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23. STRUCTURAL STYLE OF THE ACCRETIONARY WEDGE IN FRONT OF THE NORTH D'ENTRECASTEAUX RIDGE[1]

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ABSTRACT

Part of Ocean Drilling Program Leg 134 involved drilling in the collision zone between the North d'Entrecasteaux Ridge and the New Hebrides Island Arc. Two boreholes were sited in the forearc region and one in the indenting aseismic ridge. Sedimentary and igneous rock material from the North d'Entrecasteaux Ridge has been retrieved from the accretionary wedge of the New Hebrides Island Arc. Evidence of imbrication of thrust sheets within the accretionary wedge includes sharply bounded discrete shear zones containing highly deformed rock material consisting of tectono-sedimentary breccia, horizons of intense scaly fabric, cataclasites, and ultracataclasites; the shear zones display a decreasing dip angle and foliation planes from top to bottom. Shear indicators display reverse sense of movement. Nine major and four minor thrust zones were identified on the basis of age inversion, physical property anomalies, borehole measurements, and structural features. This large number of well-defined thrust horizons, some of which are only 20 m thick, was not encountered in any other accretionary wedge drilled to date. These features are considered characteristic of an arc/ridge collision.

INTRODUCTION

One of the major objectives of Ocean Drilling Program (ODP) Leg 134 in the central New Hebrides Island Arc (Vanuatu) was to investigate the influence of the collision and subduction of an aseismic ridge on the forearc structure and to determine the type of deformation occurring within the accretionary wedge. Several other forearc regions and subduction zones have been studied by ODP and the Deep Sea Drilling Project (DSDP); for an overview of DSDP research in forearc regions, see Moore and Lundberg (1986). The entire vertical sequence of accretionary prisms, composed of accreted sediment, basal décollements, underthrust sediment, and oceanic basement has been documented at two different locations (Leg 110, Barbados Ridge accretionary complex: Mascle, Moore, et al., 1988; and Leg 131, Nankai accretionary prism: Taira, Hill, Firth, et al., 1991). Both of the prisms studied formed as the result of accretion of sedimentary material on the oceanic basement of the subducting plate, and neither involved the collision of an indenter, such as an aseismic ridge.

The North d'Entrecasteaux Ridge-New Hebrides Island Arc collision zone, in contrast to the other studied collision zones, is characterized by the collision of an east-west oriented aseismic ridge system (which belongs to the Australia-India Plate that is being subducted beneath the Pacific Plate) with the central part of the island arc (Fig. 1). Leg 134 drilled the toe of a forearc accretionary wedge at the front of a colliding and subducting ridge for the first time in ODP history (Collot, Greene, Stokking, et al., 1992). Sites 827 and 829 were selected in the area where the North d'Entrecasteaux Ridge (NDR) underthrusts the central New Hebrides forearc (Figs. 1 and 2). They are located within the accretionary wedge near the base of the forearc slope. Site 828 is located on the plunging NDR just west of the deformation front. Previous geological and geophysical studies of this region, based on SeaBeam multibeam bathymetry, seismic reflection profiles and deep submersible surveys, are described in Greene and Wong (1988), Collot and Fisher (1989, 1991), Fisher et al. (1991), Collot et al. (1992), and Greene et al. (1992).

In contrast to other accretionary wedges drilled, the central part of the New Hebrides Island Arc is strongly modified by the indentation of the d'Entrecasteaux Zone. The collision of these aseismic ridges with the north–south-oriented New Hebrides Island Arc appears to have produced relative uplift in the central part of the arc, forming the large islands of Malakula and Espiritu Santo, which reach almost 1800 m above sea level (Mallick, 1973; Carney and Macfarlane, 1977; Carney et al., 1985), the deep North and South Aoba intra-arc basins located in front of the indenting ridge, and the uplifted elongate islands of Pentecost and Maewo (Fig. 1). Furthermore, the collision is thought to be responsible for the large number of well-defined and sharply bounded thrust sheets observed in Hole 829A, an expression of the deformation caused by the ongoing rapid indentation of the NDR into the New Hebrides Island forearc region.

In this paper we describe the style of deformation occurring on both the indenting NDR (Site 828) and in the New Hebrides forearc area (Sites 827 and 829). Core-scale structural fabrics have been previously described (Moore, 1986, and references therein; Behrmann et al., 1988; Agar et al., 1989), and a catalog of these fabrics from forearc regions was given by Lundberg and Moore (1986). We used the terminology of Lundberg and Moore (1986) for our structural observations.

The terms "scaly cleavage fabric" or "scaly foliation" (Lundberg and Moore, 1986; Moore et al., 1986) are used to describe tectonically brecciated rocks that commonly contain small (typically <1–3 cm maximum length), lens-shaped or trapezoidal phacoids of volcaniclastic siltstone, mudstone, or nannofossil ooze deformed by anastomosing fractures. They often have polished and/or mineralized surfaces that may exhibit striae. The occurrence of slikensides in our cores is taken as evidence for tectonic deformation rather than drilling disturbance. Although the rocks are intensely brecciated and faulted, in most places they still form a tight, interlocking network that displays the overall orientation of the scaly foliation. It approximates a set of anastomosing planes with dips varying from 20° to more than 60° that were present on core recovered. We therefore conclude that the scaly fabric is original rather than an artifact due to dessication. Zones of scaly fabric occur at irregular intervals, and range in width from a few centimeters to over 1 m, and they represent zones of strain accumulation. These zones may be interpreted as a result of tectonic movement where noncoaxial shearing occurred. However, although scaly fabric is a common connotation for noncoaxial shearing processes (Agar et al., 1989) we did not assume a discrete thrust zone on the basis of scaly fabric alone.

Several thrust horizons were penetrated particularly at Site 829, enabling us to make detailed structural observations. However, the active basal décollement appears not to have been penetrated with relatively poor core recovery (the total recovery rate at Site 829 was 33.4%: 13.4% from 200 to 400 mbsf [meters below seafloor], 25%

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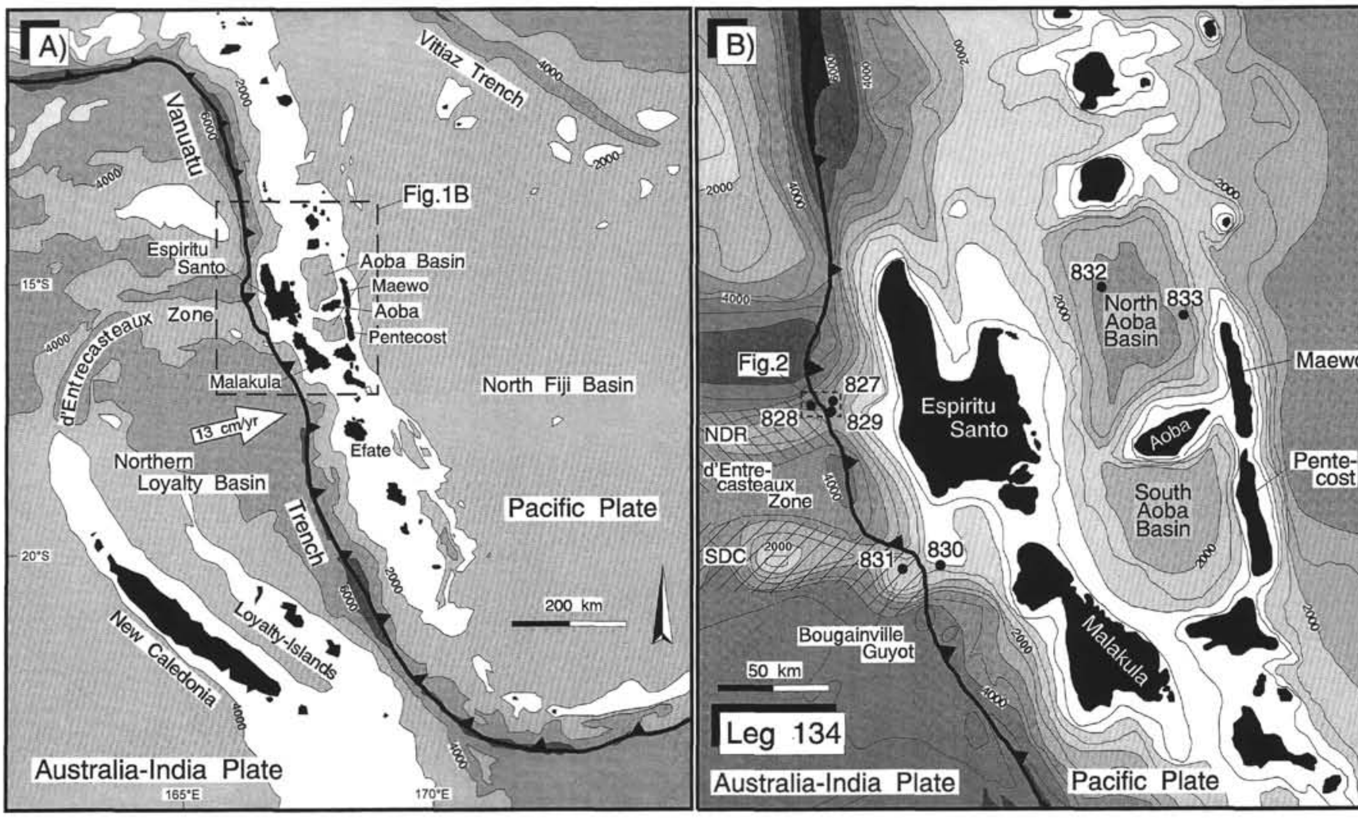

Figure 1. **A.** Bathymetric map (in meters) of the southwest Pacific (after Kroenke et al., 1983; plate motion after Taylor et al., this volume). White arrow gives relative plate convergence. **B.** Detailed bathymetric map (in meters) of the central New Hebrides Island Arc, showing location of Leg 134 sites. NDR = North d'Entrecasteaux Ridge, SDC = South d'Entrecasteaux Chain.

below 400 mbsf). Nevertheless, some excellently preserved thrust horizons were retrieved. We discuss the type, intensity, and variety of deformation found in the forearc and attempt to relate kinematic indications observed within several thrust horizons to the movement of the NDR towards the New Hebrides Island Arc.

Site 828

Site 828 is located on the northern flank of the NDR, where northwest-trending escarpments are mapped from SeaBeam bathymetric data (Collot and Fisher, 1991), and approximately 2 km west of the deformation front (Fig. 2). The stratigraphy of Site 828, which was chosen as a reference for the accretionary wegde sites, comprises Pleistocene volcaniclastic sediments and foraminiferal ooze at the top followed downhole by Pliocene foraminiferal ooze discordantly overlying Oligocene and late Eocene chalk and volcanic breccia (see Reid et al., this volume).

Conjugate small faults (e.g., Lundberg and Moore, 1986), some of them clearly indicating a normal sense of movement (Fig. 3), were found in Hole 828B in a short interval from 90 to 93 mbsf (Sections 134-828B-1R-1 and -2). Small faults typically occur as narrow sharply defined zones of displacement in which sedimentary structures are broken and sheared or the displacement zone is filled with a slightly darker material than the surrounding volcaniclastic or carbonate sediment. The amount of displacement along these faults ranges from millimeters to a few centimeters. Frequently they are conjugate or occur as sets of several faults with the same sense of movement.

These faults were reoriented using paleomagnetic data (see Pelletier et al. this volume, on the reorientation process). The reoriented strikes of the small faults are between northwest-southeast and west-northwest–east-southeast and coincide with the trend of the mapped escarpments. Based on the assumption that all faults are normal, a subhorizontal north-northeast–south-southwest extension direction with a subvertical compression axis was calculated using various mathematical and graphical methods (e.g., P-T method, Turner, 1953; right-dihedra method, Angelier and Mechler, 1977; iterative clustering method, Hardcastle and Hills, 1990; Fig. 4). Minor mineralization with slickensides on some faults indicate that the faults result from tectonic deformation rather than drilling disturbance. We interpret these tectonic features as a response to tension resulting from the bending of the ridge before subduction.

Site 827

Site 827 is located at the toe of the accretionary wedge approximately 5 km to the east of the morphological expression of the active subduction zone that separates the overriding Pacific Plate from the Australia-India Plate (Fig. 1). It is situated within a small topographic plateau (Fig. 2) that is underlain by about 100-m-thick accumulation of undeformed, horizontally bedded turbiditic siltstone and sandstone with some intercalated slump deposits that were drilled in Hole 827A. Below these turbiditic deposits inclined sedimentary strata with dip angles up to 50° were observed in Hole 827B (e.g., 134-828B-7R-5, at 32 cm), with scaly fabric observed in discrete horizons (from 150 to 250 mbsf in Cores 134-828B-6R through -15R). This indicates tectonic activity before the deposition of the turbiditic layers. We interpret the horizontal sediment beds as the result of filling of a local structural depression, which appears to have been formed by synsedimentary thrust movement within the accretionary wedge. Below 253 mbsf, relatively poor core recovery (the total recovery rate at Hole 827A is 91.1%; at Hole 827B 41.1%, with 78.7% from 110 to 253 mbsf and 5.1% below 253 mbsf) made continuous observations impossible.

A biostratigraphic inversion, accompanied by strongly developed scaly cleavage fabric restricted to a distinct 20-m-thick horizon in the

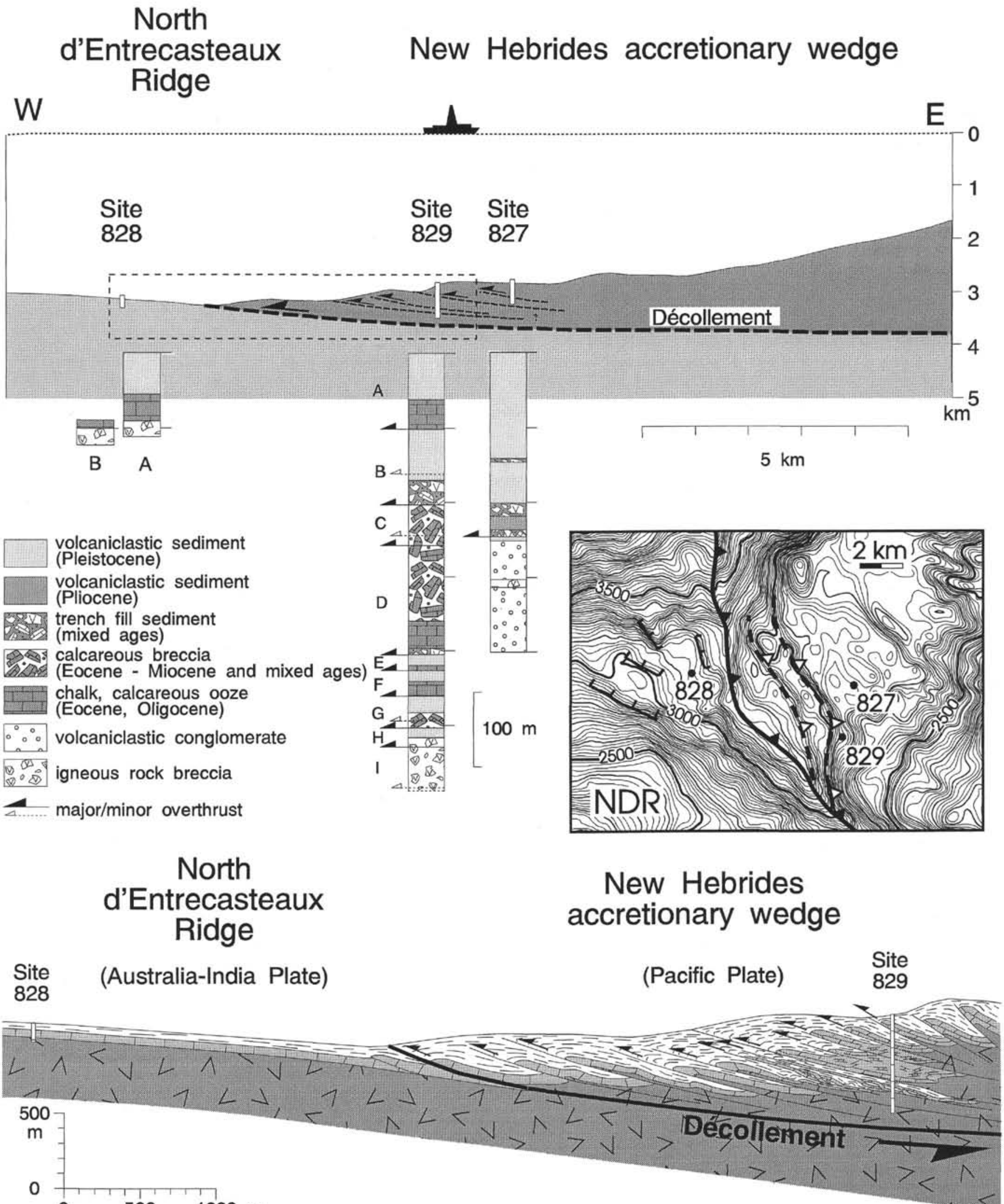

Figure 2. Simplified cross section through the New Hebrides accretionary wedge with simplified lithology and thrust horizons of Sites 827 through 829 (for more detailed lithology see Reid et al., this volume). The inset map shows a detailed bathymetry of the drilling sites (modified after Collot and Fisher, 1991). NDR = North d'Entrecasteaux Ridge. Fault scarps and overthrusts are interpreted from the topography. The lower sketch displays an idealized model of the toe region of the New Hebrides accretionary wedge.

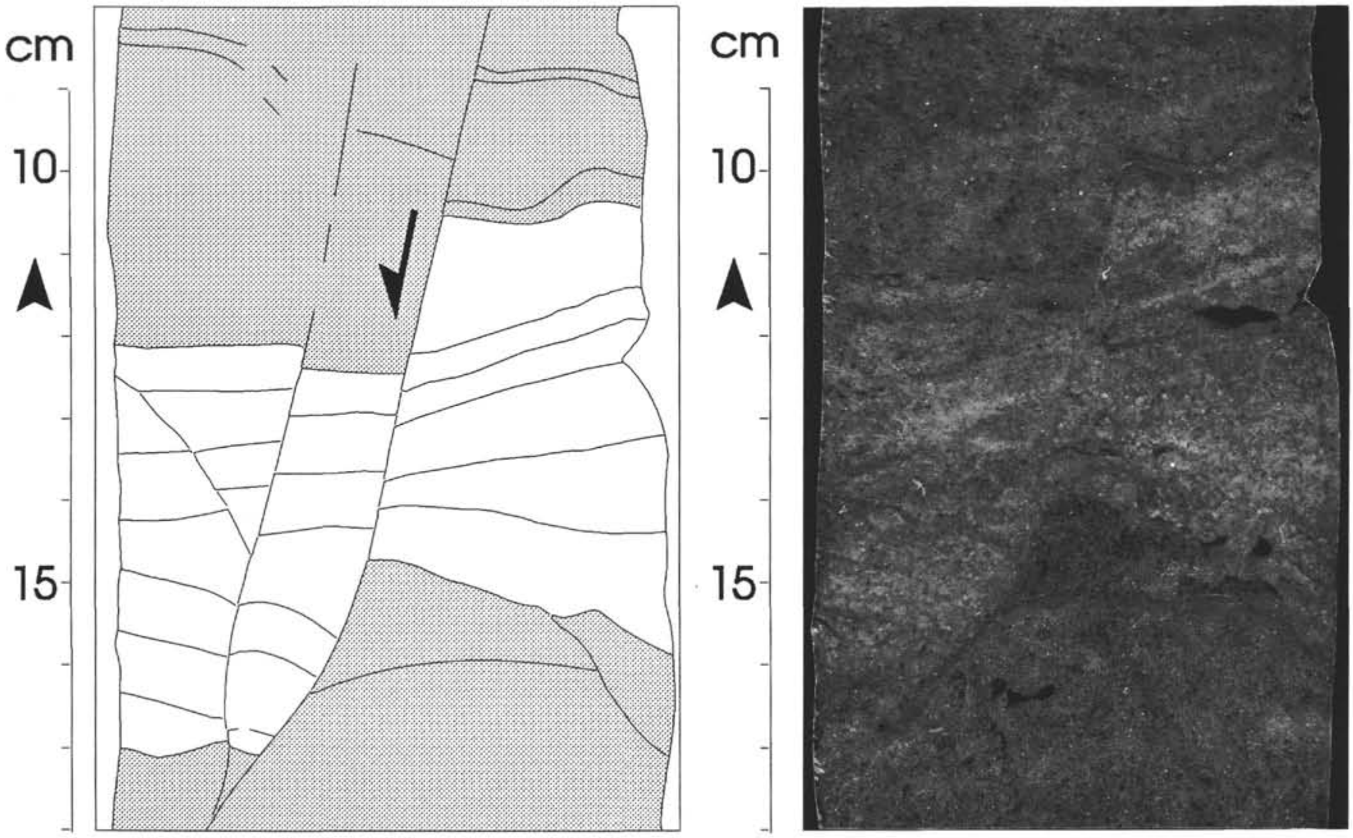

Figure 3. Sketch and photograph of conjugate normal faults in Section 134-828B-1R-6.

middle part of Hole 827B (230–250 mbsf), indicates that at least one major thrust zone was penetrated at this location. At 246 mbsf upper Pliocene sediments overlie middle to lower Pleistocene sediments (see Staerker, this volume). The dip of the scaly foliation is about 60°–70°, and thus the true thickness of the zone of deformation is <10 m. However, the azimuth of the scaly fabric planes could not be determined because paleomagnetic data were not available.

Local increases in intensity of scaly fabric indicate the accumulation of tectonic strain in Hole 827B within discrete horizons at 159 mbsf (Interval 134-827B-6R-4, 0–50 cm) and between 180 and 200 mbsf (Cores 134-827B-8R through -10R), and may define some minor thrust zones. The assumption of an overthrust at these horizons, however, is not corroborated by biostratigraphic data. As polished and striated surfaces occur on broken pieces of the scaly fabric horizons their formation is probably related to finite strain rather than to stress release of in-situ stresses (Prior and Behrmann, 1990) during core recovery. A breccia drilled between 200 and 218 mbsf in Hole 827B (Interval 134-827B-10R-5 to -12R-2) displays lithological characteristics similar to the breccia found in Hole 829A from 170 to 200 mbsf (see below), but well-preserved small (centimeter) scale shear zones or kinematic indicators comparable to those of Hole 829A were not observed. Some minor faults within Hole 134-827A indicate a reverse sense of movement (e.g., 134-827B-8R-2, at 34 cm, or 134-827B-11R-1, at 62 cm) and suggest a compressional deformation regime. Kinematic information was obtained from steps on fault surfaces or small-scale Riedel shears (Hancock, 1985; Petit, 1987). The fault surfaces are commonly polished, and some are striated. The striations consist of fine grooves that are referred to as slickensides.

The intensity of deformation although restricted to discrete horizons increases below 140 mbsf. Because of the very poor recovery below 253 mbsf, however, very little deformation (hard volcanic siltstones and sandstones with abundant microfaults filled with calcite, and some horizons of scaly fabric) was observed in the lower third of the hole (253–400 mbsf). All structures observed at Site 827 are brittle.

Site 829

Site 829 is also located at the toe of the accretionary wedge approximately 4 km to the east of the active plate boundary and 4 km to the south of Site 827 (Figs. 1 and 5). The hole drilled at this site reached 590 mbsf (Hole 829A). Although the uppermost sheared levels above the décollement zone may have been drilled (Fig. 2), the décollement itself was not penetrated due to the premature collapse of the borehole (Collot, Greene, Stokking, et al., 1992). The lithostratigraphic column of Hole 829A is very complex and contains several biostratigraphic inversions and overthrust units. Since the publication of the *Initial Reports* volume of Leg 134 (Collot, Greene, Stokking, et al., 1992) additional micropaleontological data have led to revision of the number and location of tectonic units. Based on structural observations, micropaleontological ages, and geophyscial measurements, the sequence at Site 829 was subdivided into nine composite tectonic units (Units A through I) with thicknesses ranging from about 100 m in the upper part to <20 m in the lower part of Hole 829A (Fig. 2).

Oligocene to lower Miocene calcareous sedimentary rocks and uppermost Eocene brown clay and chalks are overthrust upon Pleistocene volcaniclastic rocks. In some horizons (e.g., below the overthrust between tectonic Units F and G) Pleistocene sediments are mixed with older material including Pliocene volcanic sandstone and Oligocene chalk (Staerker, this volume). Four major thrusts were defined on the basis of distinct shear zones 0.1–3.0 m thick and were corroborated by biostratigraphic inversions. Two major and two minor thrust zones are defined by biostratigraphic inversions only. Evidence of other overthrusts is provided by structural features, physicochemical character-

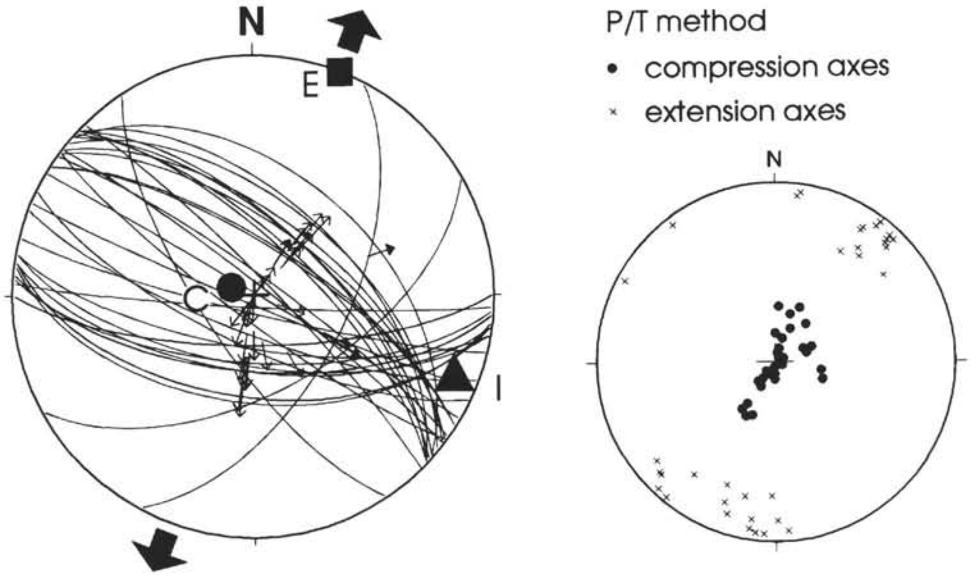

Figure 4. Reoriented conjugate normal faults in Hole 828B (Interval 134-828B-1R-1 through 1R-2). Filled arrows = faults with slickensides and known sense of movement from kinematic indicators, open arrows = faults with slickensides and/or kinematic direction assumed, C = compression axis, E = extension axis, I = intermediate axis.

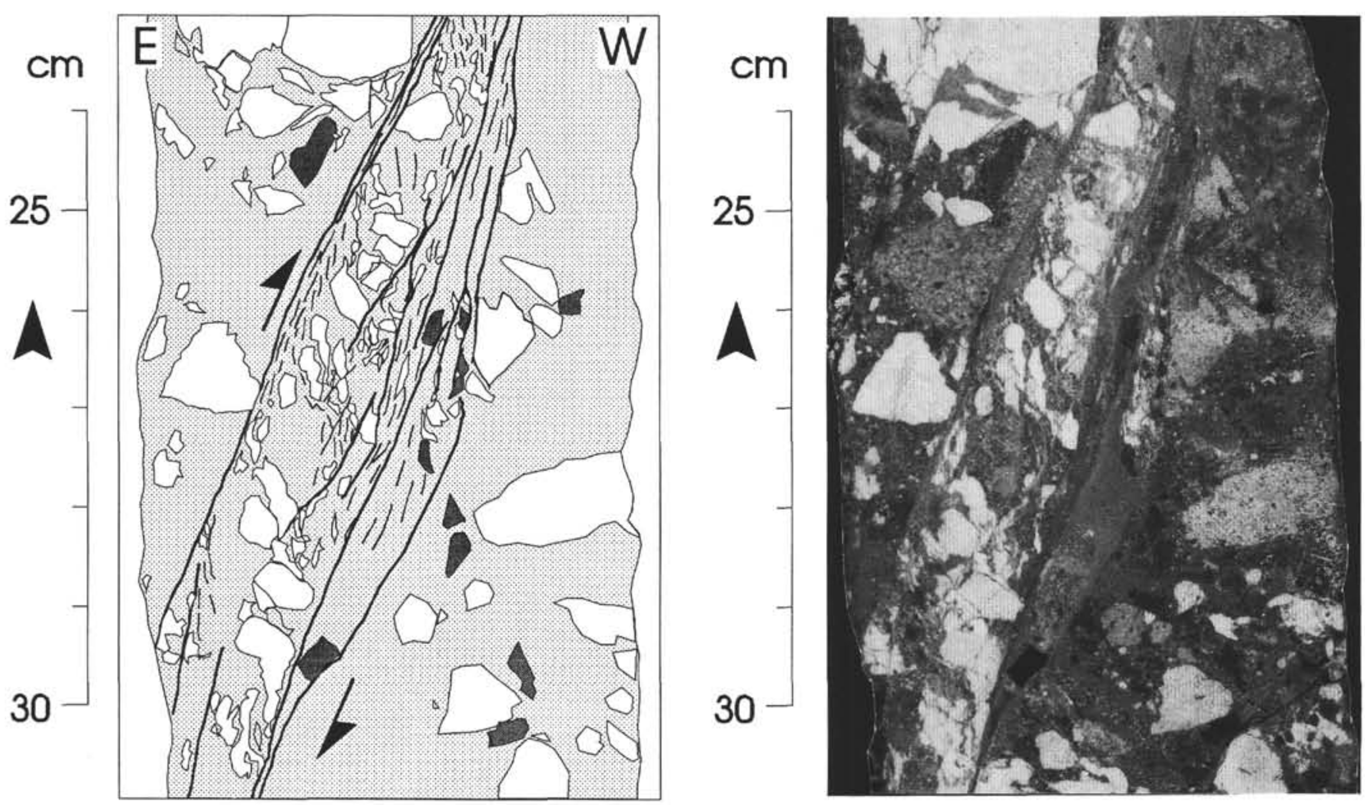

Figure 5. Brittlely deformed shear zone within zone of breccia at the base of tectonic Unit B. Sheared clasts indicate reverse sense of movement.

istics, and/or borehole imaging tools, but these cannot be confirmed paleontologically.

The contact between uppermost tectonic Units A and B at 99.4 mbsf is extremely sharp but non-planar. Undeformed Pleistocene volcanic siltstones are overlain by upper Oligocene to lower Miocene calcareous sediments which probably comprise an overthrusting unit. Structural features are very scarce and no structures at this contact can be kinematically assessed. A thin horizon above the contact consists of fine-grained breccia of probable cataclastic origin, but it does not contain kinematic indicators. The volcanic siltstone directly below the contact contains some planar structures that may indicate a first stage of scaly fabric formation or pressure solution cleavage. However, the 40-m-thick chalk assemblage above the contact may simply be a large olistolite emplaced after formation of the thrust sequence in the lower part of the hole.

A zone of breccia at the base of tectonic Unit B (from 172 to 205 mbsf) is composed of coarse-grained pieces of calcareous, sandy, and silty rocks mixed with volcaniclastic material derived from the accretionary wedge and the colliding NDR. The fossil record shows mixed assemblages of species and ages (see Staerker, this volume), with the youngest showing that the breccia formed during the Pleistocene. Deformation structures are common within the breccia. Distinct steeply inclined shear zones and small folds mostly display a reverse sense of movement indicated by bending of foliation along a 3-cm-wide shear zone (Fig. 5), bookshelve gliding of competent layers within an incompetent matrix (Fig. 6) or small folds (Fig. 7). The dip angle of all shear planes in this breccia is approximately 60° (e.g., shear planes visible in Sections 134-829A-21R-2 and -3). Sedimentary layers at the top of the breccia dip 40°–70° (e.g., in Section 134-829A-19R-3 at 45 cm). The true thickness of the breccia is therefore calculated to be <10 m. Reorientation of the shear planes using paleomagnetic measurements was possible when undisturbed intervals of the core were longer than 30–40 cm. All reoriented shear planes show similar northeast to east dip directions and thus coincide with dip directions recognized in thrust horizons at deeper levels of the hole (see below) and can be related to the general direction of compression in the NDR-New Hebrides Island Arc collision zone. We interpret the breccia as a syntectonic trench-fill sediment that was deposited within the trench at the accretionary front. This is corroborated by the identification of reworked sedimentary material from the NDR as well as from the island arc which is now mixed with Pleistocene material that was deposited coevally with the formation of the thrusts. After deposition the breccia was incorporated into the thrust zone and became deformed during the thrust movement. Deformation features observed in this breccia reflect the situation near the accretionary front where thickness of overlying sequences is still very low. Substantial overlying pressure could not develop and fluids that would facilitate the formation of zones with more intensely deformed rocks were absent.

Less than 15% of the middle part of Hole 829A (from 210 to 400 mbsf) was recovered in the cores and structures resulting from thrust movements were not observed, except in a few segments where horizons of scaly fabric could be seen (Fig. 8). Biostratigraphic data in this interval consist mainly of mixed assemblages of microfossils and are of no use in subdividing the overthrust units. However, using physical properties measurements of discrete samples (see Leonard, 1991; Leonard et al., this volume), and data from geophysical borehole tools (see Collot, Greene, Stokking, et al., 1992), thrust zones could be defined in those places where core recovery was poor or suffered drilling disturbance (Fig. 9). Thrust horizons observed at other locations in the core were compared with geohysical and logging data. We conclude that strong anomalies, which are restricted to a narrow zone and apparent in several parameters, indicate thrust horizons. In particular, a sharp short-lived increase in values of gamma-ray radiation (indicating elevated contents of clay) and increasing temperature gradient is interpreted as parameters indicating thrust horizons. In contrast, a prolonged increase or decrease in one or more parameteres is characteristic of a change in lithology (e.g., in Hole 829A at 100 mbsf where a thick layer of chalk overlies volcanic siltstone; Fig. 9). Lithologic changes are indicated particularly clearly by gamma-ray radiation, magnetic susceptibility, photoelectric factor, calcium yield, and borehole diameter. A well defined example for an overthrust horizon that is taken as reference is the boundary between tectonic Units D and E in Core 134-829A-43R (see below). It is marked by clear logging anomalies (Fig. 9) indicating elevated contents of clay that are typical for the ultracataclastic thrust horizons in Hole 829A.

Distinct anomalies are reflected by simultaneous changes in several parameters, including physical properties of individual samples. For example, at 259 mbsf in Hole 829A, we observed a decrease in bulk density, an increase in porosity, a strong temperature gradient, an increasing rate of spectral and complete gamma-ray radiation, a local increase in borehole diameter, and a decreasing photoelectric factor (Fig. 9). All these anomalies are caused by local changes in lithology (e.g., increase in clay, decrease in chalk) that are restricted to a narrow zone, and, compared to the boundary of tectonic Units D and E, are interpreted as a thrust horizon rather than as a primary change in lithology. Similar lithologies above and below this horizon are indicated by the fact that most of the geophysical and geochemical measurements do not change significantly except at this proposed tectonic boundary. We, therefore, defined one major thrust zone within the thick chalk breccia succession, subdividing the lithologically uniform unit into tectonic Units C and D at 259 mbsf (Fig. 9). The location of this zone correlates with structural observations in

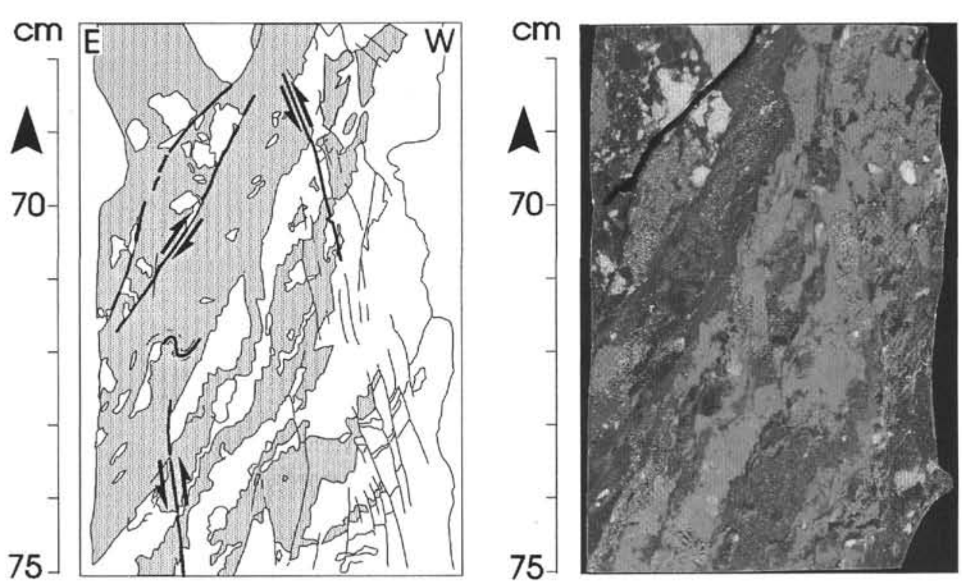

Figure 6. Shear zone with bookshelf gliding of competent layers within an incompetent matrix indicating reverse sense of movement. The sketch was made of the working half of the core whereas the photograph represents the archive half.

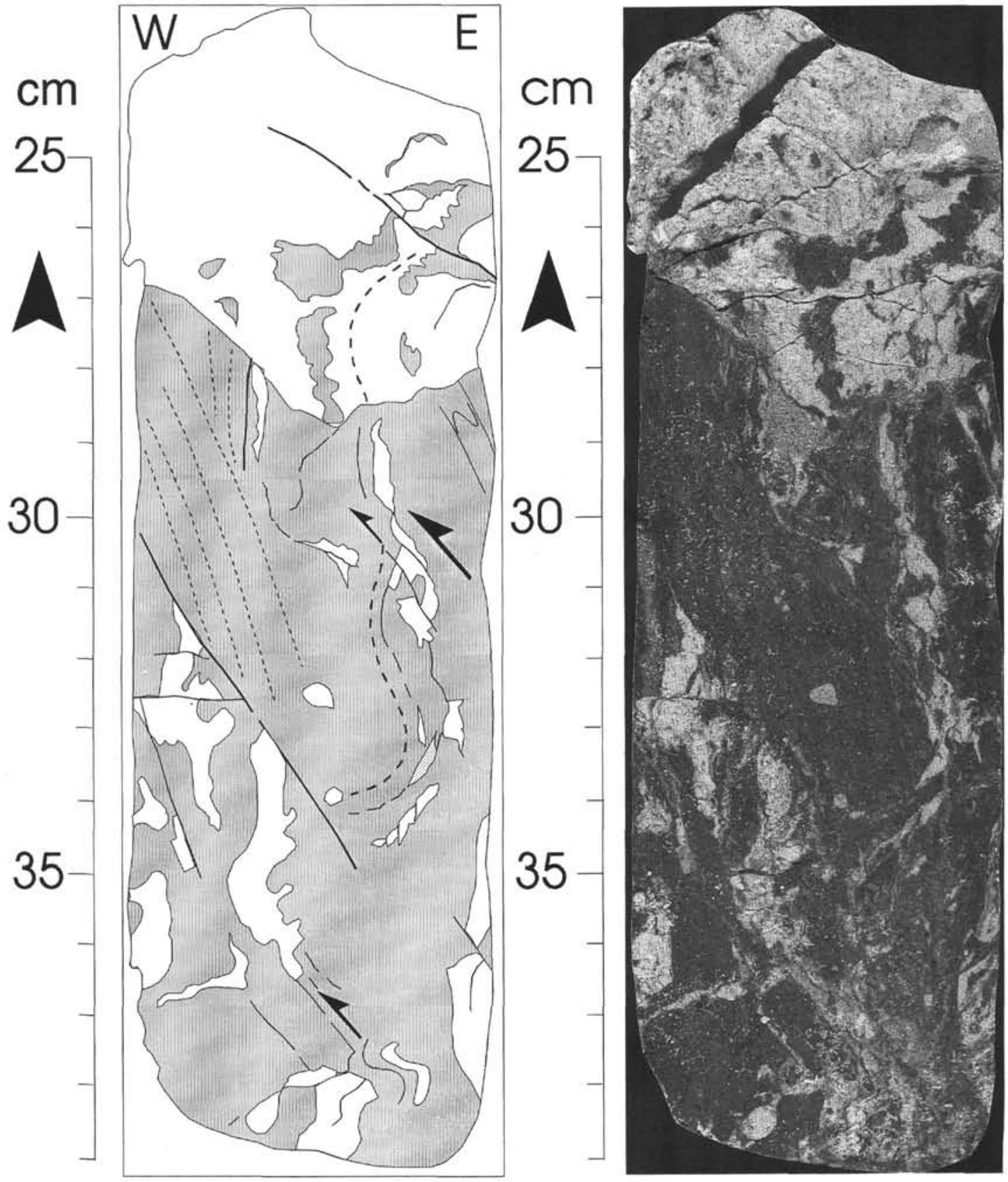

Figure 7. Small faults (solid lines), small-scale folds (widely dashed lines), and foliation (narrowly dashed lines) within zone of breccia at the base of tectonic Unit B.

Core 134-829A-28R, in which scaly fabric in chalk exhibits strongly polished surfaces, indicating tectonic brecciation and a strong accumulation of strain. The exact location of the tectonically brecciated horizon, however, is not observed in the core due to poor recovery and drilling disturbance. The Formation MicroScanner (FMS) and borehole televiewer (BHTV) data both show a strong increase in the number of observed fractures and support the assumption of a major thrust zone at this depth (Fig. 10). The majority of fractures observed with FMS or BHTV dip to the east-northeast (see Krammer et al., this volume; Chabernaud et al., this volume). Several meters above this horizon, Core 134-829A-27R (244 mbsf) contains a discrete, 0.5-m-thick zone of well-developed scaly cleavage fabric with a 40°–50° dip (Fig. 8). Reorientation of the foliation was not possible due to drilling disturbance. An increase in fractures observed by the FMS and BHTV at 245 mbsf (Krammer et al., this volume; Chabernaud et al., this volume) with a dip to the east-northeast and an increase in borehole diameter at 245 mbsf (Fig. 9) coincides with the core observation. We define this as a minor thrust horizon in order to subdivide it from better constrained thrusts. Other thrust horizons may occur at intervals with scaly fabric, but there is no supporting evidence from biostratigraphic or geophysical data.

Below 400 mbsf several thrust horizons were observed that consist of highly deformed foliated cataclasites and ultracataclasites (Wise et al., 1984) in sharply bounded narrow shear zones. Major thrust zones, indicated by foliated material occur from 398 through 401 mbsf (Core

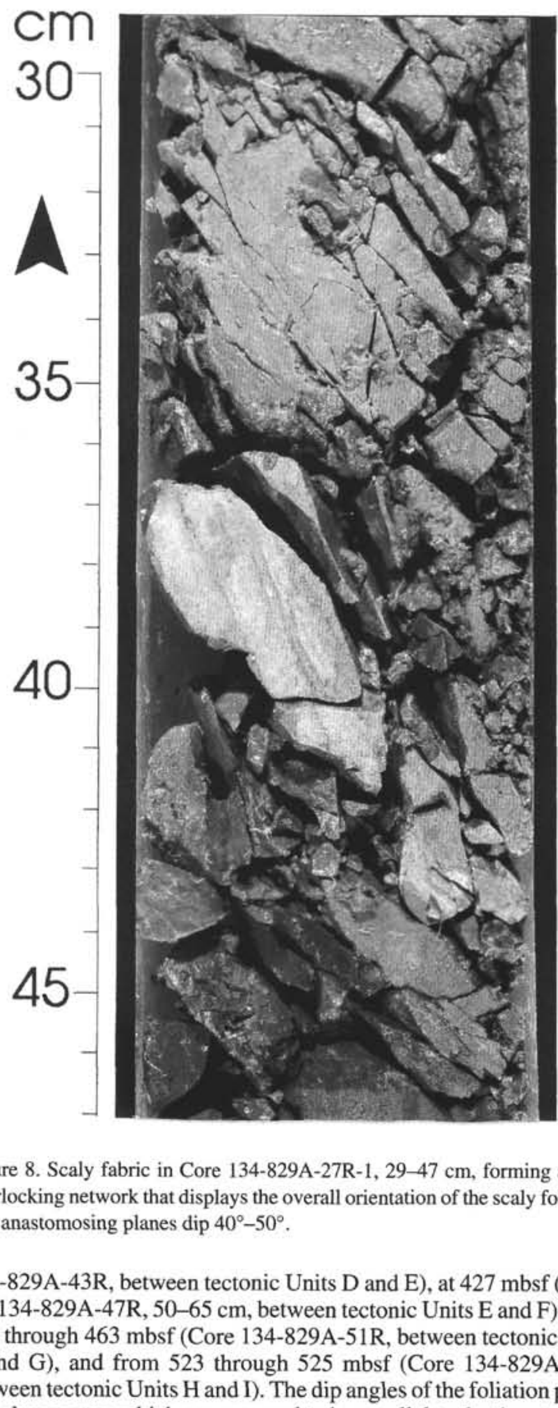

Figure 8. Scaly fabric in Core 134-829A-27R-1, 29–47 cm, forming a tight, interlocking network that displays the overall orientation of the scaly foliation. The anastomosing planes dip 40°–50°.

134-829A-43R, between tectonic Units D and E), at 427 mbsf (Interval 134-829A-47R, 50–65 cm, between tectonic Units E and F), from 460 through 463 mbsf (Core 134-829A-51R, between tectonic Units F and G), and from 523 through 525 mbsf (Core 134-829A-58R, between tectonic Units H and I). The dip angles of the foliation planes and shear zones which are assumed to be parallel to the thrust planes decrease continuously with depth from more than 60° in Core 134-829A-21R to <20° in Core 134-829A-58R (Fig. 11). The boundary between tectonic Units G and H (at the top of Core 134-829A-56R), which is constrained by biostratigraphic inversion, was not confirmed by shear structures due to poor core recovery in Core 134-829A-55R. Physical property data from discrete samples show contrasts in both bulk density and porosity on either side of the assumed boundary, indicating a change in lithology. The latter was observed in Cores 134-829A-55R and -56R as a change from calcareous rocks in the hanging wall to volcaniclastic sediments in the foot wall.

Foliation in each of the thrust zones of Cores 134-829-43R, -47R, -51R, and -58R is strongly developed within a brownish clayey matrix containing kinematic indicators that generally display a reverse sense of movement. The matrix is either a mixture of volcaniclastic and calcareous sediment derived from both hanging and foot walls of the overthrust, or it consists of volcaniclastic rocks (mostly volcanic breccia) reduced to fine-grained material, such as found in the lowermost shear zones (Cores 134-829A-58R and -64R). The foliation formed by cataclastic flow (Chester et al., 1985) with grain-size reduction of the originally coarser-grained volcaniclastic and carbonate sediments (sand, breccia) rather than by ductile shearing associated with the development of mylonitic structures. Formation of mylonites by dynamic recrystallization would require elevated temperatures; measurements in the borehole, however, do not show elevated temperatures in deeper parts of the hole (Fig. 9), and it is unlikely that the accretionary complex was ever buried to deeper crustal levels.

Shear bands in Cores 134-829A-43R and -51R (e.g., Fig. 12) dip in the most probable direction of kinematic transport and therefore display a reverse sense of movement. They indicate zones of very high strain accumulation (Simpson, 1984; O'Brien et al., 1987). Within the foliated cataclasites and ultracataclasites some rigid clasts were not completely destroyed by grain-size reduction (Core 134-829A-51R; Fig. 13). In the pressure shadow of these clasts slightly coarser-grained material (in comparison to the surrounding fine-grained matrix) persisted during the grain-size reduction. The coarser-grained material, which derived from the abrasion of the clast during the shearing process, was shaped into asymmetric tails. The outlines of these tails are similar to those known from rotated sigma clasts with asymmetric recrystallization tails observed in ductilely deformed mylonitic rocks (Simpson and Schmid, 1983; Hooper and Hatcher, 1988), from deformation experiments in a shear box (Passchier and Simpson, 1986), and from mathematical simulation experiments (Malavieille et al., 1982). The formation of tails observed in Hole 829A is most probably the result of differential cataclastic flow around the rigid clast rather than of recrystallization, since the temperatures within the accretionary wedge were not high enough to sustain recrystallization (see above). Nevertheless, the sense of movement is interpreted as analogous to that for sigma clasts described by Simpson and Schmid (1983), Passchier and Simpson (1986), Hooper and Hatcher (1988), and Malavieille et al. (1982).

Reorientation of foliation planes using paleomagnetic tools (for reorientation process see Pelletier et al., this volume) was possible in some intervals, such as in Core 134-829A-51R, where core material was unbroken and long enough to allow measurement of magnetic declination by the cryogenic pass-through magnetometer. After reorientation we obtained northeast- to east-dipping foliation planes and shear zones with a reverse sense of movement displaying the direction of overthrusting in the accretionary wedge and coinciding with the general direction of compression in the NDR-New Hebrides Island Arc collision zone. In Core 134-829A-51R further deformation is recorded by brecciation of the ultracataclasites, change of foliation dip to the west-northwest, and apparent normal sense of movement along foliation planes (Collot, Greene, Stokking, et al., 1992) However, this is probably due to local slumping or to ramp effects in a duplex rather than a significant second deformation event.

DISCUSSION

Structures found in drill cores from the NDR and the New Hebrides Island Arc forearc are mainly small faults (Lundberg and Moore, 1986), zones of tectono-sedimentary brecciation, and scaly fabric drilled in Hole 827B and in the upper part of Hole 829A. The lower part of Hole 829A is dominated by foliated ultracataclastic and cataclastic rocks. Large strain gradients could be observed between thrust horizons and thrust sheets, indicating that strain accumulates on thrust horizons while intervals between two thrust planes remain only weakly deformed by minor fracturing. Rocks at Site 828, which was drilled as a reference hole on the indenting NDR, revealed small normal faults only.

As the uppermost levels of all thrust sheets are Pleistocene in age (Staerker, this volume), the accumulation of tectonic strain observed at Sites 827 and 829, which was caused by the accretion of the NDR

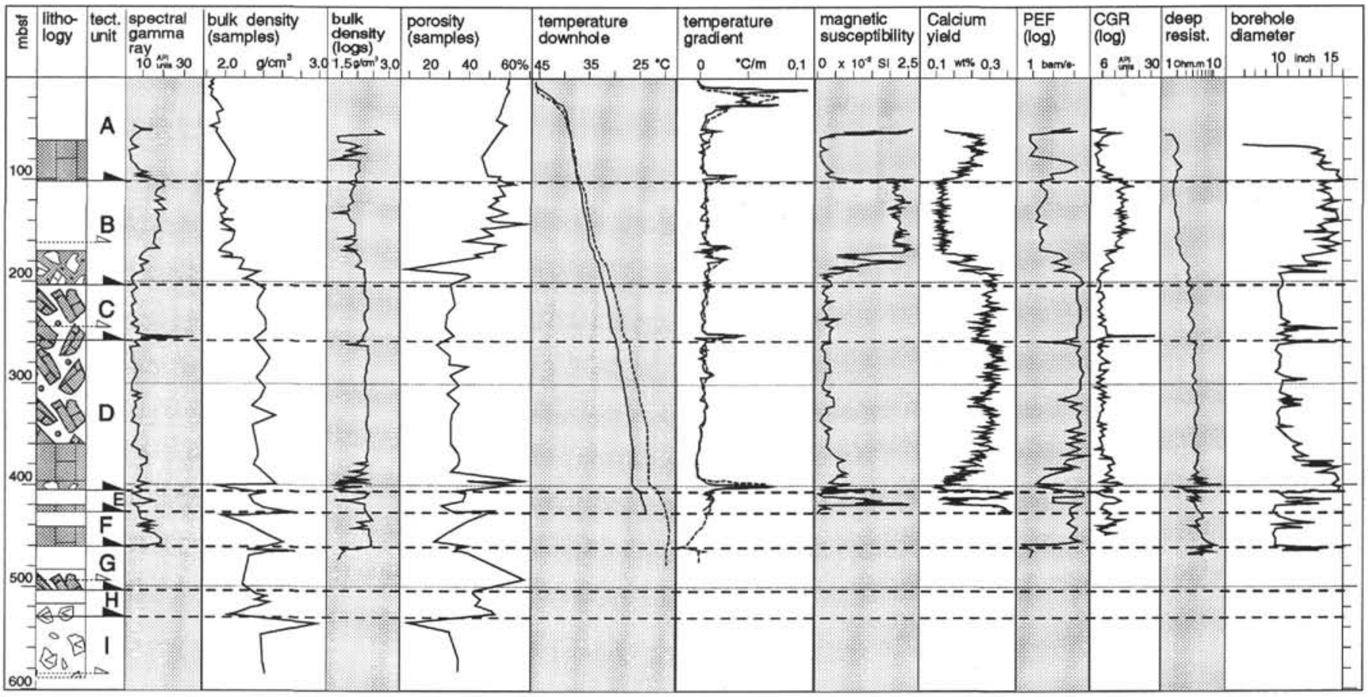

Figure 9. Comparison of measurements of physical properties on discrete samples, logs from geophysical and geochemical borehole tools, and borehole diameter indicating thrust zones at various levels in Hole 829A (data from Leonard et al., this volume; Roperch et al., this volume; and Collot, Greene, Stokking, et al., 1992). Dashed lines = separate run of the logging tool. For explanation of the column symbols see Figure 2.

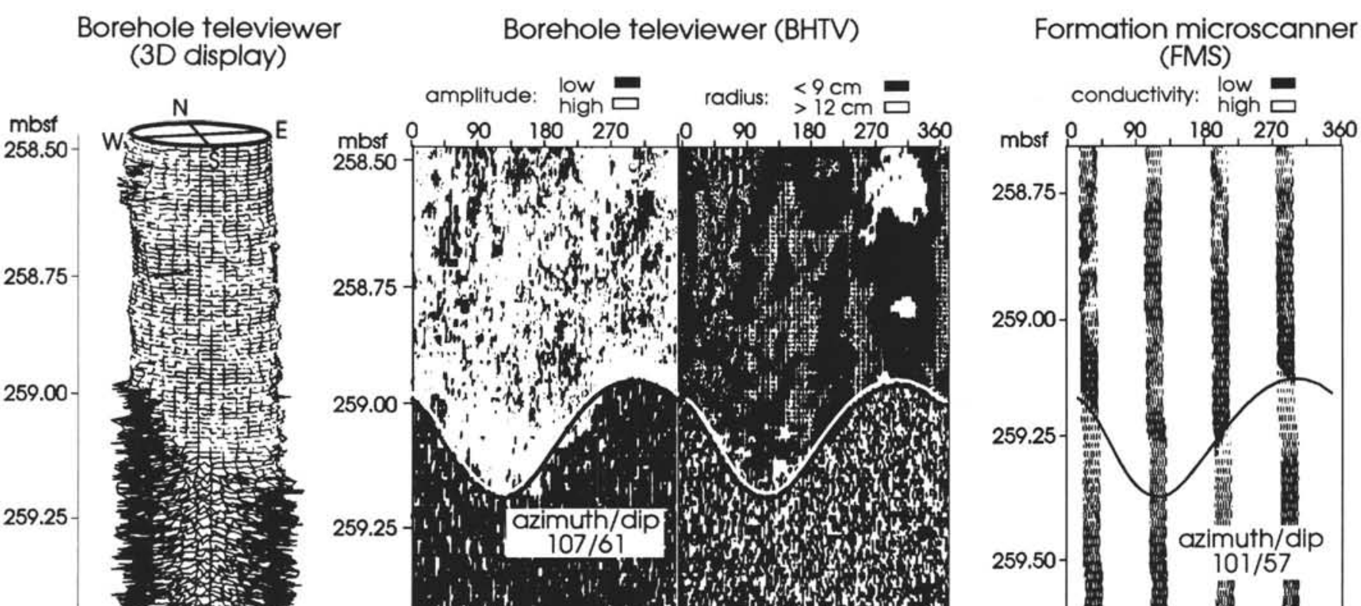

Figure 10. BHTV and FMS image from Hole 829A at 257–261 mbsf (data from Krammer et al., this volume; Chabernaud et al., this volume). The azimuth direction and inclination of the plane observed at 259.0 mbsf in the BHTV image and at 259.2 mbsf in the FMS image was calculated using a computer program. The difference in depth between BHTV and FMS images results from two separate runs of the logging tools.

onto the New Hebrides Island Arc, occurred entirely during the Pleistocene. The deeper thrust slices are assumed to be at least slightly younger than the higher ones, but this cannot be proved biostratigraphically because all tectonic movement happened within the same stratigraphic level (maximum age is 0.7 Ma). The decreasing dip angle of shear zones and foliation planes from the top to bottom of Hole 829A (Fig. 10), and the assumption that all thrust zones observed dip in the same direction, suggest imbrication of thrust sheets and an evolution similar to the classical imbricate thrust model proposed by Seely et al. (1974) where the youngest overthrust forms at the base of the accretionary complex, uplifting and tilting the older ones in the hanging wall. We speculate the following about the process of accretion and tectonic thickening that was probably enhanced by the formation of duplexes (Silver et al., 1985; Moore and Silver, 1987)

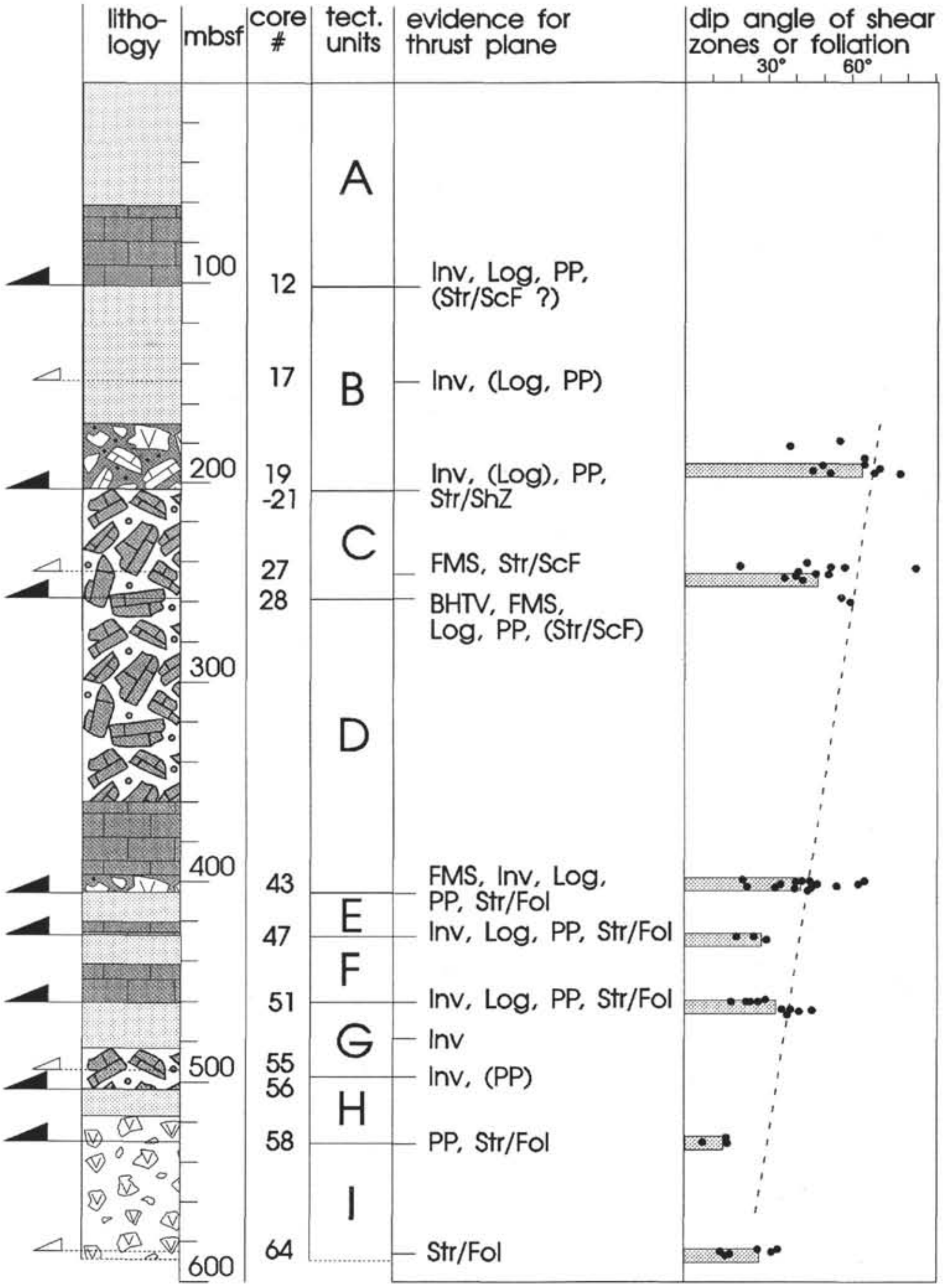

Figure 11. Evidence for thrust zones and dip angles of thrust horizons: Inv = stratigraphic inversion, Log = geophysical and/or geochemical borehole tools, PP = physical properties from discrete samples, Str = observed structures in the core (/ScF = scaly fabric, /ShZ = shear zones, /Fol = ultracataclastic foliation), BHTV = bore hole televiewer data, FMS = Formation MicroScanning data. Brackets are used when the data are not well constrained. The dip angle of shear zones or foliation is represented by data points and a mean value calcaulated from core measurements. For explanation of the column symbols see Figure 2.

and/or internal thrusting: (1) tectonic Units E and F may be interpreted as repetitions formed by a narrow duplex as they contain thin slices of nearly identical lithological packages (Fig. 5); and (2) several minor thrusts (e.g., in tectonic Unit B within a thick sequence of Pleistocene volcaniclastic sediments; Figs. 5 and 9) indicate the occurrence of tectonic thickening by small internal overthrusts.

Nine major and four minor thrust zones were identified using different parameters such as age inversion, anomalies of physical properties, borehole measurements, and structural features (Fig. 9). In comparison with other accretionary wedges drilled (Leg 110, Barbados Ridge accretionary complex: Mascle, Moore, et al., 1988; and Leg 131, Nankai accretionary prism: Taira, Hill, Firth, et al., 1991), this is a very large number of well-defined thrust horizons, and as core recovery was locally poor it is possible that we did not identify all thrust horizons occurring at Site 829. Single thrust sheets, particularly in the lower part of Hole 829A are thin and nearly devoid of fluid (see

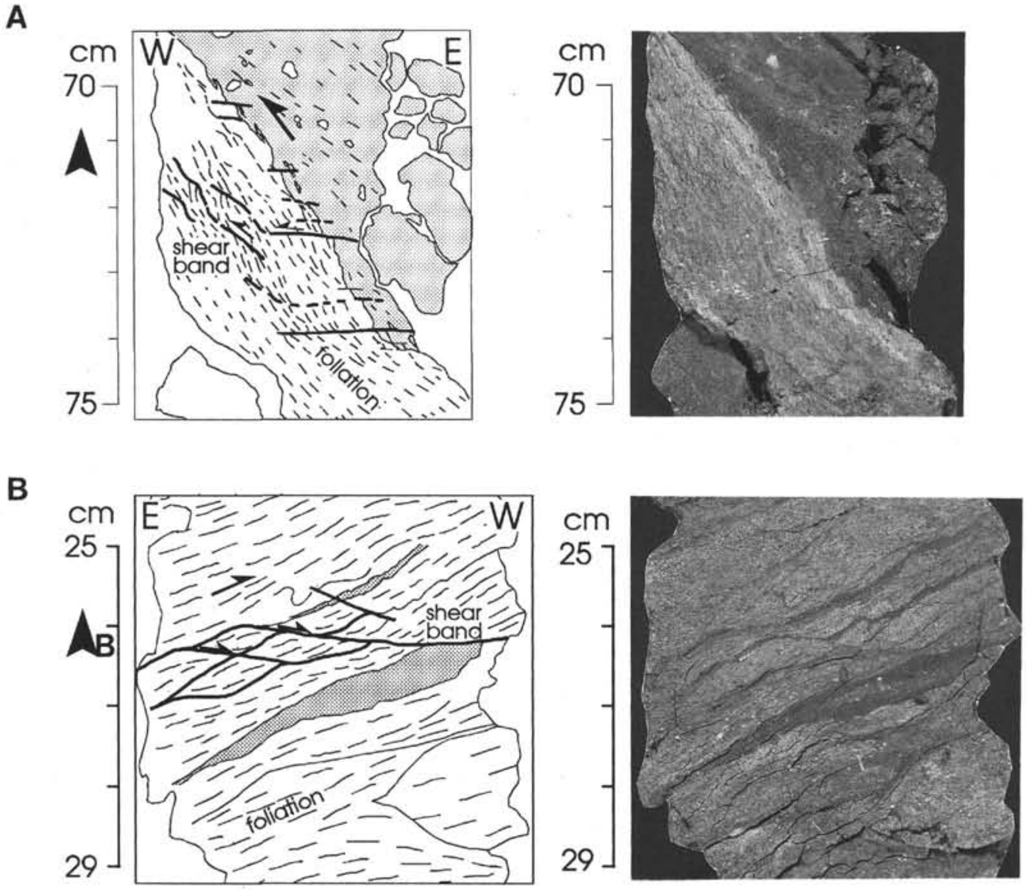

Figure 12. Foliated ultracataclasites with shear bands indicating reverse sense of movement. **A.** Interval 134-829A-43R-2, 69–75 cm (between tectonic Units D and E). The core face is oriented east-west after paleomagnetic correction. East is on the left side. Solid lines = shear bands, dashed lines = assumed shear bands. **B.** Interval 134-829A-51R-1, 24–29 cm (between tectonic Units F and G). The core face is oriented west-east after paleomagnetic correction. East is to the right.

Martin et al., this volume). Positive fluid anomalies are only observed in the neighborhood of thrust horizons and correlate with zones of high strain accumulation.

We recognized an increasing rate of strain accumulation in thrust zones with depth in Hole 829A. Thrusts in the upper part of the hole are dominated by thick horizons of brecciated rocks and coarse grained cataclasites with numerous small shear fractures where the thrust movement occurred. Tectonic movement in the lower part took place in thrust zones with fine-grained and foliated ultracataclasites of a few centimeters to 3 m thick. We suggest that most of these thrust horizons, all of which dip toward the arc, represent inactive décollement zones of earlier stages of the accretionary wedge evolution. A calculation based on the age of the thrust zones and on the relative plate motion between the NDR and the New Hebrides Island Arc of 13 cm/yr (Taylor et al., this volume), assuming a minimum age of at least 0.5 Ma for the oldest thrust sheets at Site 829, indicates a shortening of the Australia-India Plate by at least 60 km during the last 0.5 Ma. Each major thrust zone must therefore have accumulated the strain produced by several kilometers of overthrust movement. The thickness of foliated rocks may be an indication of the extent of overthrust along a thrust horizon but this, however, cannot be determined quantitatively. The upper thrust horizons representing earlier stages of the evolution of the accretionary wedge developed nearer to the subduction front and under less overlying rock material. Tectonic strain in these horizons was therefore accumulated in shear fractures rather than in zones of foliated rocks.

The breccia found at the base of tectonic Unit B was formed during accretion of the thick carbonate sequence (tectonic Units C and D).

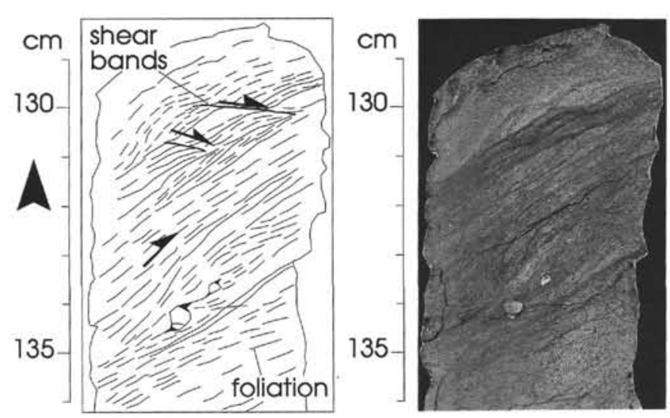

Figure 13. Foliated ultracataclasite at Interval 134-829A-51R-23, 129–136 cm, with shear bands and asymmetric tails of coarser grained material in the neighborhood of rigid clasts (between tectonic Units F and G).

Detrital chalk from the bending ridge as well as sedimentary material from the island arc were accumlated in the trench. Microfossil ages indicate influx of material from both the NDR and the New Hebrides Island Arc. The age range is similar to that found at reference Site 828 on the NDR (see Staerker, this volume). However, a middle Miocene age was not recorded at this site. This may be the result of a local unconformity on the ridge or because the middle Miocene rocks in the breccia were derived from the New Hebrides Island Arc only. After deposition the breccia suffered deformation when it became the basal décollement zone between tectonic Units B and C.

The thick carbonate sequence of tectonic Units C and D is an indication of varying sedimentary input from the DEZ in which carbonate-rich sediments alternate with volcaniclastic material. However, the extraordinary thickness of this sequence is thought to be at least partially produced due to tectonic thickening. This is suggested by the mainly mixed assemblages of species found in this sequence that may have formed in a similar way to the breccia found at the base of tectonic Unit B. Because core recovery was very poor in the carbonate rocks, we used geophysical measurements and borehole logging data to identify thrust horizons. At least one major (separating tectonic Units C and D) and one minor overthrust fault are defined by anomalies and BHTV and FMS images, some of which are supported by core observation.

During the Pleistocene the thick sequence of carbonate sediments approached the subduction zone and supplied chalk detritus to the accumulating volcaniclastic sediments in the trench. The latter were then overridden by the carbonate rocks that, according to micropaleontological data and lithological similarities, derived either from the subducting ridge or from the island arc. The variation in sedimentary input is reflected in Hole 829A by carbonate-bearing volcaniclastic rocks in the lowermost thrust units overlain by the thick carbonate sequence, which in turn is overlain by thrust sheets with volcaniclastic rocks containing considerably less carbonate material.

Deformation in the NDR-New Hebrides Island Arc collision zone seems to be more concentrated on narrow thrust horizons than is the case at plate boundaries between normal oceanic plates that have no substantial positive relief. In deeper levels of the accretionary wedge (below 400 mbsf) strain is accumulated within strongly deformed ultracataclasites and cataclasites rather than in horizons of scaly fabric. The number of thrust sheets is much higher and single thrust sheets are remarkably thin in comparision with other accretionary wedges drilled. These features are considered characteristic of an accretionary wedge in front of a colliding submarine ridge such as the NDR. The indentation of the DEZ into the New Hebrides Island Arc is also expressed by modifications of the island arc topography, producing highly elevated islands and deep back arc basins and an assumed east-vergent backthrust in the easternmost part of the arc (Collot et al., 1985; Louat and Pelletier, 1989; Tiffin et al., 1990; Greene et al., this volume) which uplifts the oblong island of Pentecost and Maewo.

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