH, DEEP SEA DRILLING PROJECT LEG 87B[1]

Neil Lundberg, Earth Sciences Board, University of California, Santa Cruz
and
Jeremy K. Leggett, Department of Geology, Imperial College of Science and Technology[2]

ABSTRACT

Consistently good recovery at Site 584 permits unusually complete characterization of structural features. At this site hemipelagic mudstone exhibits intervals of consistently steep bedding dips, abundant healed and open fractures, and vein structure.

Core-scale structures indicate primarily extension, although reverse faults are present in the lower part of the section. Bedding dips steepen smoothly downhole to a maximum of 60 to 70° at 739 to 827 m sub-bottom, below which they flatten slightly. Tilting was apparently caused by displacements along large growth faults with listric normal geometry, inferred on the basis of large-scale and small-scale structures. Three deep holes penetrate stratigraphically equivalent horizons at comparable depths despite steep, homoclinal dips. Healed fractures for which the sense of displacement can be determined are mainly normal faults, and several are apparently small-scale listric normal faults that rotate bedding. Tilting occurred from the middle Miocene into the earliest Pliocene; it was preceded by the development of vein structure and healed normal faults, respectively, and followed by minor additional normal faulting.

The geometry and internal fabric of vein structure suggest that veins formed by initial extensional disaggregation and subsequent compressional closing in response to layer-parallel shear, rather than by hydrofracturing. Vein structure is associated with extensional faulting at Site 584 and at a number of other DSDP sites and on-land examples. Vein structure and healed normal faults appear to reflect downslope, and thus probably gravity-driven, movement of slope sediments, rather than tectonic dewatering and shearing or compressional stress resulting from plate convergence.

Depths to the shallowest indications of lithification, fractures, and veins fit reasonably into the pattern noted at previously drilled sites in the Japan forearc, although there is no corona of open fractures evident above sediment cut by healed fractures.

INTRODUCTION

Modern convergent margins are becoming much better known, largely as a result of deep-sea drilling at a number of subduction zones over the past decade. One of the key aspects revealed by this work is the extreme variability of tectonic styles in forearc regions. Tectonic processes postulated to be active in modern subduction zones range from offscraping and underplating of incoming sedimentary sections (at some margins mimicking the structure of classic fold and thrust belts) to efficient subduction of the incoming section along major décollements and further still to subduction of inner-slope deposits and perhaps underlying basement by sediment-poor subducting plates with rough topography.

Of this recent flurry of deep-sea drilling at active margins, perhaps the most useful to geologists studying ancient analogs on land is the small but growing number of studies of small-scale deformational structures in the DSDP cores (Arthur, Carson, et al., 1980; Lundberg and Moore, 1982; Cowan, 1982; Dengo, 1982). Uplifted subduction complexes typically show a number of superimposed deformational events, the unraveling of which involves the inference of environmental conditions during the various phases of deformation. These deformational events commonly begin with syn-sedimentary processes that accompany deposition itself and range up to a variety of mechanisms of brittle and ductile deformation in hard rocks (e.g., Cowan, 1974; Draper, 1978; Quinquis et al., 1978; Byrne, in press). The inferred environmental conditions may then imply a specific tectonic setting within a given forearc terrane (e.g., Byrne, 1982; Cloos, 1982). The study of DSDP samples, on the other hand, provides close constraints on environmental conditions and unequivocal tectonic settings.

DSDP cores from active margins show a range of structural features, including folds, faults, scaly foliation, stratal disruption, spaced cleavage, veins, kinks, and crenulations. Many of these have been described in cores from a number of active margins, and their geometry and kinematics have been outlined. Genetically, however, most of these structures are still poorly understood. A further complication arises when core-scale structures are compared to large structures defined seismically. For example, we may see stratal disruption, brecciation, and development of scaly foliations on the scale of the cores (Lundberg and Moore, 1982; Cowan et al., 1984), but on the scale of seismic reflection, coherence of strata and structures is retained (Arthur, Carson, et al., 1980; von Huene et al., 1982; Shipley, 1982; Westbrook, 1982).

The forearc terrane landward of the Japan Trench is characterized by fairly efficient sediment subduction through much of the most recent episode of convergence, reflected in subsidence revealed by a transect of sites drilled on DSDP Legs 56 and 57 (von Huene et al., 1980). Site

[1] Kagami, H., Karig, D. E., Coulbourn, W. T., et al., *Init. Repts. DSDP*, 87: Washington (U.S. Govt. Printing Office).

[2] Addresses: (Lundberg, present address) Department of Geological and Geophysical Sciences, Princeton University, Princeton, New Jersey 08544; (Leggett) Department of Geology, Imperial College of Science and Technology, London, United Kingdom.

584 was drilled on Leg 87B to evaluate the history of vertical motions of the Japanese continental margin near the trench and to test for the presence of a seismically defined regional unconformity at the base of a locally thin slope blanket. Although hole instability problems precluded penetration of the target unconformity, a wealth of structural features were recovered, some quite unexpected.

Herein we present a summary of small-scale structural features in cores from Site 584, which we relate to large structures inferred from seismic and drilling results. We also compare these structures to features reported in cores recovered during Legs 56 and 57 and re-evaluate previous interpretations of their kinematic and genetic significance in light of evidence provided by Leg 87B cores.

TECTONIC SETTING AND GEOLOGIC STRUCTURE

The Japan Trench is the site of rapid convergence (8 to 10 cm/yr., Minster and Jordan, 1978) between the Pacific Plate and Japan, an island arc built on a continental fragment isolated by the opening of a back-arc basin. Judging from the record of arc magmatism on Japan, the current phase of subduction began in the latest Oligocene (Honza et al., 1977). An earlier episode of subduction during the Cretaceous was apparently followed by a period of limited or no convergence through much of the Paleogene. More than 1000 km of ocean crust are inferred to have been subducted here since the early Miocene. Throughout much of this time, however, the forearc region has subsided, and any accretion of trench or ocean deposits during this episode of convergence is apparently restricted to a small zone at the toe of the slope (von Huene et al., 1981).

Reference sites drilled on Legs 56 and 57 sampled the presently incoming section on the Pacific Plate (Site 436) and the landward forearc section on a broad structural high (Sites 438 and 439; Fig. 1; von Huene et al., 1982). Both areas are characterized seismically by coherent reflective sequences cut by normal faults (Nasu et al., 1980). The lower slope was sampled at four sites drilled along Profile JNOC 2 on Legs 56 and 57 (von Huene et al., 1982), and at Site 584, located near Profile JNOC 1 (Fig. 2).

The landward reference section is located on a deep-sea terrace, the equivalent of a forearc basin. Coherent reflectors of the landward section can be traced with confidence to the location of Site 435, just landward of a "midslope terrace," a distinct bench on the lower slope (Fig. 2). Similar reflectors underlie the midslope terrace, drilled at Sites 440 and 584, although they cannot be traced directly to the reference section (von Huene et al., 1982; site chapter, Site 584, this volume). It is not possible to distinguish from the seismic profiles whether the region of the midslope terrace is characterized by compressional or extensional structures (Nasu et al., 1980). Seaward of the midslope terrace, Sites 441 and 434 drilled a thin slope blanket (defined by discontinuous reflectors), which overlies faint landward-dipping reflectors that apparently represent a small accretionary zone (von Huene

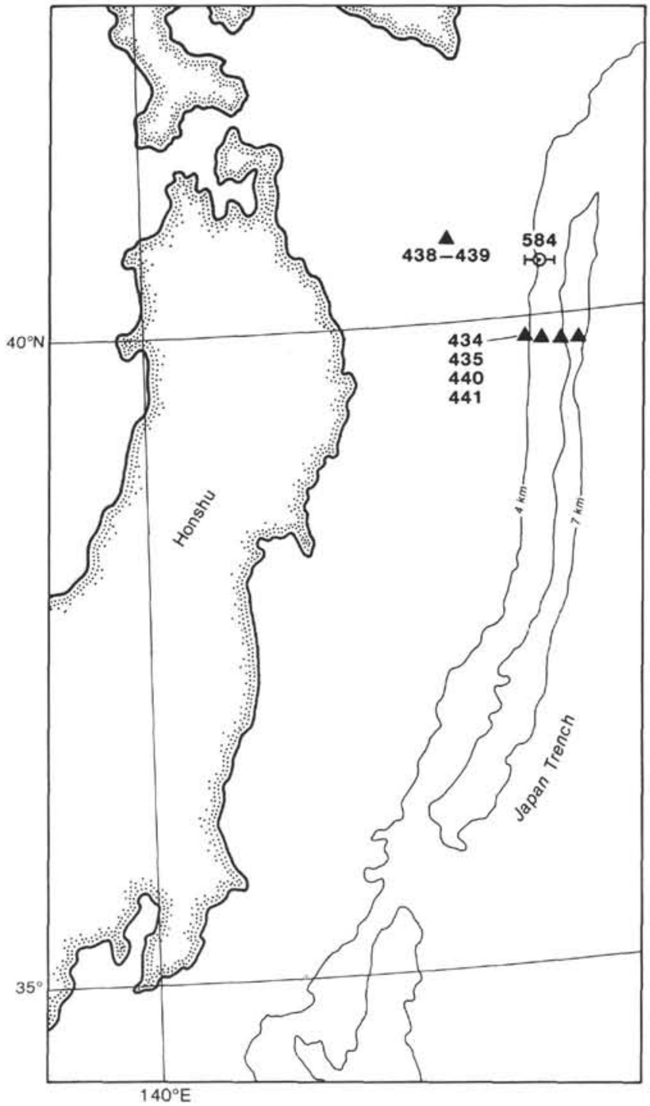


Figure 1. Location of sites drilled on Leg 87B, plus sites transecting the Japan Trench drilled on Legs 56 and 57. The approximate location of the seismic profile line drawing of Figure 2 is also indicated.

et al., 1982). Site 434 may possibly have penetrated the slope sediments into offscraped deposits below, but this relationship is not clear.

The acoustically coherent landward section overlies a regional unconformity, below which are faint but continuous landward-dipping reflectors. Where this deeper sequence was sampled at Site 439 it comprises Cretaceous shales. This older section must be repeated by faulting, because it is otherwise unrealistically thick. Based on the interpretation of the landward dipping reflectors as bedding-parallel surfaces in a homoclinal sequence and assuming no repetition by faulting, the thickness is on the order of 45 km (von Huene et al., 1982). It may represent an accretionary prism correlative with abundant Cretaceous volcanism in the magmatic arc (von Huene et al., 1982). At least a portion of this older terrane was emergent in the Paleogene, only to subside and be covered by a seaward-transgressive sequence in the Neo-

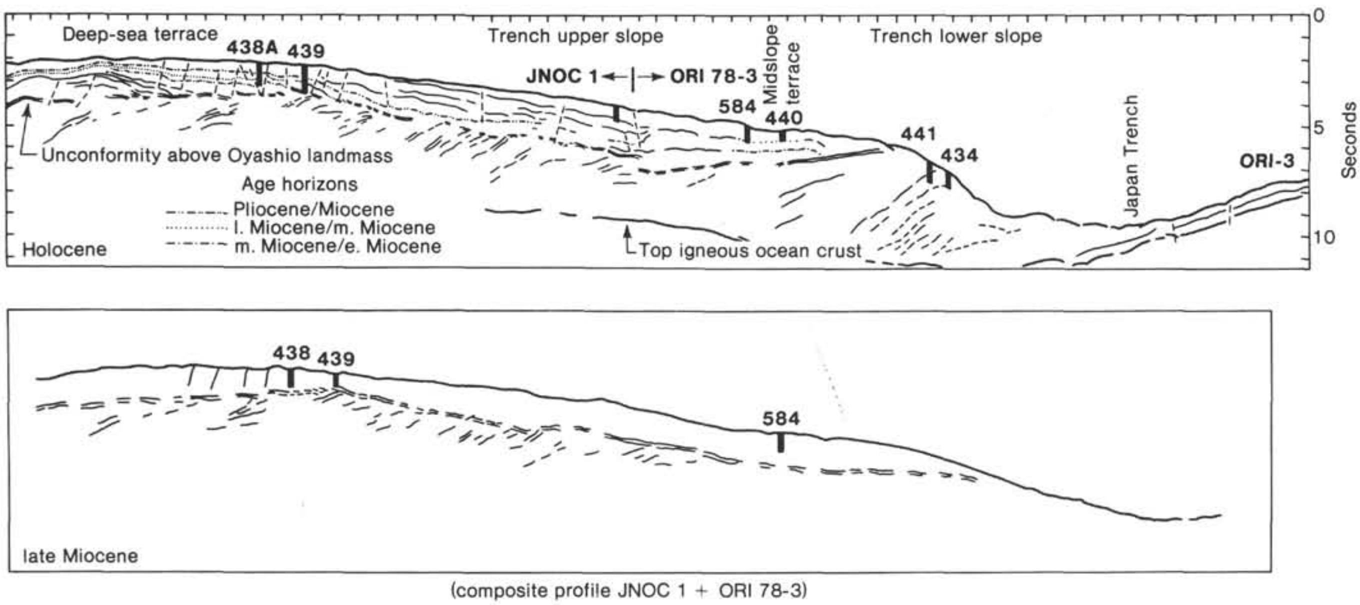


Figure 2. Schematic diagram showing evolution of forearc region off northern Honshu. Composite line drawing of JNOC 1 and ORI 78-3 lines. Location of Sites 435, 440, 441, and 434 are projected about 90 km along strike from a somewhat different structural setting, and their relation to this profile is represented only approximately.

gene (Arthur, von Huene, et al., 1980). Periods of subsidence associated with sediment subduction or tectonic erosion apparently persisted throughout the Miocene and early Pliocene and diminished or gave way to relative uplift and perhaps accretion since the late Pliocene or Pleistocene.

SEDIMENT LITHOLOGY AND PHYSICAL PROPERTIES

The section cored at Site 584 is fairly uniform diatomaceous mud to mudstone, similar to Neogene deposits recovered from all sites drilled during Legs 56 and 57 in the Japan forearc (Fig. 3). Most of the recovered section is of the lower Pliocene to middle Miocene, with a hiatus representing the upper lower Pliocene and lower Pleistocene overlain by only 4 m of Holocene mud.

Intervals of muddy diatomite near the top of the section are composed predominately of diatom frustules (>60%), and a downhole decrease in diatom frustules is paired with a correlative decrease in opal-A (see site chapter, Site 584, this volume). Aside from the above, there are no major changes in lithology, and the four lithologic units recognized are defined primarily on the basis of relatively subtle changes in minor components through the section. Minor lithologies interbedded with the typically green to gray hemipelagic mud or mudstone include numerous ash layers, up to 20 cm thick, pumice clasts (especially near the top of the section), and minor silt and fine sand layers, commonly reworked by bioturbation.

Bioturbation is evident in virtually all cores, although it is not always present in all layers of a given core. Bioturbated intervals alternate with laminated diatomite between 173 and 202 m, suggestive of recurring episodes of poorly oxygenated bottom waters. Also, layers interpreted as muddy turbidites near the base of the section are composed of intervals of structureless mudstone several tens of centimeters thick, occurring between laminated bases and bioturbated tops. Except for these examples, bioturbation is ubiquitous.

Sediment accumulation rates calculated for Site 584 vary from 20 m/Ma in the middle Miocene to 200 m/Ma in the lower Pliocene. This is similar to the rates calculated for sites drilled on Legs 56 and 57. In particular, the pattern of sediment accumulation rates found at Site 584 closely resembles that calculated for Hole 438A, which recovered the Neogene section at the landward reference site. On the basis of logs and physical properties data, however, the area drilled at Site 584 received little or no sediment during the late Pliocene (site chapter, Site 584, this volume).

Shipboard measurements of the wet-bulk density, porosity, and sonic velocity of sediment cored at Site 584 document an anomalous zone at 460 to 775 m (Fig. 4; site chapter, Site 584, this volume). This zone correlates closely with a band of strong reflectors at 460 to 800 m (see site chapter, Site 584, this volume, for discussion). There are no apparent lithologic variations seen in the cores, however, that might explain the anomalous physical properties in this interval.

METHODS

We collected data on the occurrence and orientation of bedding, fractures and faults, and veins in Site 584 cores. Preliminary interpretations of shipboard measurements indicated a need for quantification of structural features. We re-examined all the Site 584 cores at the La Jolla Repository, rechecking shipboard observations and collecting a consistent set of structural measurements. We measured true dips and dip azimuths, relative to the split core surface, in each case and noted coherent intervals in the cores throughout in which no demonstrable drill-induced rotation had taken place. These coherent intervals permit the assessment of comparative orientations of bedding and secondary features. The vertical deviations of the drill hole as determined by a downhole instrument were generally 2° and never exceeded 2.5°. Be-

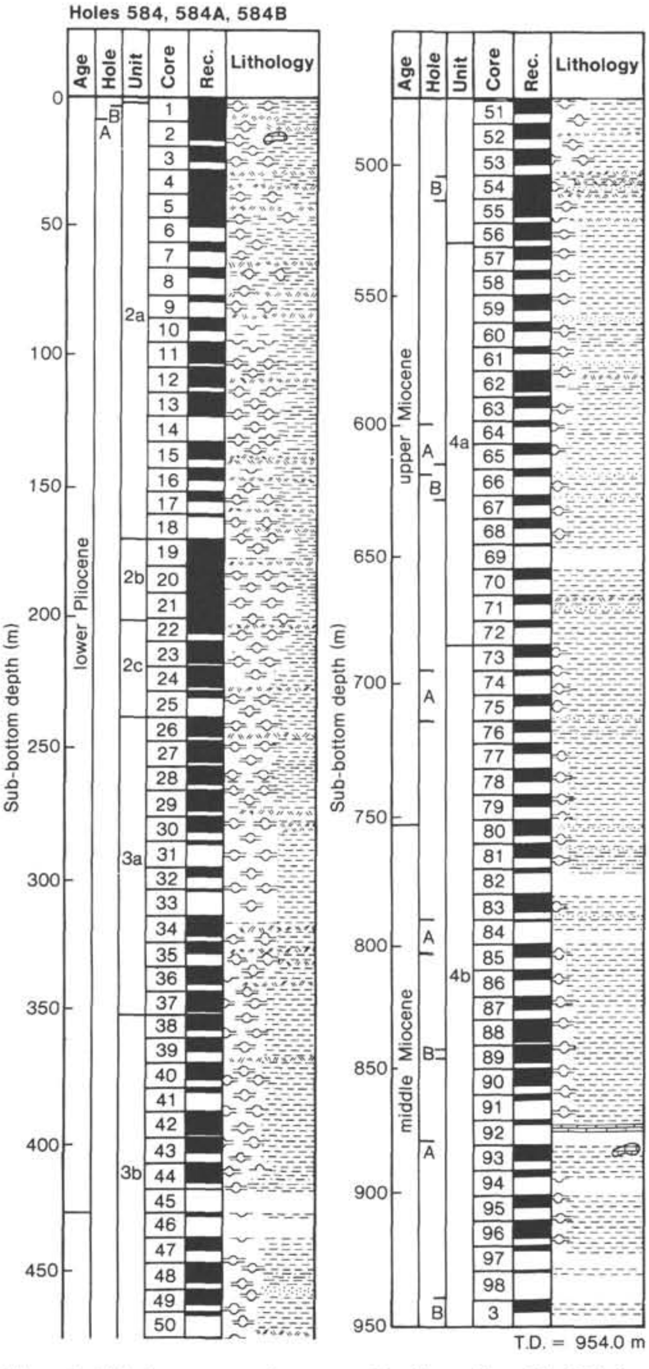


Figure 3. Lithology, age, and recovery of sediment from Site 584. See Explanatory Notes chapter (this volume) for lithologic symbols. T.D. = total depth.

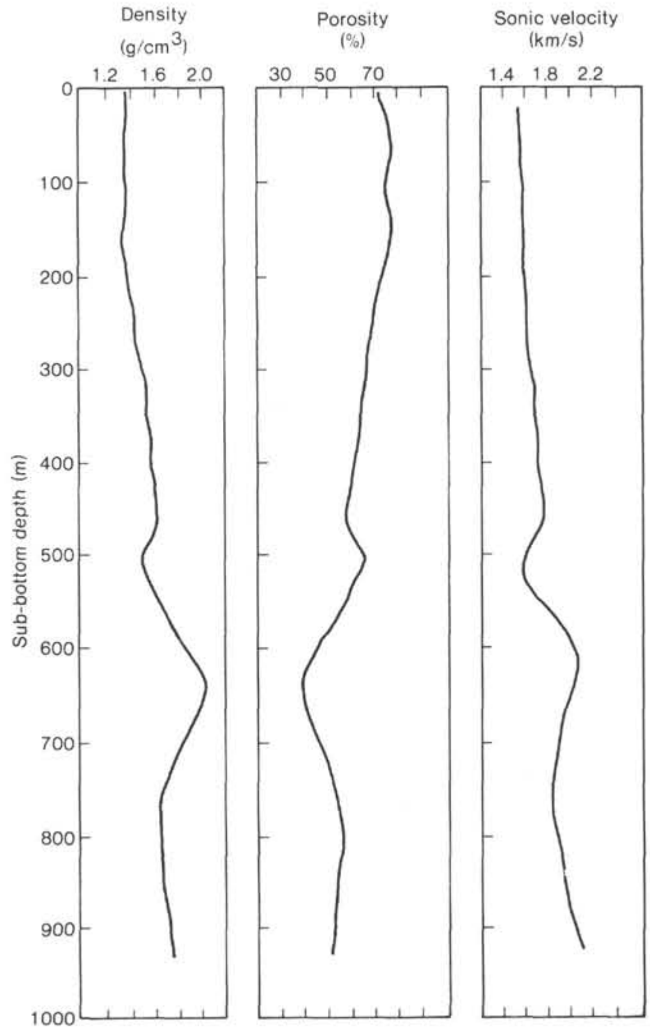


Figure 4. Wet-bulk density, porosity, and compressional-wave sonic velocity profiles for sediments recovered at Site 584, plotted against depth. The profiles shown are visual estimates of average values of shipboard determinations taken from Bray (Appendix at the end of this volume).

cause these deviations are comparable to our measurement errors, we have assumed the drill hole to be vertical.

The graphic structural log (Fig. 5) depicts the location and dip of structural features of the Site 584 cores. For purposes of graphic portrayal and discussion, we have divided structural data into three groups: bedding dips, penetrative secondary fabrics (penetrative on a scale of millimeters to a few centimeters), and discrete structures, comprising mainly fractures and faults. We discuss each group of data in turn, make interpretations, and draw comparisons with results of previous drilling in the Honshu forearc.

Site 584 is quite remarkable among trench-slope sites in several ways and admirably suited for the evaluation of structural features. First, it penetrated uncommonly deep for a site drilled on a lower trench slope (nearly 1000 m) and recovered a good percentage of the section drilled (50% overall). Drilling at Site 440 had similar success (Site 440 is the earlier site drilled in the same tectonic position). Second, there is sufficient sediment contrast to distinguish the orientation of bedding in most cores, further enhancing the potential for resolving patterns of faulting and folding. Third, the section shows a degree of lithification sufficient to display healed fractures at a relatively shallow depth (< 100 m). The development of penetrative fabrics and discrete structures is clearly dependent on a minimum degree of lithification, among other things. Finally, the drilling of three holes across the strike of the margin at this site allows us to extend our results, to link the essentially one-dimensional data sets compiled at each hole, and to evaluate the continuation of large-scale structures in the midslope terrace.

ORIENTATION OF BEDDING

In our data collection, we attempted to include at least one measurement of bedding dip for each 1.5 m section of each core. In sections that display numerous bedding surfaces, we measured representative dips and noted consistency of dips where present (± 5° over 1.5 m). Despite extensive remolding of primary layering in most Site 584 cores by burrowing organisms, the orientation of bedding is typically well displayed by aligned traces of originally horizontal burrows, especially *Zoophycos* traces, in addition to locally preserved laminations and sandy layers. Where aligned burrows and primary bedding traces are observed together, they are parallel in all cases.

Bedding dips vary downhole in a regular fashion at Site 584, and the lack of any sizable gaps in data on bedding dip allows us to characterize downhole variations with confidence. Beginning with essentially horizontal bedding in the upper 250 m, dips steepen gradually downhole to reach a maximum of 67 ± 8° at 739 to 827 m sub-bottom, below which they become slightly less steep (Fig. 5). A table of 50-m averages of bedding dips clearly shows this downhole pattern of increasingly steeper dips followed by a slight decrease near the bottom of the hole (Fig. 6A). Less objectively but perhaps more meaningfully, the section can readily be divided into intervals of consistent dip (Fig. 6B). The section can be characterized as a number of intervals of internally consistent dip, although these are typically gradational. Except for the boundaries of a short interval of unusually shallow dip (36°) at about 900 m, there are no large jumps in dip values between adjacent intervals. This gradual change in bedding dips is most remarkable, especially the smooth and persistent increase in dip down to the steeply inclined strata between 739 and 827 m.

Bedding dips measured in cores recovered at Holes 584A and 584B are comparable to those measured at similar depths in Hole 584 (Fig. 5). In detail, however, they do not all fit into specific intervals of consistent dip at the same depth, especially below the zone of maximum dip at Hole 584. Eight wash cores were also recovered at these two holes, most of which are not represented in Figure 5. The precise depth within the washed interval that was sampled by these cores cannot be determined with confidence. In general, measurements of structural features in these wash cores merely confirm the patterns seen in the precisely located cores, adding nothing substantially different. Wash Core 584A-H4 was included, however, to demonstrate that there are steep dips below the level of Core 584A-3, at 800 m. The beds in this core, which dip 60°, could thus have been recovered from any level between 805 and 895 m.

Paleomagnetic measurements indicate that bedding at Site 584 dips uniformly to the east and northeast (Niitsuma, this volume), toward the Japan Trench. Unless there is significant folding or faulting, then, the steep bedding dips at depth predict that given stratigraphic levels would be considerably shallower to the west (Hole 584A) and deeper to the east (Hole 584B). If we assume a conservative average dip of 45° and hole separations normal to the strike of bedding, the distances to Hole 584A (524 m) and Hole 584B (701 m) suggest stratigraphic offsets on the order of 500 and 700 m, respectively. Stratigraphic horizons in the sections drilled at Holes 584A and 584B are not offset by more than 100 m, however (see Niitsuma, this volume), indicating that the predicted stratigraphic offset of these horizons has been compensated structurally by folding or faulting.

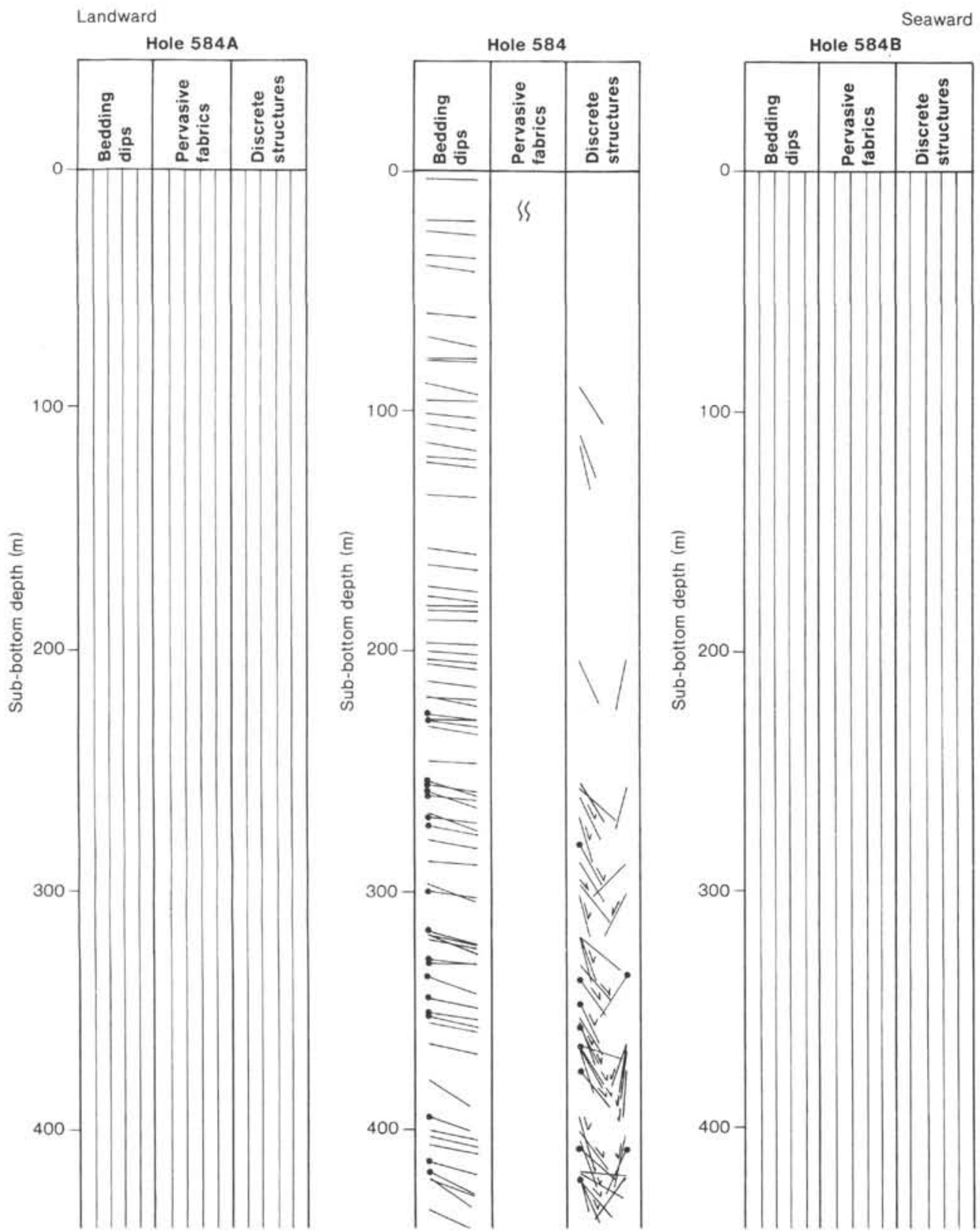
Folding was probably not responsible for the tilting observed in the cores from these holes. Growth folding would be required to generate the smooth pattern of downward-steepening dips, but could not adequately explain the shallower dips at depth, below the zone of maximum dip; also, it would be highly fortuitous to drill through three different east-dipping limbs. The data are explained better by faulting, even though major faults are not clearly displayed on the reflection profile (see site chapter, Site 584, this volume). Listric normal faults are capable of both tilting the section and at the same time maintaining comparable depths to identifiable horizons, as seen in these three holes. Small-scale structures in the cores confirm the interpretation of an extensional environment and even some apparent listric normal faults (see following discussion). Multiple episodes or one greatly protracted phase of listric normal faulting can explain quite satisfactorily the simple increase in dips seen through much of the section, as well as the more complex zone at the base of the hole (made up of small domains with internally consistent bedding dips). Assuming such listric faulting has indeed been active, it might have been accomplished along many small faults, thus masking the presence of large faults that otherwise might be distinguished seismically. Alternatively, the steep dips characterizing much of the section here may be responsible for the lack of seismic resolution. Faulting might produce short segments of inclined strata, whereas folding would produce more continuous reflections that ought to be resolvable. Tilting of these strata has not taken place since sometime in the early Pliocene because the uppermost tilted sediments are lower Pliocene mudstones at about 250 m.

FAULTS AND FRACTURES

Cores from Site 584 exhibit numerous open and healed fractures. We label as "faults" those that show demonstrable offset, and we have collected data on apparent displacements as well as orientations for representative fractures.

We present the orientations and interpretations of measured faults graphically in Figure 5. The fractures represented include only those we interpret to be natural features, rather than artifacts of drilling or handling. Healed fractures we take to be natural in all cases, but the interpretation of open fractures is less straightforward. Many of the latter may be artifacts, and some can be demonstrated to be such. We refer the reader to Arthur, Carson, et al. (1980), Lundberg and Moore (1982), and Dengo (1982) for summaries of criteria useful in identifying drill-induced deformation. Generally, we are skeptical of a natural origin for (1) open fractures with hackly or rough surfaces; (2) open fractures with no slickenlines or poorly developed slickenlines that indicate purely dip-slip motion; and (3) conjugate fractures that show fortuitous symmetry relative to the originally vertical core axis and/or the split core surface.

For each fracture analyzed, we measured the true dip and dip azimuth (relative to the split core surface) and the trend and plunge of each resolvable set of striations (slickenlines). In order to classify striated faults, we call those with striations that rake 70° or more dip-slip faults,


Landward
Seaward
Hole 584A
Hole 584
Hole 584B
Bedding dips
Pervasive fabrics
Discrete structures
Sub-bottom depth (m)
0
100
200
300
400

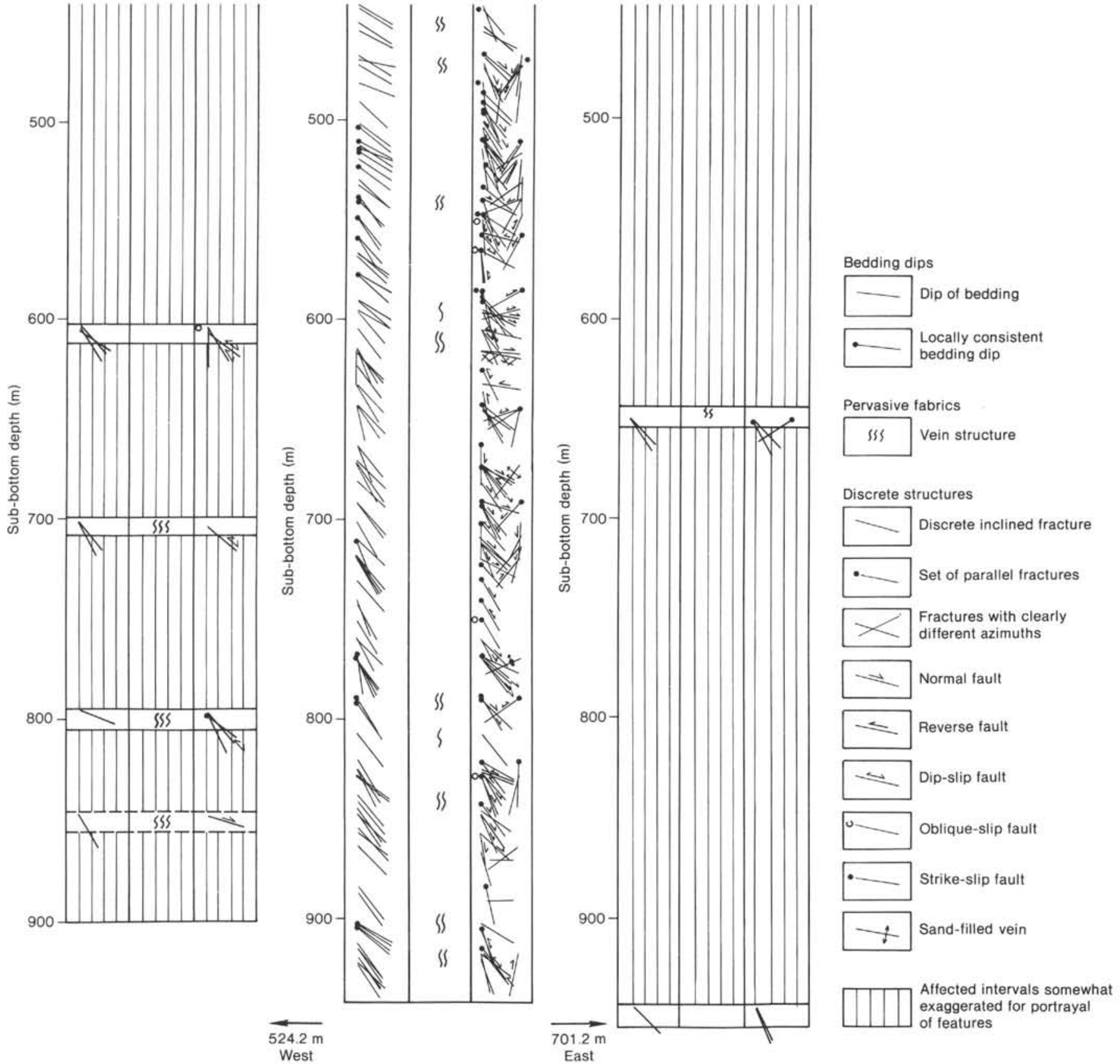


Figure 5. Graphic structural log depicting location, frequency, and orientation of bedding, penetrative fabrics, and discrete structures in sediment cored at Hole 584, Leg 87B.

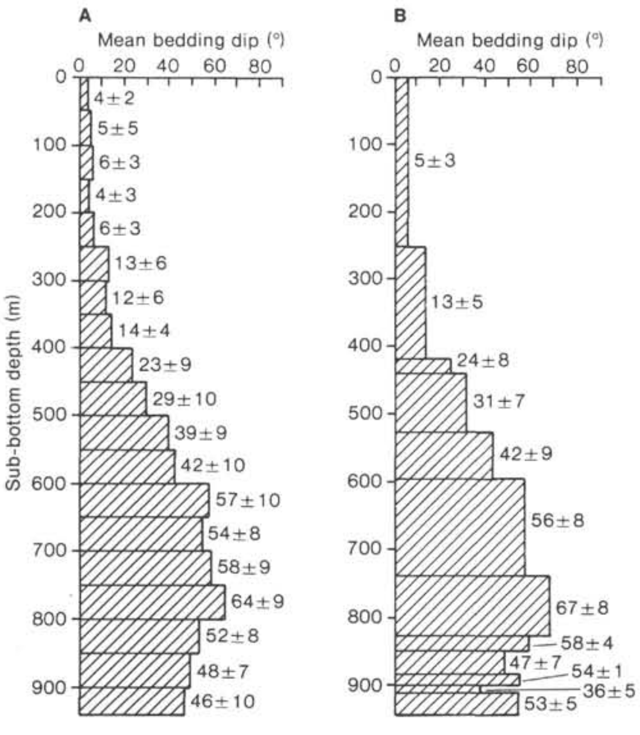


Figure 6. Average values of bedding dips, Hole 584. Dips increase with depth to about 800 m. A. Means and standard deviations for bedding dips averaged over 50-m intervals. B. Means and standard deviations for bedding dips averaged over intervals interpreted as internally consistent.

those with striations that rake less than 20°, strike-slip faults, and the remainder, oblique-slip faults. We used offset beds and burrows, where present, to determine the sense of offset along minor faults, and we used drag features and sigmoidal lenses of relict mudstone included in thicker fault zones. We also noted the sense of steps developed on slickensides, although these should be interpreted with caution (Durney and Ramsey, 1973; Hobbs et al., 1976, pp. 303–305), and we did not use these data for the interpretations presented in Figure 5. We also collected data on the presence of sets of consistently parallel fractures and of apparently conjugate fractures. The dip azimuths of fractures, bedding, and paleomagnetic measurements can be compared throughout coherent intervals, defined as segments of individual cores that have rotated as single blocks during drilling.

Healed Fractures

Healed fractures are present in Site 584 cores at a surprisingly shallow level, 89 m (Core 584-10), although they are much more abundant below 255 m (Core 584-27). The shallowest fractures may have formed before erosion occurred at a significant hiatus that was recovered in the first core (see site chapter, Site 584, this volume). A simple extrapolation of sediment accumulation rates in the lower Pliocene section suggests that this hiatus may represent the deposition and subsequent erosion of an interval on the order of several hundred meters thick. Thus, the shallow fractures may have been somewhat more deeply buried when they formed. Physical properties data would seem to preclude, however, the erosion of a thick overlying section (site chapter, Site 584, this volume); porosity at 89 m sub-bottom is over 70% (Fig. 4), considerably higher than corresponding values at other DSDP active-margin sites. Porosity values for the shallowest fractures observed at six sites drilled landward of the Middle America Trench on Leg 66, for example, range from 38 to 53% (Lundberg and Moore, 1982). The presence of healed fractures in such poorly consolidated sediment at Site 584 remains puzzling.

Healed fractures and faults are usually planar or nearly so and are generally less than a millimeter wide, although a small percentage are broader, ranging up to shear zones on the order of 10 cm across (Fig. 7). They are typically dark gray, darker than surrounding sediment, and are filled with clay-sized material. The dark fracture filling may be, in part, clay deposited during fluid migration; a thin section of the shear zone illustrated in Figure 7, however, shows the movement zone to be composed of finely comminuted sediment. Numerous subparallel, anastomosing slip zones are defined by strongly aligned phyllosilicates (Fig. 8), and these movement zones encase lenses of mudstone (Figs. 7B, 8C, and 8D). Bedding within these lenses is generally preserved, but has been folded, apparently by drag, near their borders. Additional movement zones cut across these lenses longitudinally and are bounded by drag features, so that bedding has been rotated on a microscopic scale toward parallelism with the shear zone. A radiolarian test is sufficiently strong that movement zones detour around it rather than breaking it (Fig. 8A).

A number of cores display intervals riddled with healed fractures, with apparently random (or at least uninterpretable) orientations and varying senses of offset (Cores 78, 83, 92, 93, and 97 of Hole 584). It is noteworthy that the faults in these intervals have become sufficiently lithified to be recovered intact, despite their pervasive nature. The presence of such intervals suggests that some of the poorly recovered zones may represent similar zones of fracturing that were not yet lithified or that were rebroken by the bit. In fact, each of the cores listed above is adjacent to at least one core with very poor recovery (Cores 77, 82, 84–85, 91–92, and 97–98 of Hole 584). In a hole generally characterized by good recovery, this is a suspiciously strong correspondence and suggests that intervals of poor recovery reflect pervasive predrilling fractures.

Open fractures in some cases clearly were healed at one time (as shown by thick seams of dark, fine-grained fracture filling) and were likely opened during drilling and handling. There is no apparent systematic difference, however, in the distribution of open versus healed fractures.

Kinematic Interpretation

Most striated faults in Site 584 cores are dip-slip faults, and most of these display apparent normal offsets. There is a problem, however, in classifying offsets as normal or reverse in steeply inclined beds, even if primary features are clearly offset and displacements can be readily measured. The interpretation of a given fault as normal

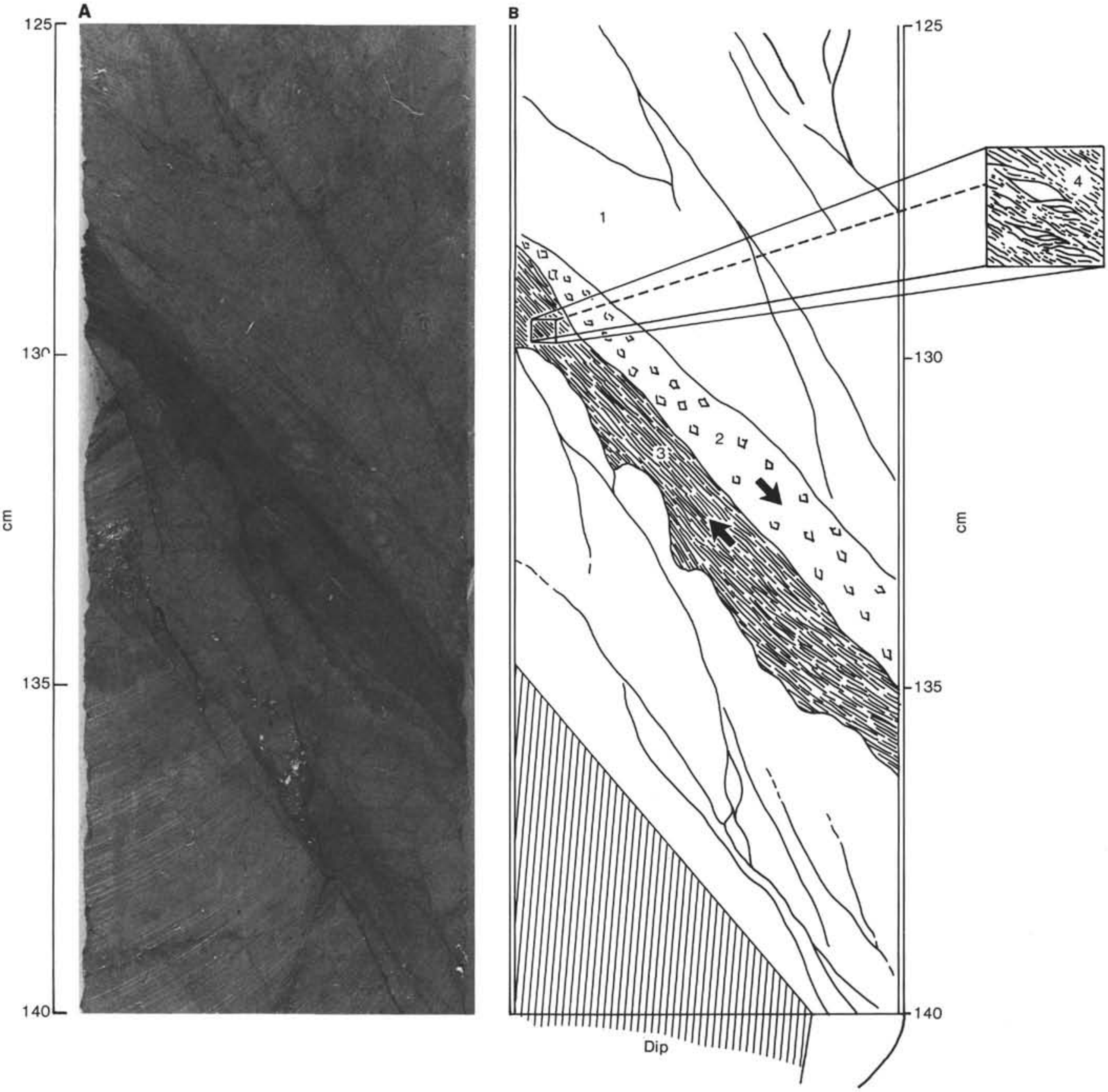


Figure 7. Shear zone at 584-80-2, 125–140 cm (760 m sub-bottom; ?middle Miocene). A. Core photo, showing brecciated zone above black zone of milled sediment. B. Drawing of same interval. Note sigmoidal lenses of relict sediment preserved in shear zone, implying normal-fault displacement. Steeply dipping mudstone (1) with a bedding-parallel disrupted layer comprising upper brecciated mudstone (2) and lower, intensely sheared claystone with very fine disseminated pyrite (3). "Fish" structure (flow-smeared mudstone chips) indicates normal-fault offset (4).

or reverse (that is, as an extensional or a compressional feature) depends in many cases on an interpretation of when the fault formed (before or after tilting of the section). Given a monotonic history of tilting, if the fault dips roughly toward the same azimuth as does bedding, a shallower fault dip than bedding dip produces an ambiguous geometry: a pretilting normal fault produces the same geometry as a posttilting reverse fault, and vice versa. Conversely, if a fault dips in roughly the opposite direction as does bedding, the ambiguous case occurs where the sum of bedding dip and fault dip angles exceeds 90°. Virtually all possible cases are exemplified in the cores from Site 584. For the interpretations presented in our graphic structural log (Fig. 5), we assigned senses of offset only to those cases that are unequivocal, classifying all ambiguous examples as simply dip-slip faults. We assumed monotonic tilting, an assumption supported by paleomagnetic measurements, which define a uniformly east-dipping to northeast-dipping section.

For our interpretations of fault patterns, however, three other approaches help to distinguish compressional from extensional fracture patterns. These all utilize the geom-

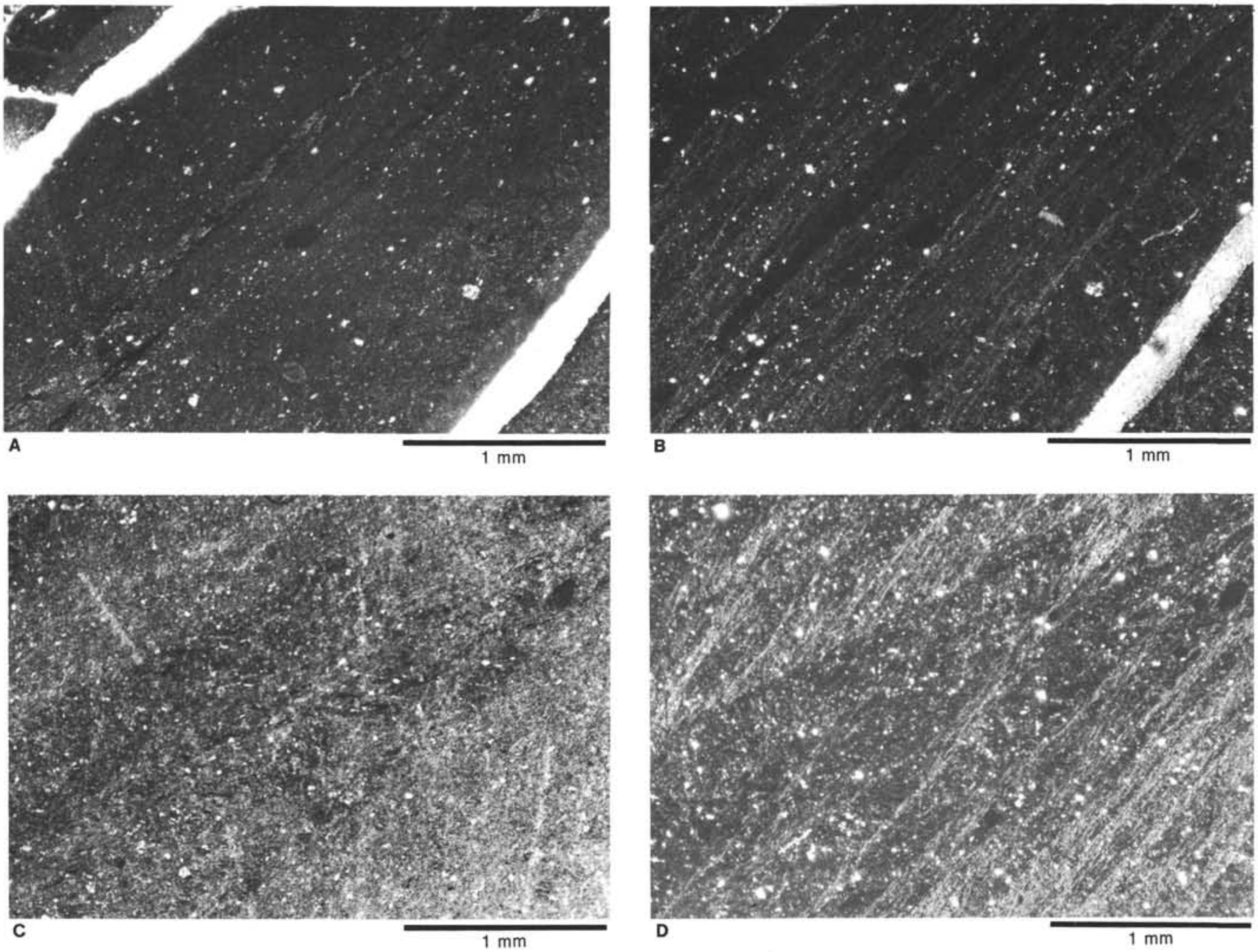


Figure 8. Photomicrographs of shear zone illustrated in Figure 7. A. Plane light (compare with 8B). Note grain size reduction within shear zone and radiolarian test preserved intact in lower center of photo. Section normal to shear zone and bedding, up (as cored) is toward top of photo. B. Same field of view as in 8A, crossed nicols. Subparallel, anastomosing zones of strongly aligned phyllosilicates bound lens-shaped domains that show little or no preferred orientation. C. Plane light (compare with 8D). Darker domain in center of photo is lens of relict sediment preserved within shear zone. Note sigmoidal traces of relict bedding, folded by drag along slip surfaces that penetrate nearly coherent lens. Section normal to shear zone and bedding, up (as cored) is toward top of photo. D. Same field of view as in 8C, crossed nicols. Slip surfaces, marked by aligned phyllosilicates, bound and penetrate lens of relict sediment. Slip surfaces discordant to upper surface apparently deflect along it.

etry of apparently conjugate fractures and fracture sets. The first is based on patterns of conjugate fractures symmetric with respect to bedding. We observed such instances in 11 cores during our data collection, often involving sets of multiple fractures, and these all show normal fault offsets relative to bedding. The conclusion is that the section experienced significant layer-parallel extension before tilting. The second approach is based on relative offsets in conjugate fractures that are symmetric relative to present orientations. This was done during collection of paleomagnetic measurements, and seven instances recorded at the base of the hole suggest that some faulting also occurred after tilting of the section. A simple geometric consistency of the principal stress axes found in these examples, indicating horizontal extension, is destroyed by bedding corrections, and therefore most likely was produced after tilting (Niitsuma, this volume). The third approach taken was to compare the abundant, but often ambiguous, results for the steeply inclined beds, found throughout much of the section at Site 584, with less prevalent but unambiguous faulting patterns found in shallow-dipping beds above. These are dominated by normal faults, with five instances of conjugate sets in three different cores. These results also suggest horizontal extension, although they offer no indication of whether this occurred before or after tilting.

Horizontal extension is a consistent pattern seen in structural features at Site 584, but it is by no means the only one. Reverse faults are also present, although we found no unequivocal examples above 555 m (Core 59). There are also a number of complex examples of multiple generations of faulting, typically with varying senses of relative displacement (Cores 54, 59, 76, 78, 92, and 93 of Hole 584).

Sand-Filled Fractures

Thin sand-filled seams cut across bedding at 770 m (Core 584-81). These are thin, generally about 1 mm across, and somewhat irregular locally, but have sharp and very planar parallel boundaries over much of their traces on split core surfaces (Fig. 9A). They are filled with a mixture of fine sand, silt, glass shards, and clay (Fig. 9B). This fill is now lithified, but was clearly slurried during emplacement. The seams form a parallel set, oriented at a high angle (66°) to bedding, spaced about every 15 cm as measured along bedding. There is no obvious offset across these seams, yet they are not simply clastic dikes. The paucity of injection features and the planar, even geometry of the seams suggest initial extensional fracturing followed by emplacement of slurried sandy sediment. A fine sand bed of similar color and texture immediately above the interval that contains the seams is a likely source for the sand, and the fractures were probably filled from above.

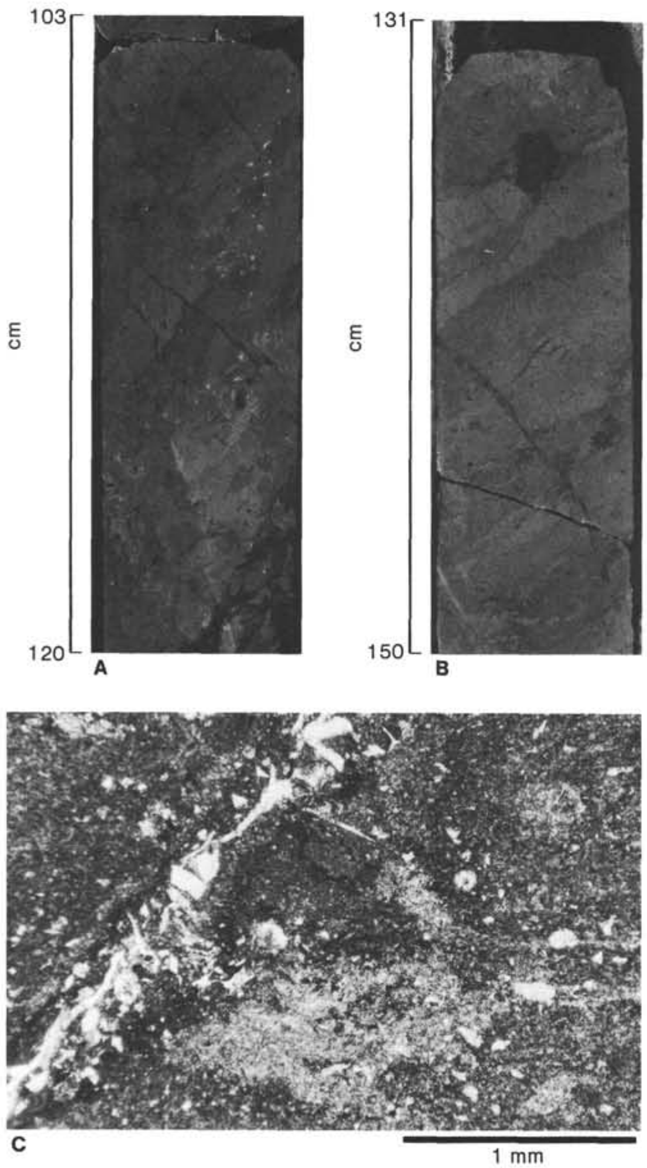


Figure 9. Sand-filled extensional fractures in 584-81-3. A. Core photo of 584-81-3, 103–120 cm. Sand-filled seams are lithified and are oriented at 66° to bedding. B. Core photo of 584-81-3, 131–150 cm. Angular mudstone clasts are enclosed in lithified sandy slurry that fills extensional fracture. C. Photomicrograph of sand-filled seam at 584-81-3, 100–103 cm; seam is filled with a mixture of glass shards, sand, silt, and clay. Plane light, section normal to bedding, which is shown horizontal in photo.

A similar feature, a broad sand-filled crack, cuts roughly perpendicular to bedding at about 673 m (Core 584-71; Fig. 10). This crack tapers downward from 6 cm (measured normal to bedding) to terminate completely and so must have been filled from above. The fill is lithified and is composed of grains of moderately well-sorted fine sand, mixed with silt and clay at the top, and includes angular chips of mudstone, similar to the surrounding sediment, at the base of the crack (Fig. 10C). Some of these mudstone chips have sand-filled fractures themselves, and they are apparently clasts of the sediment that occupied this zone before fracturing occurred. The boundaries of the crack are smooth, and fracturing clearly took place after lithification of the surrounding mudstone, but before lithification of the sandy fill. Near the top of the crack-fill feature, a number of sill-like injections of sandy fill extend from the main crack into the surrounding sediment, subparallel to bedding. Low-angle faults offset the crack-fill by small amounts (less than 1 mm), and so faulting occurred after lithification of the fill. On the whole, however, the sand-filled fractures represent extension parallel to bedding.

Listric Normal Faults

Listric normal faults provide a potential mechanism for tilting of the section at Site 584, and core-scale features include faults we interpret as listric normal faults. A 3-mm-thick, planar shear zone in Section 584-34-2 separates intervals with disparate bedding dip. Bedding above the shear zone dips 22°, whereas bedding in the foot wall dips 11°. The shear zone dips 39°, in roughly the opposite direction as bedding below. The difference in bedding dip azimuth between bedding above and below the shear zone can be explained by rotation of the hanging wall along a listric normal fault that dips in the direction of the shear zone. A fault in Section 584-44-5 also separates a more steeply dipping hanging-wall section from a more shallowly dipping foot-wall section (Fig. 11). Here the fault dips 50°, bedding above the fault dips 36°, and bedding below the fault dips 22°. Rotation along a listric normal fault represented by the observed fault explains not only the difference in dip angle, but also a 27° clockwise rotation of the direction of bedding dip of the beds above the fault relative to those below (the dip direction of the fault is 84° counterclockwise from the dip direction of the beds above the fault). In these two examples, bedding has been tilted by 11 and 14° by rotation along a fault. This is the same magnitude of tilting as that observed between intervals of consistent dip interpreted from data on bedding dip (Fig. 6), although the latter is in the opposite sense, with deeper beds tilted more steeply than shallower beds. It is likely that similar faults have rotated the strata at Site 584 on a larger scale, and that deeper strata have been tilted more steeply than have shallower strata by virtue of having experienced progressively more episodes of recurrent faulting.

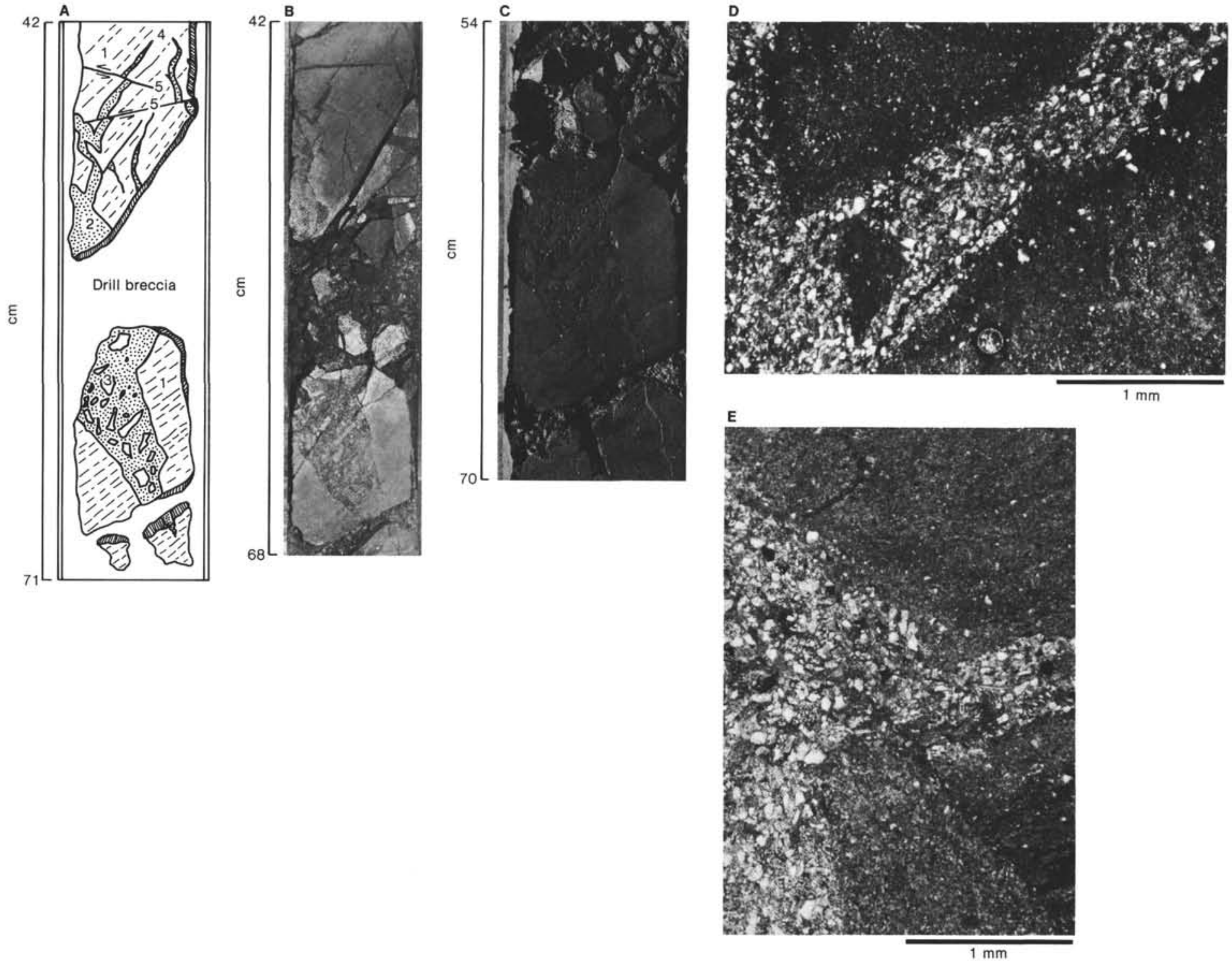


Figure 10. Crack-fill at 584-71-2, 43–67 cm. A. Sketch of crack-fill. Host gray to dark olive gray mudstone shows bedding by color change laminations, represented schematically (1). Fine sand fills a wide, irregular crack perpendicular to bedding. In the upper part of the crack, the fill is solely sand (2), but in the lower part, highly angular chips of mudstone (3) form a matrix-supported fill. In the upper part, other sand-filled cracks penetrate the mudstone, including one parallel to bedding (4). These are cut by healed fractures (5). B. Core photo. Note sill-like injections of sandy fill in upper part. C. Close-up of base of crack-fill. Note mudstone clasts. D. Photomicrograph of base of crack-fill illustrated in Figures 10A and 10B. Mudstone clasts similar texturally and compositionally to mudstone surrounding crack-fill. Plane light, section normal to crack boundaries and bedding. E. Photomicrograph of upper part of crack-fill illustrated in Figures 10A and 10B. Sand-rich matrix injected along bedding at right. Plane light, section normal to crack boundaries and bedding.

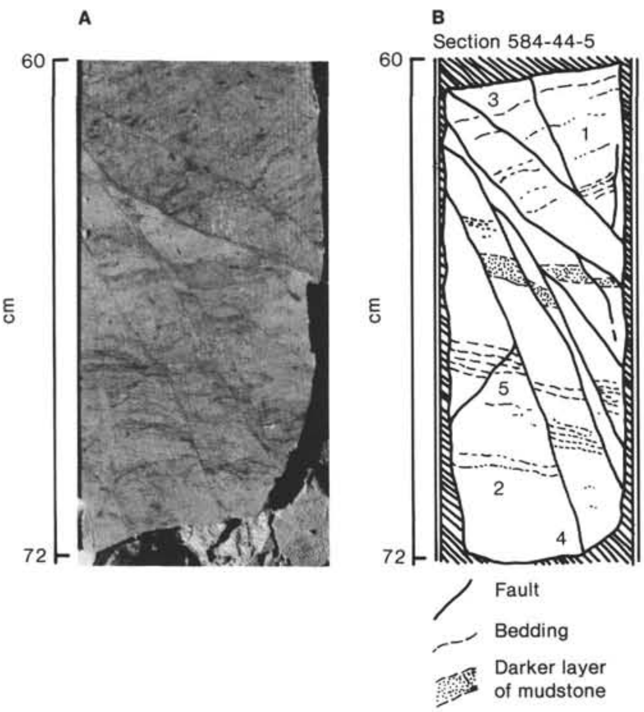


Figure 11. Apparently listric normal fault at 584-44-5, 60–72 cm. A. Photo of archive half of core. B. Sketch of working half of core. (1) Bedding dips 36° above fault. (2) Bedding dips 22° below fault. (3) Major fault dips 50°, slightly concave upward; offset is clearly greater than length of trace seen in core (10 cm). (4) and (5) Conjugate normal faults, which dip 67 and 54°, respectively; 5 terminates at 4.

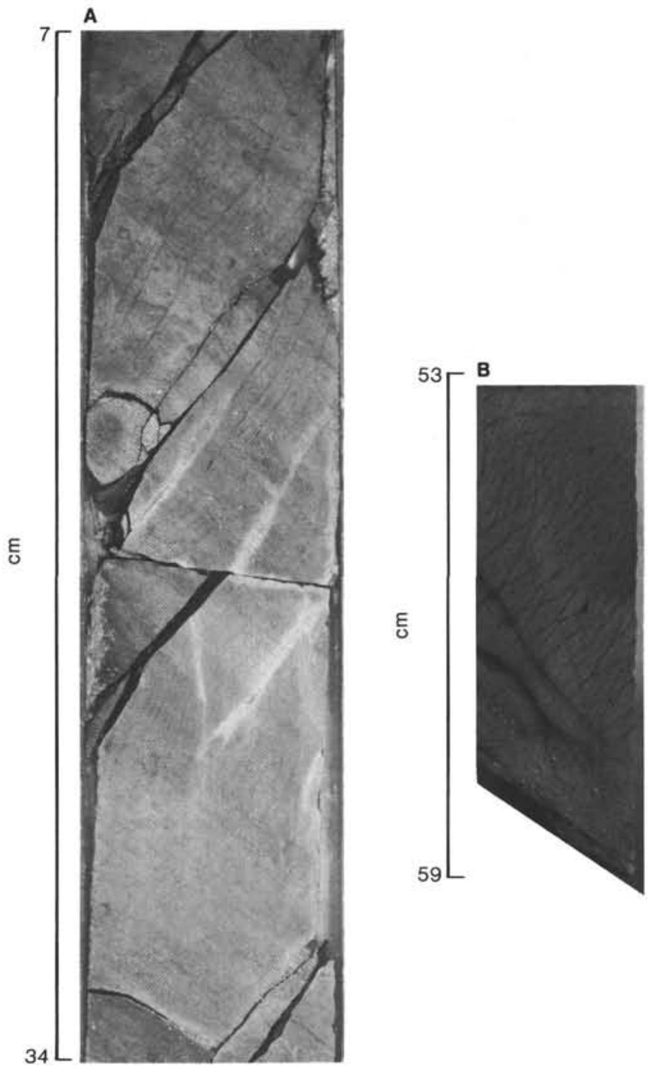


Figure 12. Vein structure in Site 584 cores. A. Slightly sigmoidal, densely spaced veins, nearly normal to bedding at 584-95-2, 7–34 cm. B. Branching and intersecting sigmoidal veins, terminating downward into a sand layer at 584-95-1, 53–59 cm.

VEIN STRUCTURE

The only semipervasive secondary fabric well developed in cores from Site 584 is made up of subparallel sets of dark, sediment-filled veins, observed in sediment below 450 m (Core 584-48). These veins are generally less than 1 mm across and closely spaced (typically 2 to 10 mm apart). They are planar or curviplanar, and traces on split core surfaces are linear, curved, or sigmoidal. Individual veins are very nearly perpendicular to bedding, and they nest within adjacent veins to form bands that, in virtually all cases, parallel bedding (Fig. 12). Veins are thickest near the center of these bands and taper in both directions, commonly bifurcating at their tips into two or more strands (Fig. 12).

Small offsets are commonly discernible across individual vein traces, but only locally exceed 1 mm along any given vein. Although the veins are, on the average, perpendicular to bedding, many examples, when examined in detail, show offsets that appear to be very small-scale normal faults.

This fabric has been called dewatering veins by Arthur, Carson, and others (1980) and a number of subsequent workers, and vein structure by Cowan (1982). We prefer the latter because it is descriptive. Although most workers agree that, once formed, these veins serve as dewatering conduits, they are apparently not formed by active dewatering. Similar features in DSDP cores from the southern Mexico transect grade into a spaced foliation (Lundberg and Moore, 1982), and Ogawa (1980) has reported a virtually identical fabric, which he calls beardlike veinlet structure, in an on-land example from the Boso Peninsula, Japan.

The development of vein structure is clearly controlled in part by lithology. Bands of veins typically (although not always) terminate where they contact fine sand layers (Fig. 12B), and in many cases are developed in specific beds so that both the bed and the band of veins are bounded by subtle color changes (Fig. 12A).

Bands of slightly sigmoidal veins in Cores 584-48 (450 m) and 584-95 (903 m) are bounded at the base by bedding-parallel shear zones (Fig. 13A). These and several other shear zones that parallel bedding (Fig. 13B) differ in detail from the bulk of healed faults and shear zones described in the last section. They are very planar and moderately thick (1.5 to 3 mm) dark slip surfaces, and all show evidence of displacement exceeding the width of the core. In thin section they show an alignment of mineral grains and diatom frustules considerably strong-

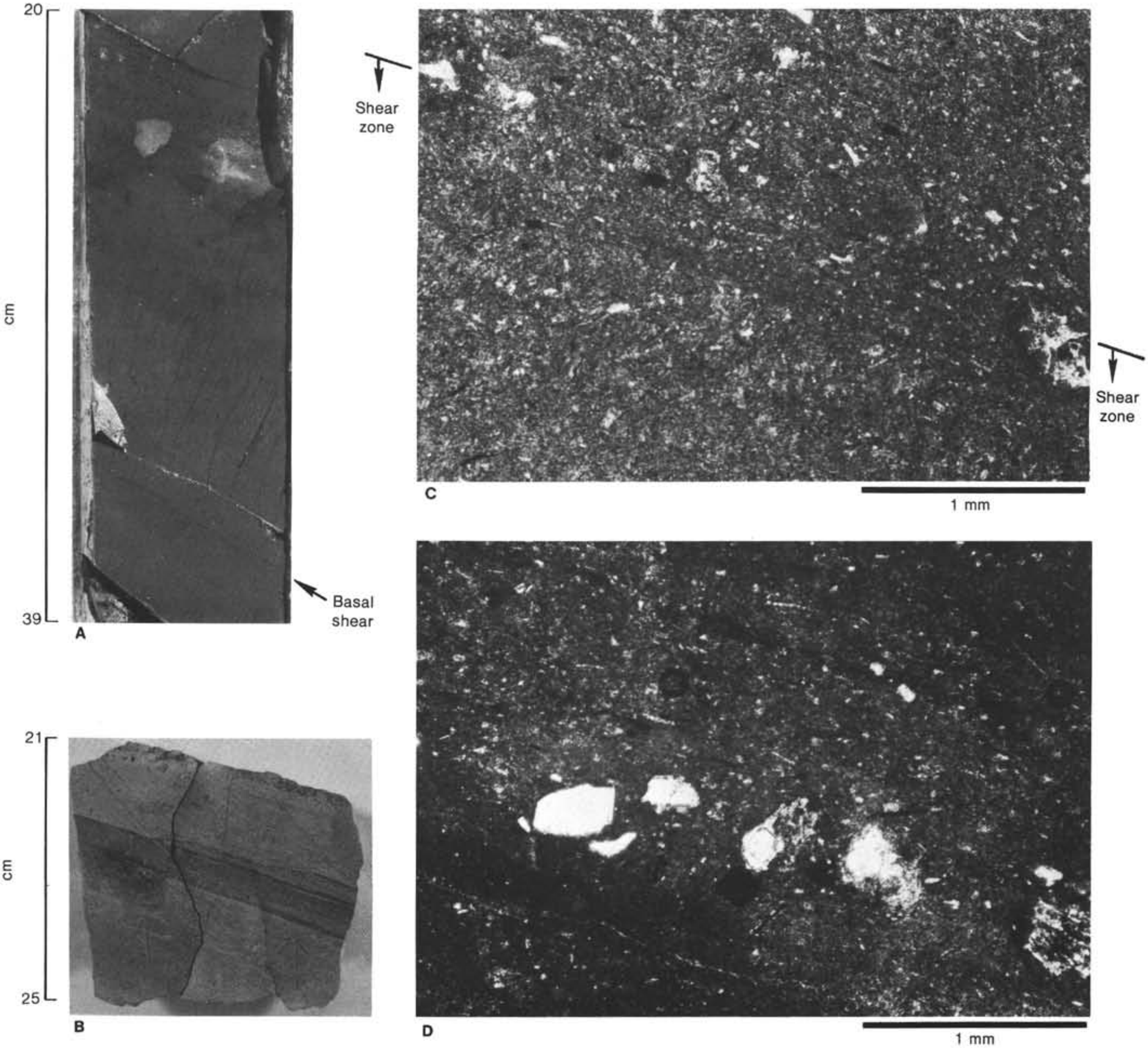


Figure 13. Low-angle shear zones and vein structure in Site 584 cores. A. Low-angle shear zone, at 584-95-1, 33 cm, bounds the base of a band of slightly sigmoidal veins. B. Low-angle shear zone at 584-44-4, 21–25 cm. Bedding in this interval dips 27°, in roughly the same direction as the 30° dipping shear zone. C. Photomicrograph of low-angle shear zone illustrated in 13B. Mineral grains show strong alignment in shear zone (below line) but relatively little grain-size reduction. Plane light, section normal to shear zone. D. Photomicrograph of low-angle shear zone illustrated in 13B. Shear zone contains trains of sand grains and dark organic matter (upper left to center right), subparallel to shear zone. Plane light, section normal to shear zone.

er than that in the surrounding sediment, but no lithologic change and little or no reduction in grain size (Fig. 13C). Instead, domains of larger grains form trains (or stringers) parallel to the shear zone, and they were apparently disaggregated and strung out by movement along the zone (Fig. 13D).

The veins themselves are defined in thin section by concentrations of realigned phyllosilicates, oriented parallel to vein boundaries (Fig. 14A). It is unclear at the optical-microscope scale whether phyllosilicates are crystallizing within the veins or are mechanically bent into parallelism with vein boundaries. Some veins appear lighter in color than surrounding sediment, whereas others are darker, and most exhibit a selvage (or halo) of slightly darkened or stained sediment (Fig. 14B). This aspect, in addition to the apparent truncation of dark grains (organic matter?) by veins, suggests minor solution effects. Vein boundaries detour around quartz grains in a fairly intricate fashion, however, and radiolarian tests are commonly well preserved within veins; so pressure solution is apparently not the primary mechanism for the development of vein structure. Gross layering continues through veins in several examples (Fig. 14C), suggesting that at least part of the vein filling is *in situ* sediment, rather than sediment that had migrated in from elsewhere to fill void spaces.

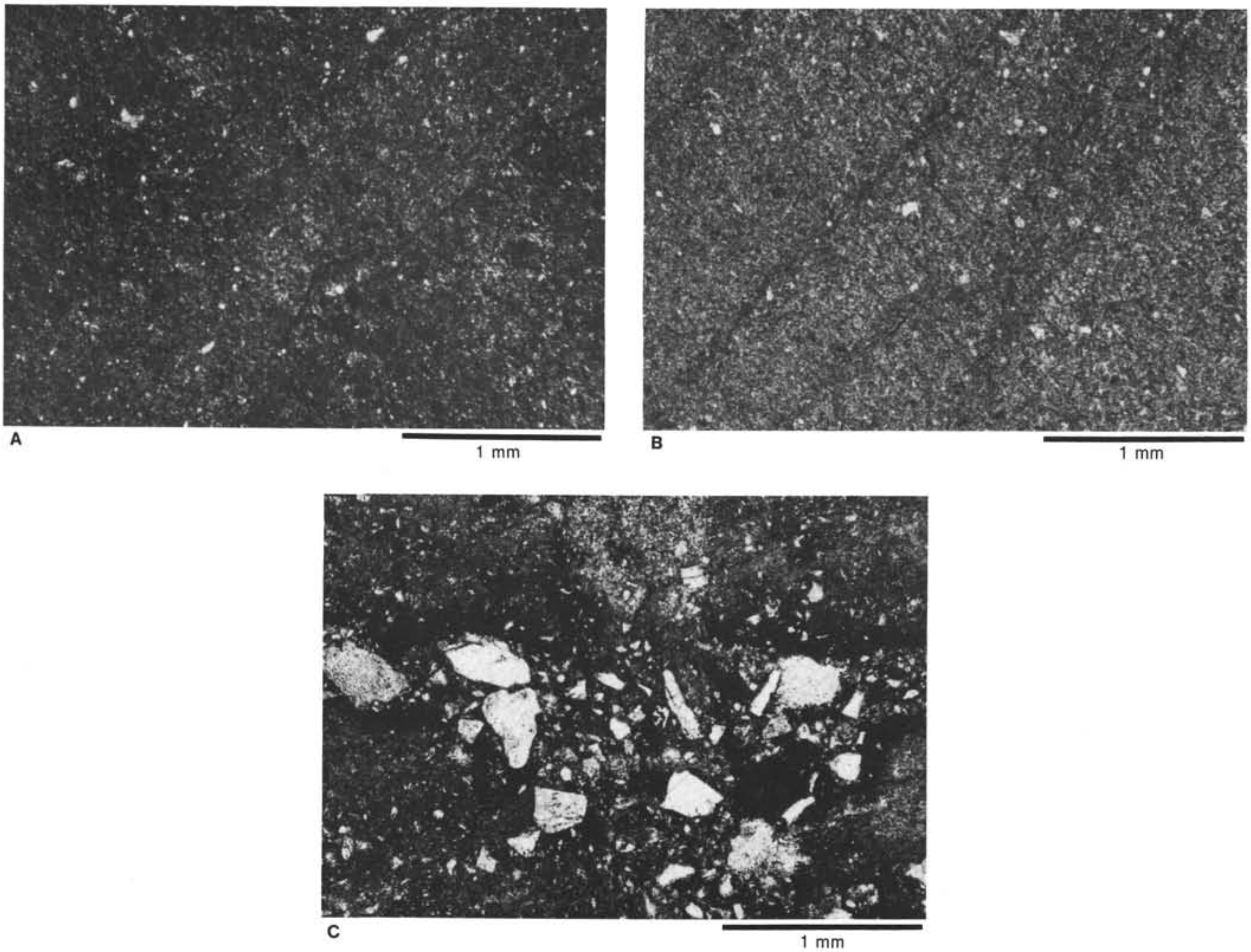


Figure 14. Photomicrographs of vein structure in Site 584 cores. A. Vein structure at 584-96-4, 112–119 cm. Preferred orientation of phyllosilicates in broad vein (light color, upper right to bottom left), oriented nearly perpendicular to bedding. Crossed nicols, section normal to vein and bedding. B. Dark staining along subparallel veins, oriented nearly perpendicular to bedding. Photomicrograph of interval illustrated in 12B. Plane light, section normal to veins. C. Vein crosses rare layer of coarse sand at 489A-11-4, 128–130 cm (Leg 66). Coarse sand grains present in vein where it intersects layer are not present elsewhere in vein, suggesting that at least some of the vein-filling is *in situ* sediment. Plane light, section normal to bedding and vein.

Vein structure in all cases postdates bioturbation and predates healed fractures. The consistent orientation of vein structure nearly perpendicular to bedding in almost all reported occurrences, despite highly variable dips of bedding (Arthur, Carson, et al., 1980; Cowan, 1982; Dengo, 1982; Lundberg and Moore, 1982; Cowan et al., 1984; Ogawa and Miyata, 1985), argues strongly that it developed early, prior to tilting. Vein structure has also been observed in poorly consolidated intervals of firm mud (or soft mudstone). The veined sediment was sufficiently consolidated, however, to disaggregate along fairly restricted, discrete planar zones.

Hydrofracturing Versus Applied Deviatoric Stress

As pointed out by Carson and others (1982), there are two principal mechanisms that might lead to vein structure and associated fracturing. One is dilation of the sediment by an applied deviatoric stress; the other, favored by Carson and others, is essentially hydrofracturing: an influx of pore water induces high fluid pressures, reduces effective stress, and thus permits fractures in response to *in situ* stresses. These are distinctly different mechanisms, but they are by no means mutually exclusive; both, in fact, can be expected to operate in trench-slope environments. Deviatoric stresses caused by both tectonic and gravitational forces are to be expected, resulting from convergence and from the typically steep submarine slopes found landward of trenches. At the same time, high fluid pressures are predicted to arise from dewatering of rapidly consolidating deep-sea deposits, which are in the process of being subducted or accreted below, at the base of the forearc wedge or accretionary prism. These two mechanisms can operate in tandem, and no doubt both contribute somewhat to the development of vein structure and associated fracturing. The question is which of these two mechanisms is the controlling factor. In other words, does the presence of vein structure reflect primarily an increase (local or temporal) in deviatoric stress or in pore pressure?

We would argue that the distribution, geometry, and microscopic fabric of vein structure all suggest that it developed as a result of applied deviatoric stresses. Vein structure is consistently associated with normal faulting, as discussed below. The interpretation of vein structure as a response to layer-parallel shear is consistent with the geometry of veins, which are typically oriented at high angles to bedding and commonly sigmoidal in cross section. This interpretation is also consistent with microscopic observations, which have not revealed injection features, but which commonly indicate displacement (E. Beutner, personal communication, 1983).

The precise deformational mechanism by which vein structure develops is unclear at this point, although current research by R. Knipe (personal communication, 1984) using scanning-transmission electron microscopy (STEM) methods is elucidating microstructural details. Preliminary results of Knipe's work indicate veins initially dilated by disaggregation of sediment and subsequently closed up again under compression, thereby aligning platy mineral grains parallel to vein boundaries. Knipe's interpretation is that alternating coaxial extension and compression are caused by stick-slip behavior of sediment in a zone of simple shear. This is consistent with Cowan's (1982) suggestion that vein structure in DSDP (Leg 67) cores from off Guatemala may be geometrically and kinematically analogous to tension gashes developed in simple shear zones. Based on a study of more recently collected cores from off Guatemala (Leg 84) and by analogy to recent experimental work, however, Helm and Vollbrecht (1985) have suggested that vein structure forms as antithetic second-order Riedel shears associated with a first-order simple shear zone, rather than as simple tension gashes.

Vein structure is found typically in regions characterized in seismic reflection profiles by normal faulting. This is true at the landward reference sites of the Japan transect (Arthur, Carson, et al., 1980), the southern Mexico transect (Lundberg and Moore, 1982), and in the Mariana forearc (Lundberg, unpublished data). The structure of the upper slope of the Guatemalan forearc and at Site 440 on the midslope terrace off Japan, both of which recovered abundant vein structure, are unclear seismically. Site 584 was drilled in approximately the same position as Site 440, however, and the high rate of recovery at Site 584 allows us to see the abundance of normal faults and other extensional features in the cored section. Furthermore, as argued above, the overall structure revealed by three deep holes across strike is suggestive of normal faulting on a large scale.

Conversely, vein structure is absent, or nearly so, in cores from sites that are in clearly compressional regimes, at the base of trench slopes in the Nankai forearc (Lundberg and Karig, this volume), the Barbados forearc (Cowan et al., 1984), and the Mexico forearc (Lundberg and Moore, 1982). Although these sites were not drilled to as great a depth as was Site 584, and vein structure at Site 584 was found only at depths greater than 400 m, many DSDP sites drilled on upper slopes have recovered vein structure at shallow depths (< 200 m sub-bottom). Elevated pore pressures resulting from dewatering deposits underthrust beneath the forearc should be at least as high at the toe of the slope as on the upper slope, because water content will be highest here, and yet vein structure is not observed in overlying slope deposits. One might argue that vein structure at Sites 438 and 439, the landward reference sites for the Japan transect, is related to water percolating up from the subduction zone below. This percolation effect is more difficult to argue for vein structure at Site 489 on the upper slope off southern Mexico, however, because drilling penetrated to crystalline continental crust at less than 350 m sub-bottom. These basement rocks, including schist and diorite recovered at Sites 489 and 493, are presumably impermeable in the absence of open fractures at depth, and it is not likely that a significant amount of water could migrate up from the plate interface below. On the other hand, as mentioned above, there is seismic evidence of normal faulting at Site 489. This appears to be a case of vein structure produced by extensional stresses in the absence of abnormally high fluid pressures, although unfortunately no fluid-pressure measurements are available.

Vein structure is weakly developed at Site 582, located in the Nankai Trough, in an interval of Shikoku Basin hemipelagites underlying a thick trench fill (Lundberg and Karig, this volume). This interval also exhibits healed normal faults. Both faults and vein structure have apparently been produced here by mild extension caused by lithospheric flexure, combined with high fluid pressure produced by rapid loading of overlying trench deposits (Bray and Karig, this volume).

Vein structure appears to reflect primarily extension and subsequent coaxial compression, aided in at least some cases by high fluid pressures. Once formed, veins likely serve as dewatering conduits and may be modified in the process.

The orientation of vein structure nearly perpendicular to bedding strongly suggests layer-parallel extension before tilting. Veins typically strike subparallel to bedding, with an opposite direction of dip (or in other words, the intersection of bedding and veins is a nearly horizontal line) in cores from Site 584 as well as from other DSDP sites. This observation, coupled with paleomagnetic evidence that bedding in most cores from Site 584 dips toward the Japan Trench, indicates that the initial extension that opened the veins was oriented roughly east-west (across the strike of the margin).

CONCLUSIONS

Large-scale and small-scale structures recovered and defined by drilling at Site 584 indicate that extensional and downslope, layer-parallel, shear stresses have dominated the deformational history of the upper kilometer of slope deposits at the midslope terrace. Large listric normal faults are interpreted to have tilted bedding at all three holes drilled at Site 584. Core-scale structures recovered comprise healed faults, including apparent listric normal faults and conjugate sets of normal faults, sand-filled extensional fractures, and vein structure.

Vein structure appears to be primarily a response to layer-parallel shear, although its formation was no doubt aided by presumed high fluid pressure. These can be thought of as tension gashes of a sort, as suggested by Cowan (1982), although it appears that the most common geometry is more closely analogous to second-order Riedel shears, as suggested by Helm and Vollbrecht (1985). Furthermore, at least some of the fill is altered *in situ* sediment, rather than material that has migrated in to fill void spaces.

Sequence of Deformation

The general sequence for the development of the various structural features encountered in cores from Site 584 is as follows. Near the sediment surface, primary depositional structures were extensively reworked by bioturbation throughout the section, and locally surficial slumping affected soft muds. Vein structure developed in response to downslope movement along layer-parallel shear zones, following initial consolidation of the hemipelagic muds. Locally extensional fractures were filled by sand-rich slurries. As lithification proceeded, marked by the consolidation of sand layers and the induration of mudstone to a point at which it would no longer readily disaggregate, continued extension caused more throughgoing normal faults, which appear in the cores as healed fractures. Continued extension induced offset along major listric normal faults, tilting the strata. This tilting apparently occurred episodically along growth faults throughout much of the deformation. Episodicity is required because intervals first developed vein structure and healed fractures indicative of layer-parallel extension, even though offset along the major growth faults had already begun tilting underlying strata. Following tilting of the strata, additional healed normal faults attest to continued extension. Minor reverse faults have developed in at least the lower part of the section (below 555 m sub-bottom), but unfortunately these cannot be placed with confidence into the sequence of deformational events, because of a lack of definitive cross-cutting relationships.

Comparison with Results from Legs 56 and 57

Structures in Site 584 cores may be compared with those developed in cores from sites previously drilled in the Japan forearc. Arthur, Carson, and others (1980) report systematic variations across the Japan transect in the depths to lithification (defined by the necessity to cut cores with a power saw) and to the shallowest occurrences of veins, open fractures, and healed fractures. These depths increase with increasing distance from the trench, although the shallowest occurrences are from sites that may have had hundreds of meters of overlying sediment stripped off by erosion (Sites 434 and 441; see discussion in Arthur, Carson, et al., 1980). Corresponding depths at Site 584 are shallower than at the previously drilled sites, slightly shallower than other sites on the lower slope (see site chapter, Site 584, this volume for details). A documented hiatus in the first core at Site 584 may represent deposition and erosion of several hundred meters of sediment (site chapter, Site 584, this volume), and so originally the depths to these shallowest occurrences might actually have been closer to those found at the landward reference sites. No evidence was found of an interval characterized by open fractures postulated by Arthur, Carson, and others (1980) to occur above the zone containing healed fractures at the previously drilled lower-slope sites.

The major difference in structures found at Site 584 and those found in previous sites in this forearc is the documentation of consistently steep bedding dips. Especially useful for comparison is the deep and well-recovered section drilled at Site 440, located on the midslope terrace in nearly the same position as Site 584. A compilation of true bedding dips measured in cores from Site 584 shows a much more systematic structure than that found at Site 440. Bedding dips at Site 440 do not vary regularly, in contrast to the gradual downhole increase through most of the section at Site 584. Dips at Site 584 reach a maximum of 60 to 70° at 739 to 827 m sub-bottom, below which there are intervals of varying but predominately steep bedding dip. Although dips at Site 440 locally attain 75° (Arthur et al., 1980), no intervals show consistently steep dips, and near-horizontal to shallow dips persist to the base of the hole (Lundberg, unpublished data).

Extension in Slope Deposits

Judging from patterns of tilting, faulting, and vein structure, the area drilled at Site 584 suffered extension and downslope movement of slope sediment from the middle Miocene into the early Pliocene. Much of this extension was apparently accommodated by displacement along a series of large listric normal faults, which must have rooted in a major detachment surface. Thus, at least in the upper kilometer of slope sediment, this region may have a structure that mimics that of a typical passive margin, although tilting is in the opposite sense one would expect, and the postulated listric normal faults dip landward rather than seaward. By analogy with low-angle detachment faults and superjacent tilted blocks studied in the Great Basin of the western U.S., however, there is no a priori reason to assume that the underlying detachment surface must dip in the direction opposite to the listric normal faults that lead up to the surface (Wernicke and Walker, 1982; Wernicke and Burchfiel, 1982).

Structural features in Site 584 cores suggest that an extensional regime affected at least the upper kilometer of slope deposits until early Pliocene time. Subsidence of the forearc and extension in the slope deposits may have accompanied subduction erosion at depth (von Huene et al., 1980). Drilling results of Legs 56 and 57 suggest that subsidence of the Japan forearc ended in late Pliocene time (Arthur, von Huene, et al., 1980). Uplift of the deep-sea terrace and cessation of extension in midslope deposits may reflect a major change in tectonic style during the Pliocene to one of accretion (von Huene et al., 1980). However, the underlying cause of this hypothesized change remains unknown.

ACKNOWLEDGMENTS

We thank our fellow shipboard participants on Leg 87, M. A. Arthur, E. C. Beutner, R. J. Knipe, and J. C. Moore for helpful discussion and comments. M. A. Arthur, D. S. Cowan, and W. T. Coulbourn provided helpful reviews of the manuscript. This work was funded in part by NSF grant OCE 81-10394 to J. C. Moore. Finally, we thank Gene Gonzales for skillful preparation of the ultra-thin thin sections of partially lithified muds.

REFERENCES

Arthur, M. A., Carson, B., and von Huene, R., 1980. Initial tectonic deformation of hemipelagic sediment at the leading edge of the Japan convergent margin. *In* Scientific Party, *Init. Repts. DSDP*, 56, 57, Pt. 1: Washington (U.S. Govt. Printing Office), 569-614.

Arthur, M. A., von Huene, R., and Adelseck, C. G., Jr., 1980. Sedimentary evolution of the Japan fore-arc region off northern Honshu, Legs 56 and 57, Deep Sea Drilling Project. *In* Scientific Party, *Init. Repts. DSDP*, 56, 57, Pt. 1: Washington (U.S. Govt. Printing Office), 521-568.

Byrne, T., 1982. Structural evolution of coherent terranes in the Ghost Rocks Formation, Kodiak Islands, Alaska. *In* Leggett, J. K. (Ed.) *Trench-Forearc Geology*. Geol. Soc. Lond., Spec. Publ., 10: 229-242.

__________, in press. Structural geology of melange terranes in the Ghost Rocks Formation, Kodiak Islands, Alaska. *In* Raymond, L. (Ed.), *Melanges: Their Origin and Significance*. Geol. Soc. Am. Spec. Pap.

Carson, B., von Huene, R., and Arthur, M., 1982. Small-scale deformation structures and physical properties related to convergence in Japan Trench slope sediments. *Tectonics*, 1:277-302.

Cloos, M., 1982. Flow mélanges: numerical modeling and geologic constraints on their origin in the Franciscan subduction complex, California. *Geol. Soc. Am. Bull.*, 93:330-345.

Cowan, D. S., 1974. Deformation and metamorphism of the Franciscan subduction zone complex northwest of Pacheco Pass, California. *Geol. Soc. Am. Bull.*, 85:1623-1634.

__________, 1982. Origin of "vein structure" in slope sediments on the inner slope of the Middle America Trench off Guatemala. *In* Aubouin, J., von Huene, R., et al., *Init. Repts. DSDP*, 67: Washington (U.S. Govt. Printing Office), 645-650.

Cowan, D. S., Moore, J. C., Roeske, S. M., Lundberg, N., and Lucas, S. E., 1984. Structural features at the deformation front of the Barbados Ridge complex, DSDP Leg 78A. *In* Biju-Duval, B., Moore, J. C., et al., *Init. Repts. DSDP*, 78A: Washington (U.S. Govt. Printing Office), 535-548.

Dengo, C. A., 1982. A structural analysis of cores from the Leg 67 transect across the Middle America Trench—offshore Guatemala. *In* Aubouin, J., von Huene, R., et al., *Init. Repts. DSDP*, 67: Washington (U.S. Govt. Printing Office), 651-666.

Draper, G., 1978. Coaxial pure shear in Jamaican blueschists and deformation associated with subduction. *Nature*, 276:735-736.

Durney, D. W., and Ramsey, J. G., 1973. Incremental strains measured by syntectonic crystal growths. *In* De Jong, K. A., and Scholten, R. (Eds.), *Gravity and Tectonics*: New York (John Wiley and Sons), pp. 67-96.

Helm, R., and Vollbrecht, A., 1985. Brittle-ductile shear zones in slope sediments off Guatemala, Sites 568 and 569, Deep Sea Drilling Project Leg 84. *In* von Huene, R., Aubouin, J., et al., *Init. Repts. DSDP*, 84: Washington (U.S. Govt. Printing Office), 625-632.

Hobbs, B. E., Means, W. D., and Williams, P. F., 1976. *An Outline of Structural Geology*: New York (John Wiley and Sons).

Honza, E., Kagami, H., and Nasu, N., 1977. Neogene geological history of the Tohoku Island Arc System. *J. Ocean. Soc. Jpn.*, 33: 297-310.

Lundberg, N., and Moore, J. C., 1982. Structural features of the Middle America Trench slope off southern Mexico, Deep Sea Drilling Project Leg 66. *In* Watkins, J. S., Moore, J. C., et al., *Init. Repts. DSDP*, 66: Washington (U.S. Govt. Printing Office), 793-805.

Minster, J. B., and Jordan, T. H., 1978. Present-day plate motions. *J. Geophys. Res.*, 83:5331-5354.

Nasu, N., von Huene, R., Ishiwada, Y., Langseth, M., Bruns, T., and Honza, E., 1980. Interpretation of multichannel seismic reflection data, Legs 56 and 57, Japan Trench transect, Deep Sea Drilling Project. *In* Scientific Party, *Init. Repts. DSDP*, 56, 57, Pt. 1: Washington (U.S. Govt. Printing Office), 489-503.

Ogawa, Y., 1980. Beard-like veinlet structure as fracture cleavage in the Neogene siltstone in the Miura and Boso Peninsulas, central Japan. *Sci. Rept. Dept. Geol. Kyushu Univ.*, 13:321-327.

Ogawa, Y., and Miyata, Y., 1985. Vein structure and its deformational history in the sedimentary rocks of the Middle America Trench slope off Guatemala, Deep Sea Drilling Project Leg 84. *In* von Huene, R., Aubouin, J., et al., *Init. Repts. DSDP*, 84: Washington (U.S. Govt. Printing Office), 811-830.

Quinquis, H., Audren, C., Brun, J. P., Cobbold, P. R., 1978. Intense progressive shear in Ile de Groix blueschists and compatibility with subduction or obduction. *Nature*, 273:43-45.

Shipley, T. H., 1982. Seismic facies and structural framework of the southern Mexico continental margin. *In* Watkins, J. S., Moore J. C., et al., *Init. Repts. DSDP*, 66: Washington (U.S. Govt. Printing Office), 775-790.

von Huene, R., Arthur, M. A., and Carson, B., 1981. Ambiguity in interpretation of seismic data from modern convergent margins: an example from the IPOD Japan Trench transect. *In* McClay, K. R., and Price, J. J. (Eds.), *Thrust and Nappe Tectonics*, Geol. Soc. Lond., Spec. Publ., 9:393-406.

von Huene, R., Langseth, M., Nasu, N., and Okada, H., 1980. Summary, Japan Trench transect. *In* Scientific Party, *Init. Repts. DSDP* 56, 57, Pt. 1: Washington (U.S. Govt. Printing Office), 473-488.

__________, 1982. A summary of Cenozoic tectonic history along the IPOD Japan Trench transect. *Geol. Soc. Am. Bull.*, 93: 829-846.

Wernicke, B., and Burchfiel, B. C., 1982. Modes of extensional tectonics. *J. Struct. Geol.*, 4:105-115.

Wernicke, B., and Walker, J. D., 1982. Some geometrical aspects of extensional allochthons. *Geol. Soc. Am. Abstr. Progr.*, 14:645. (Abstract)

Westbrook, G. K., 1982. The Barbados Ridge Complex: tectonics of a mature forearc system. *In* Leggett, J. K. (Ed.), *Trench-Forearc Geology*. Geol. Soc. Lond., Spec. Publ., 10:275-290.

Date of Initial Receipt: 13 January 1984
Date of Acceptance: 11 February 1985