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The Collision Zone Between the North d'Entrecasteaux Ridge and the New Hebrides Island Arc
2. Structure From Multichannel Seismic Data

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The d'Entrecasteaux zone (DEZ) collides with the central New Hebrides island arc and consists of two subparallel ridges that strike east-west, stand 1-2 km above the surrounding oceanic plate, and subduct obliquely (15°) northward beneath the arc. Rocks dredged from the north ridge as well as reflections evident in multichannel seismic reflection data indicate that this ridge has a volcanic origin. Crystalline volcanic rocks are common along the lower flank of the ridge, but sedimentary, probably volcaniclastic, rock caps the ridge. Seismic reflection data collected over the lower arc slope reveal that mass wasting deposits locally make up most of the accretionary wedge. These deposits appear to form discrete bodies, suggesting that mass wasting occurred episodically. Large anticlines and thrust faults having large vertical separation are not readily evident where the colliding ridge intersects the arc slope; apparently, slope rocks have low strength so that mass wasting deposits formed instead of large-relief structures. Mass wasting is thought to occur as the accretionary wedge is uplifted in response to the northward oblique subduction of the north ridge. The toe of the north ridge flank marks an abrupt transition in the lithologies that make up the footwall of the interplate decollement. Footwall lithologies change from ocean basin to volcaniclastic ridge material, and this transition probably marks a discontinuity in friction along the decollement or in rock mechanical properties because north of the transition, thrust faults deform the accretionary wedge whereas south of the transition, steep reverse faults crosscut the wedge and pierce the north flank of the ridge. This piercement means that the decollement at least locally lies within the ridge and that ridge material exotic to the New Hebrides arc may be incorporated into the accretionary wedge.

INTRODUCTION

The New Hebrides island arc forms part of the sinuous tectonic boundary that separates the Australia-India plate on the west from the North Fiji basin and Pacific plate on the east (Figure 1). Numerous high-standing features surmount the Australia-India plate and range in size from isolated seamounts to extensive submarine plateaus and mountain chains. One such chain, the d'Entrecasteaux zone (DEZ), extends northward from New Caledonia, curves eastward, and collides with and is subducted beneath the central New Hebrides island arc [*Daniel and Katz*, 1981; *Collot et al.*, 1985; *Marthelot et al.*, 1985]. In this report we describe the tectonics of this collision zone.

Previous reports concerning the structure of rocks within the accretionary wedge of the New Hebrides arc [*Fisher*, 1986; *Fisher et al.*, 1986] described the tectonic consequences of the DEZ-arc collision as interpreted solely from migrated multichannel seismic reflection sections. Since these reports, French scientists resurveyed the collision zone, obtaining single channel seismic reflection, gravity and magnetic data as well as crucial, detailed Sea Beam bathymetric information. An integrated interpretation of all data sets provided new insight into the tectonics of the collision zone and forms the foundation for this report as well as its companion [*Collot and Fisher*, this issue]. The companion report describes how deformation of the accretionary wedge is expressed in seabottom morphology and in the structure of shallow rocks; the report relies primarily on Sea Beam and single-channel seismic reflection data. In contrast, this report deals little with shallow features but draws heavily from migrated multichannel seismic reflection sections to focus on the deep structure within the accretionary wedge and the DEZ.

The earlier reports concerning the accretionary wedge [*Fisher*, 1986; *Fisher et al.*, 1986] described the apparent absence from the collision zone of large folds and thrust or reverse faults having large vertical offset. We aim to show, however, that some stratigraphic and structural features revealed by multichannel seismic sections demonstrate the previously unrecognized, pervasive influence exerted by mass wasting on the stratigraphy and structure of the accretionary wedge. We show, moreover, that the style of forearc deformation is complicated by abrupt changes in lithologies juxtaposed by the interplate decollement, which lies chiefly within and on top of subducted ocean basin sediment but locally lies along the flanks and crest of the subducted DEZ.

In this report we reserve the word "slope" to refer to the west dipping surface of the accretionary wedge of the island arc, whereas "flank" refers to the north and south dipping

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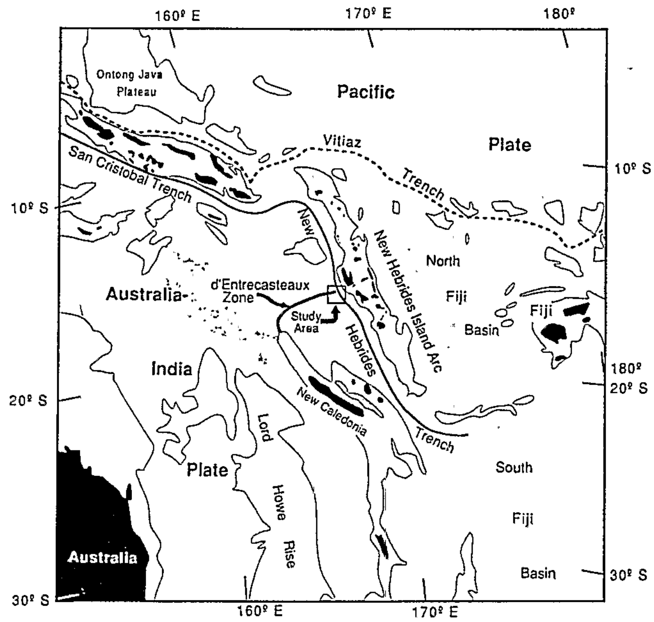

Fig. 1. Geography and main tectonic features of the southwest Pacific region.

faces of the DEZ. We use the term "ridge" to denote largely aseismic, linear mountains rather than spreading ridges. Near the New Hebrides island arc, two parallel, east-west trending ridges comprise the DEZ and are involved in the collision (Figures 2 and 3*a*). This report describes the tectonics of the collision that involves the northern ridge; the collision involving the southern ridge forms grist for another report.

GEOPHYSICAL DATA

During 1982 and 1984, a team of scientists from Australia, France, New Zealand, and the United States aboard the U. S. Geological Survey research vessel the R/V *S.P. Lee* collected gravity, magnetic, seismic refraction, and multichannel seismic reflection data over the arc-ridge collision zone (Figure 2). Seismic reflection data were obtained using a 2400-m, 24-channel streamer that has a group interval of 100 m. A tuned array of five air guns with a total volume of 24.4 l was fired every 50 m, yielding 24-fold data. These data were recorded using a GUS 4200 digital system. Stacked and migrated sections were produced with a DISCO (trademark of Cogniseis Development) seismic data processing system. The main processing steps included velocity analysis using semblance estimation, stacking, migration with a finite difference program, and filtering. Migration velocities were selected by migrating stacked data with several constant velocities and with stacking velocities reduced by 10-20%. Cross sections through the collision zone were made from digitized line drawings of migrated seismic sections.

During 1985, Sea Beam bathymetric, singlechannel seismic, gravity and magnetic data were obtained aboard the French research vessel the N/O *Jean Charcot*. This report's companion [*Collot and Fisher*, this issue] includes a detailed analysis of these data.

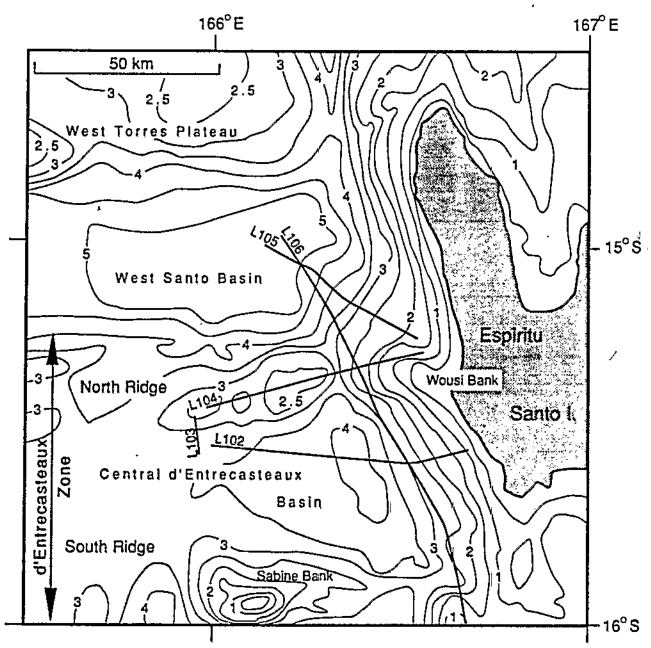

Fig. 2. Bathymetry and geography of the study area as well as track lines of multichannel seismic data collected over the collision zone of the d'Entrecasteaux zone with the New Hebrides arc. Lines numbered L102 - L106 denote multichannel seismic reflection sections.

REGIONAL SETTING

Geographic features on the Australia-India plate that have particular importance to this report include the West Torres Plateau, the DEZ, and the deep-ocean West Santo and Central d'Entrecasteaux basins (Figures 3a and 4). The poorly known West Torres plateau lies 50 km north of the DEZ. Much of the plateau underlies water shallower than 2000 m; local areas are as shallow as 900 m. Although data concerning this plateau are scarce, it may be similar geologically to other oceanic plateaus, under the southwest Pacific Ocean, that have been described by *Hussong et al.* [1979]. The plateau is separated from the New Hebrides island arc by the northern part of the New Hebrides trench, which is locally as deep as 8000 m. Seismic reflection sections do not show clearly whether part of the plateau has been subducted.

The West Santo basin lies just south of the West Torres plateau and contains about 1 km of sediment. In north-south cross section this basin is strongly asymmetric, in that its thickest fill lies adjacent to the north ridge of the DEZ.

The DEZ borders the West Santo basin on the south. Near New Caledonia the DEZ consists of a main ridge, which stands about 1.5 km above the ocean floor, as well as other parallel ridges that exhibit considerably less relief. All ridges are thought to be horsts, of Eocene oceanic crust, that may have formed since the middle Miocene [*Maillet et al.*, 1983; *Collot and Fisher*, 1988]. Near the New Hebrides arc the main ridge of the DEZ forks into two parallel, east-west trending ridges that stand 1-2 km above the level of the abyssal plain. In Figure 3a, these ridges appear to have steep-sided relief, an appearance that results from the 5:1 vertical exaggeration used to emphasize subtle submarine features. In fact, the ridges have gentle slopes, as shown by the same bathymetric information presented without exaggeration (Figure 3*b*). Together, the two ridges of the DEZ and the lower slope of the island arc encircle the Central d'Entrecasteaux basin (Figures 3 and 4), which contains horizontally bedded fill that totals about 1 km in thickness.

The azimuth of relative convergence between the DEZ and the island arc is constrained by focal mechanism solutions for

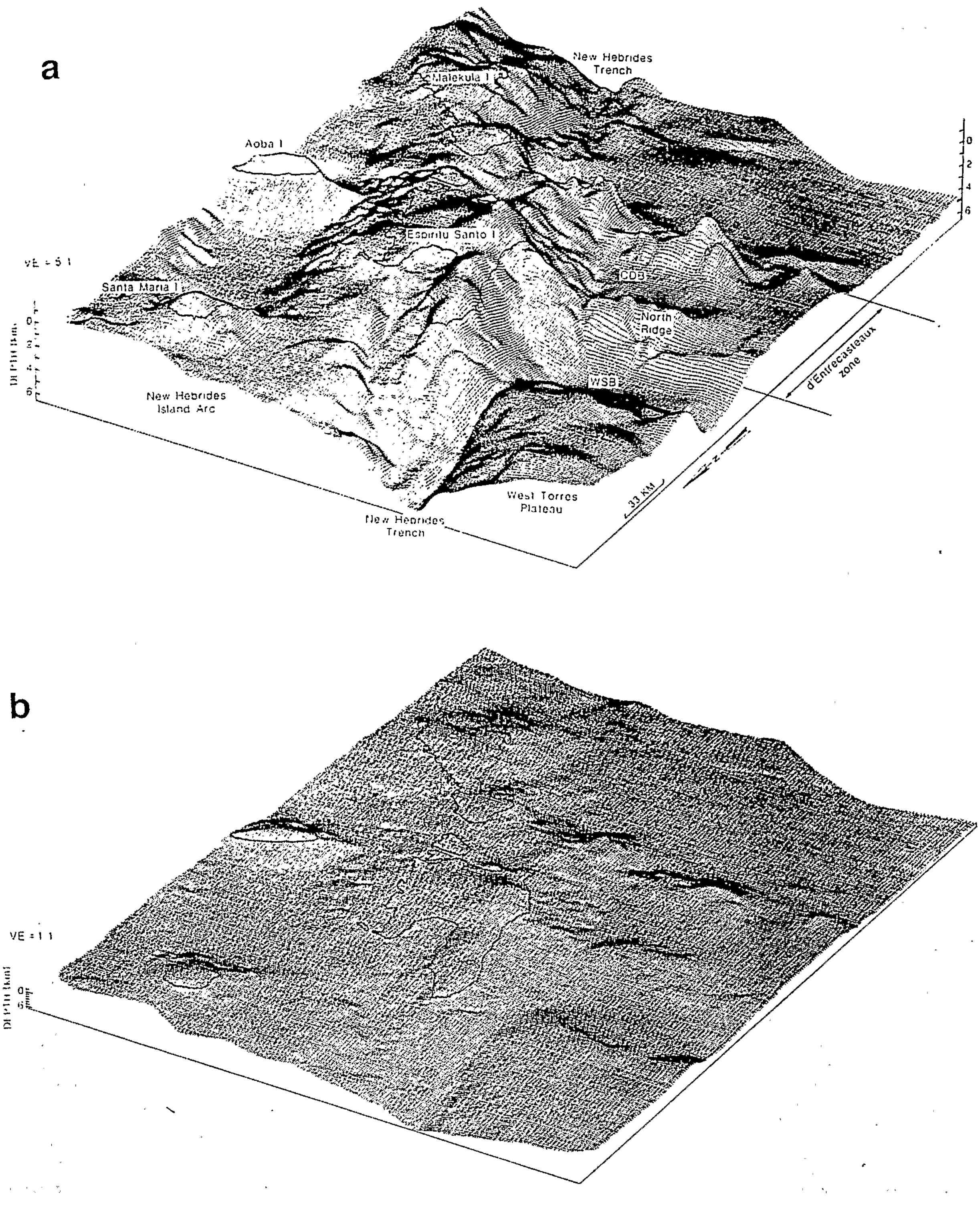

Fig. 3. Bathymetry [T.E. Chase et al., unpublished reports 1983] of the arc-ridge collision zone and topography of islands that neighbor this zone. View is from northeast to southwest from a point elevated 30° above the horizontal. To show small features of the bathymetry, Figure 3*a* has a vertical exaggeration is 5:1; to portray the correct size of features, Figure 3*b* has a vertical exaggeration of 1:1. WSB, West Santo basin; CDB, Central d'Entrecasteaux basin.

subduction-zone earthquakes that have thrust fault first motions [*Pascal et al.*, 1978; *Isacks et al.*, 1981]. The convergence direction is N 76° E, nearly perpendicularly to the arc (Figure 4). Owing to plate motion within the North Fiji basin [*Chase*, 1970; *Malahoff et al.*, 1982; *Auzende et al.*, 1988], the convergence rate at the New Hebrides trench is less well known (5-20 cm/yr) than is the azimuth. We assume a convergence rate of 10 cm/yr, in accordance with models of global plate motion [*Minster and Jordan*, 1978; *Doutch*, 1981]. Thus, although the obliquity of the relative motion between the Australia-India plate and the New Hebrides arc amounts to only 15°, the ridge scrapes northward, parallel to the trench, at about 2 cm/yr. As

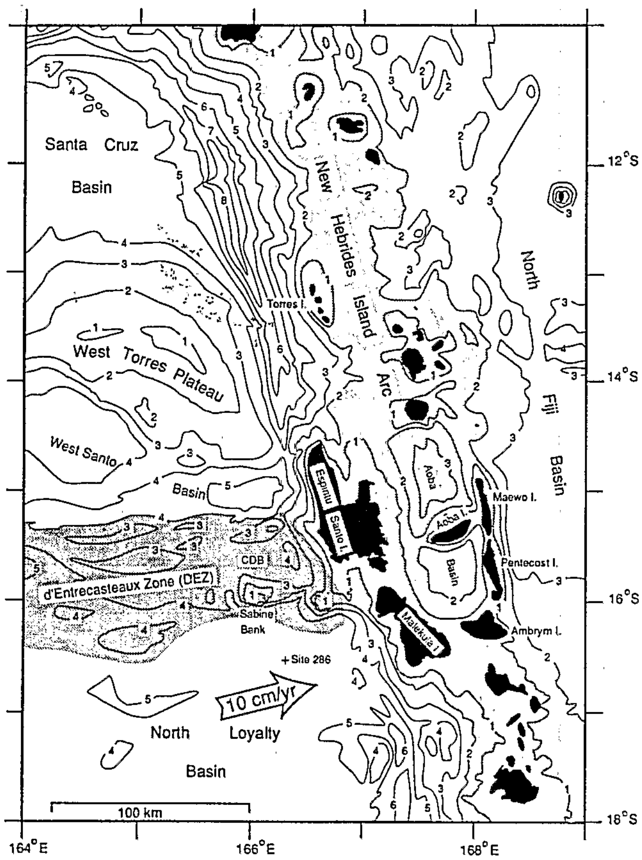

Fig. 4. Region of the collision zone between the d'Entrecasteaux zone and the central New Hebrides island arc. CDB, Central d'Entrecasteaux basin.

we discuss below, this oblique motion exerts considerable influence on the structure of the accretionary wedge within the collision zone.

Previous work in the New Hebrides island arc has already established the main offshore tectonic features of this arc [*Karig and Mammerickx*, 1971; *Luyendyk et al.*, 1974; *Ibrahim et al.*, 1980]. From shore-based investigations, the bulk of the island arc appears to be early Miocene and younger in age [*Mitchell*, 1966, 1971; *Robinson*, 1969; *Mallick and Greenbaum*, 1977; *Carney and Macfarlane*, 1978, 1982; *Greene et al.*, 1988; *Macfarlane et al.*, 1988]. Oligocene(?) rocks outcrop in small isolated areas, but lower Miocene volcanic and volcaniclastic units are exposed commonly on islands scattered along the length of the arc. These Miocene units are highly indurated and typically include poorly bedded, coarse, volcanic agglomerates, breccias and lava flows. Espiritu Santo and Malekula Islands adjoin the collision zone (Figures 3*a* and 4) and expose lower Miocene units that are overlain unconformably by strata of middle Miocene and younger age. The overlying rocks, which are considerably less indurated than are older strata, consist primarily of sandstone, siltstone, and calcareous deposits.

Discontinuous Quaternary reef terraces mantle the western escarpments of mountainous Espiritu Santo and Malekula Islands and record rapid late Quaternary terrace uplift (2-6 mm/yr [*Jouannic et al.*, 1980, *Taylor et al.*, 1980, 1985, 1987]). This uplift, may result as the upper plate of the subduction zone overrides subducted features on the oceanic plate [*Taylor et al.*, 1980, 1985, 1987]. The Torres Islands, which lie north of the collision zone (Figure 4), have undergone comparatively slower uplift [*Taylor et al.*, 1985].

Sea Beam bathymetric data collected over the accretionary wedge within the collision zone show the main features of shallow deformation caused by subduction of the north ridge (Figure 5)[*Collot and Fisher*, this issue]. Wousi Bank, an unusual circulate high that projects about 1000 m above the upper arc slope, is capped by reefs and lies along the eastward extension of the north ridge beneath the accretionary wedge and island. The seafloor neighboring this bank is interrupted on the north and south by steep bathymetric scarps that strike subparallel to the flanks of the exposed part of the north ridge and appear to be normal faults. The accretionary wedge has highly irregular, small-scale features, whose arcuate shape suggests widespread mass wasting.

OVERVIEW OF COLLISION ZONE STRUCTURE

In this overview section we briefly summarize the main structural features that are revealed by multichannel seismic reflection data collected over the collision zone. Depth converted line drawings of seismic sections that depict this structure (Figures 6*d*, 8*d*, and 9*d*) and were produced using interval velocities that were calculated from seismic reflection data. Such velocities are prone to substantial error due not only to the relatively short (2400 m) streamer used to record seismic reflection data but also to the high density of diffractions commonly produced by rocks within accretionary wedges. Nonetheless, the velocity distribution within this accretionary wedge appears to be unusual in that rocks having high velocities (3-4.5 km/s) extend westward from the islands of this arc to within 1-3 km of the toe of the accretionary wedge. The only verification for this velocity distribution is that it successfully removes obvious distortion of reflections on time sections. For example, along line 105, apparently thick ocean basin sediment that lies northwest of the accretionary wedge bulges downward below the toe of the wedge and then thins sharply to the southeast to merge with an apparently thin section of accreted and subducted rocks (Figure 6*a*). After the distortion caused by lateral and vertical velocity gradients is removed from the migrated seismic data (Figure 6*d*), the structure of the lower accretionary wedge below line 105 appears similar to that of other wedges.

North of the ridge the accretionary wedge deforms as the ridge moves slowly northward. Seismic section 105 and the northern one-third of section 106 cross this area of the wedge (Figure 7) and are nearly perpendicular to the azimuth of arc-ridge convergence. The West Santo basin extends eastward beneath the accretionary wedge and pinches out abruptly southward against the north ridge. This pinchout delimits an abrupt lithologic discontinuity, from ocean basin to ridge rocks, that occurs in the footwall of the interplate decollement.

Seismic section 104 crosses the unsubducted part of the north ridge as well as the part of the accretionary wedge that is perched ontop of the subducted ridge (Figure 7). This seismic section shows that the ridge crest has low relief and can be traced for 12 km beneath that part of the accretionary wedge that bears the full brunt of the collision. The interpreted ridge top dips only shallowly (2-3°) toward the arc (Figure 8*d*), despite the high velocities (about 3.5 km/s) used to convert time to depth. A shallow, thin sediment layer and the decollement produce coherent reflections, but accreted rocks are mainly nonreflective.

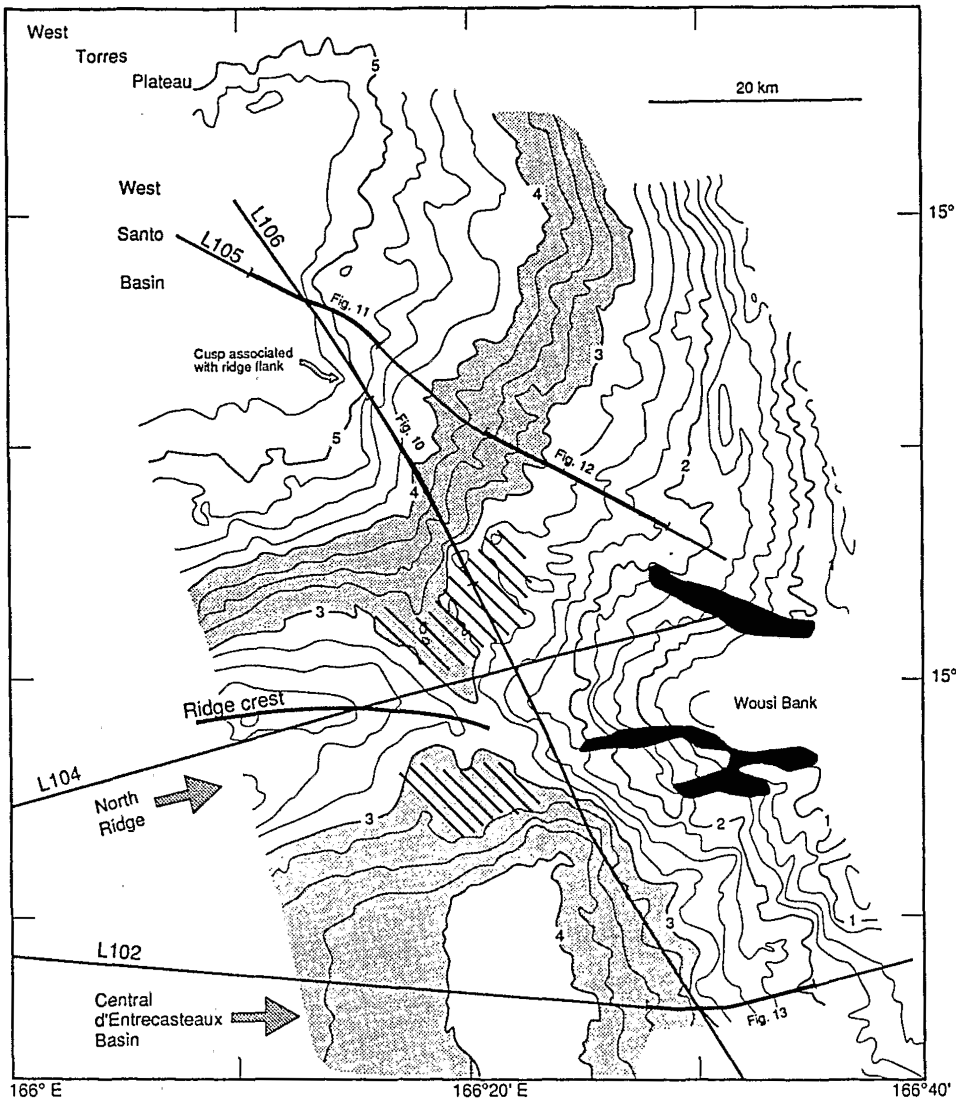

Fig. 5. Sea Beam bathymetry of the arc-ridge collision zone. Cross hatching indicates flat areas along the crest of the north ridge. Black indicates steep seafloor scarps that are probably normal faults. Lines numbered L102-L106 denote multichannel seismic reflection sections.

South of the ridge, seismic section 103 (Figure 7) crosses northward from the Central d'Entrecasteaux basin to near the ridge crest and shows that highly reflective basin fill thins onto the south flank of the ridge. A similar thinning of subducted basin deposits occurs beneath the accretionary wedge, as shown on seismic section 102 (Figure 9). This pinchout of ocean basin sediment against the ridge flank probably marks a mechanical discontinuity in the rocks juxtaposed along the interplate decollement.

EVOLUTION AND GEOLOGY OF THE NORTH RIDGE OF THE DEZ

Geologic and Geophysical Data

The geology of the north ridge is known primarily from rock samples dredged about 150 km west of Espiritu Santo Island [*Maillet et al.,* 1983]. Samples ripped from the lower flank of the north ridge include primarily mid-ocean ridge basalt (MORB) that yields a corrected fission track date of 56 Ma (site GO314 D of *Maillet et al* [1983]). Scarce samples of claystone and mudstone were also recovered. Rock fragments dredged from near the summit of the ridge (site GO315 D) contain abundant mudstone and claystone fragments and subsidiary, undated basalt samples. Dredge hauls located 200-400 km west of Espiritu Santo Island revealed much MORB, some of which has a corrected fission track age of about 36 Ma, and less common fragments of sedimentary rock, none of which has been dated. Thus dredge data indicate that Eocene MORB is commonly recovered from along the ridge flanks, and undated, fine-grained sedimentary rocks were obtained near the ridge crest.

Geophysical information collected over the ridge includes gravity and magnetic data as well as seismic refraction and reflection information. A low-relief (200-300 nT) magnetic anomaly parallels the north ridge but is offset northward from the ridge [*Collot and Fisher,* this issue], in accordance with the direction of the present magnetic field. Modeling these data suggests that ridge rocks have a low bulk magnetic susceptibility (0.0015 G) [*Collot and Fisher,* this issue]. Our modeling of gravity data indicates that most of the gravity anomaly mea-

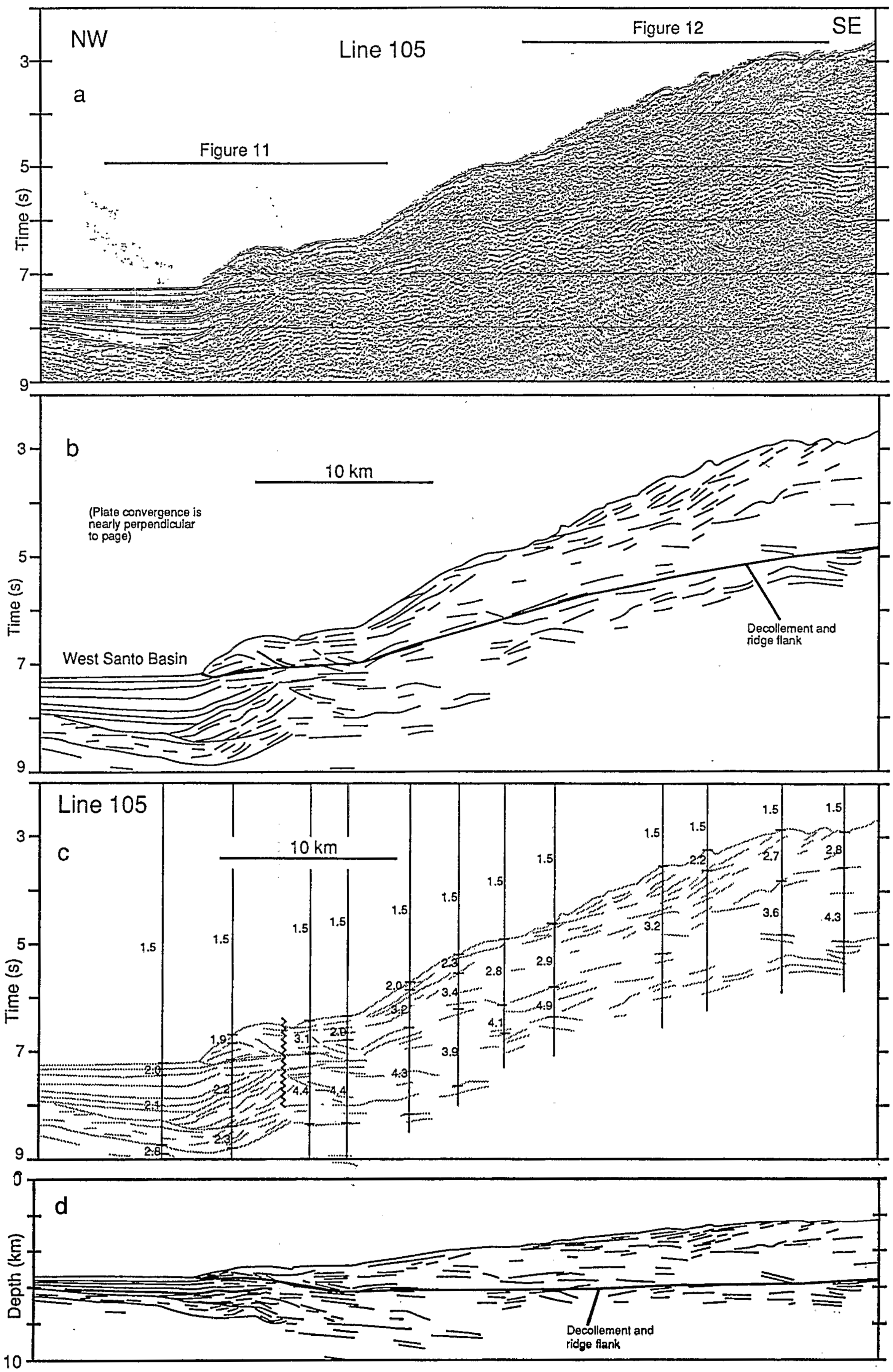

Fig. 6. (*a*) Migrated multichannel seismic section 105. (*b*) Line drawing of the time section. (*c*) Velocity structure derived from stacking velocities superimposed over the line drawing of the time section. Vertical zig-zag line indicates sharp horizontal velocity gradient. Velocities in km/s. (*d*) Depth converted line drawing.

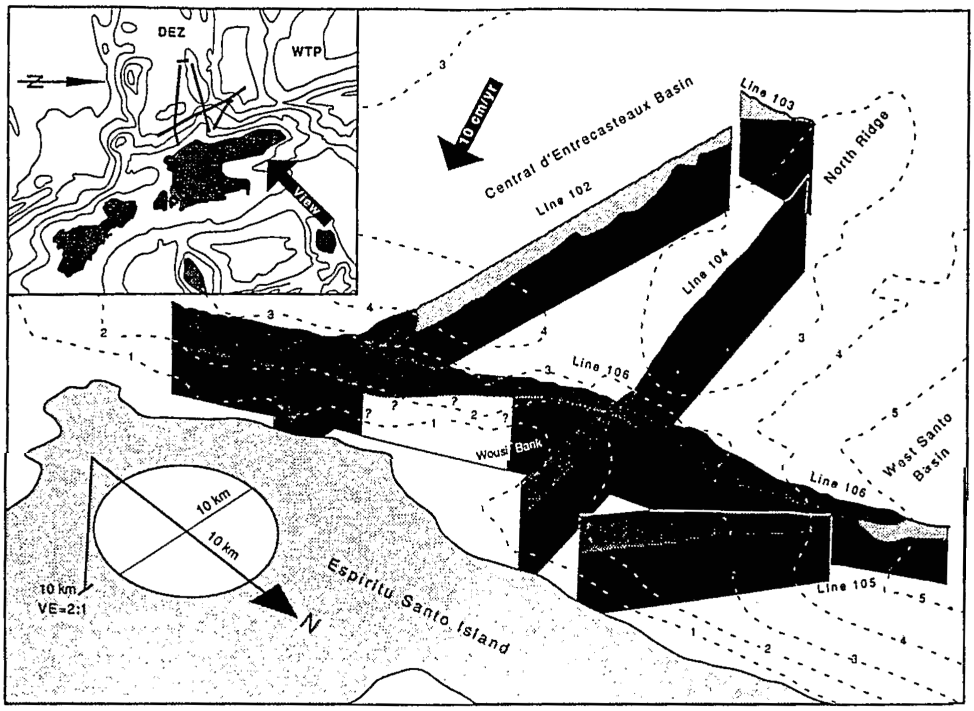

Fig. 7. Oblique view of the collision zone showing generalized interpretation of the multichannel seismic sections. View is from northeast to southwest. Light grey shows sediment in oceanic basins; dark grey shows the accretionary wedge; black indicates oceanic basement or the north ridge of the DEZ. The northwest end of seismic line 105 was deleted near its intersection with line 106.

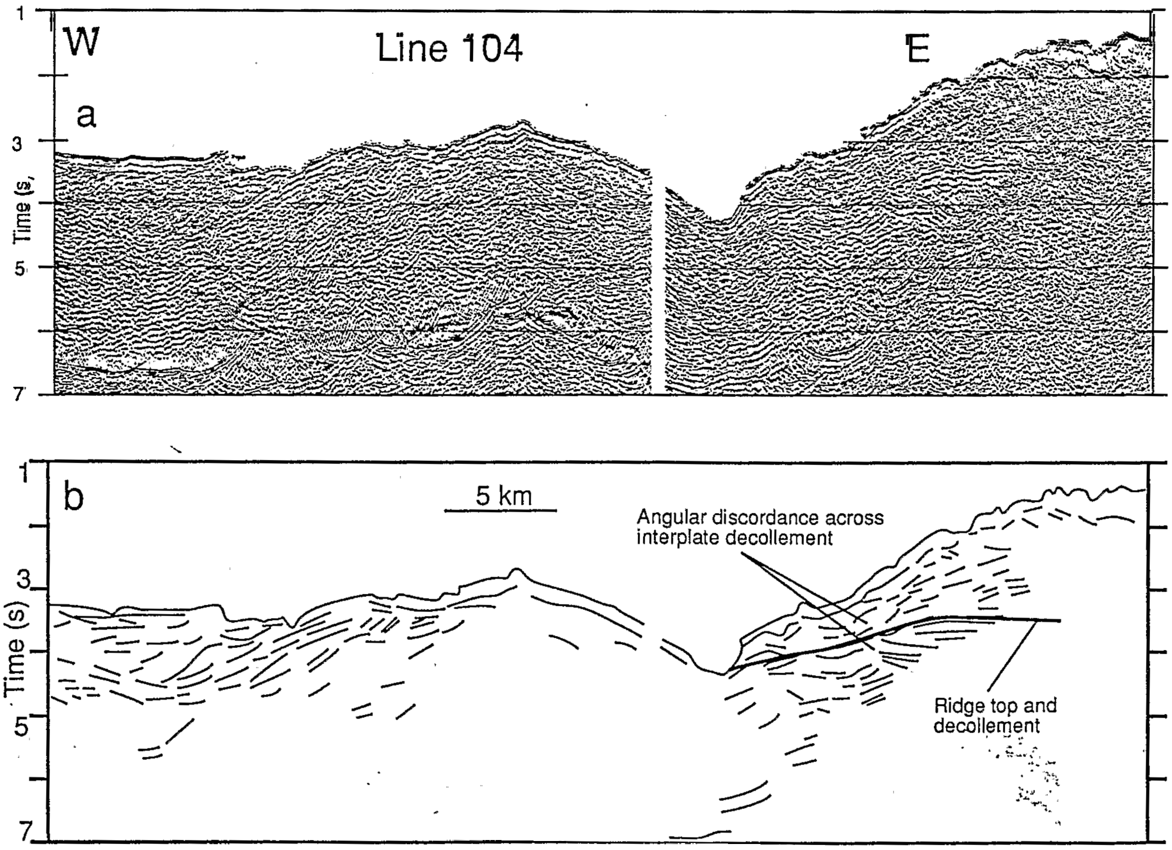

Fig. 8. (*a*) Migrated multichannel seismic section 104. (*b*) Line drawing of the time section. (*c*) Velocity structure derived from stacking velocities superimposed over the line drawing of the time section. Velocity function labled E1OR15 (left side of figure) is from ocean bottom seismometer refraction data [Pointoise and Tiffin, 1986] that were collected west of seismic line 104, which explains why the water depths do not match. Velocities in km/s. (*d*) Depth converted line drawing.

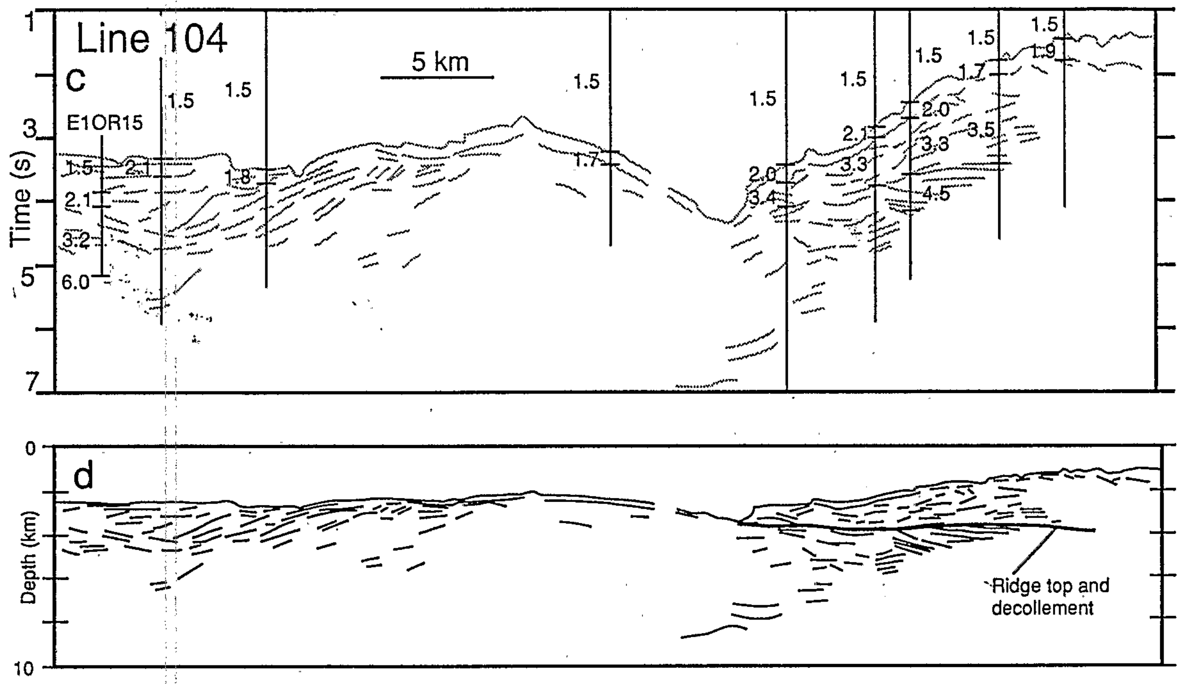

Fig. 8. (continued)

sured over the north ridge is accounted for by the bathymetric relief of the ridge and a bulk density of 2.65 g/cm^3 [*Collot and Fisher*, 1988].

Velocity data from ocean bottom seismometer information collected at station E1OR15 [*Pontoise and Tiffin*, 1986] (Figure 8c) indicate that low velocity (2.1 km/s) rock, about 400 m thick, covers the ridge and that basement rocks, which have velocities (6. km/s) appropriate for crystalline rock, underlie the ridge crest at a depth of about 2.4 km. These velocities and the results of dredging agree that although the ridge core and flanks appear to be high-velocity, possibly crystalline rock, sedimentary rock probably caps the ridge.

Seismic reflection data indicate that most rocks forming the north ridge are nonreflective but that stratified, reflective ridge rocks are present locally. For example, the west end of seismic section 104 (Figure 8) shows that the ridge crest is underlain by variably reflective strata that dip generally west Other reflective rocks lie deep within the ridge; particularly strong reflections derive from rocks deep below the toe of the accretionary wedge (Figures 8*a*, and 8*b*). Eastward from this

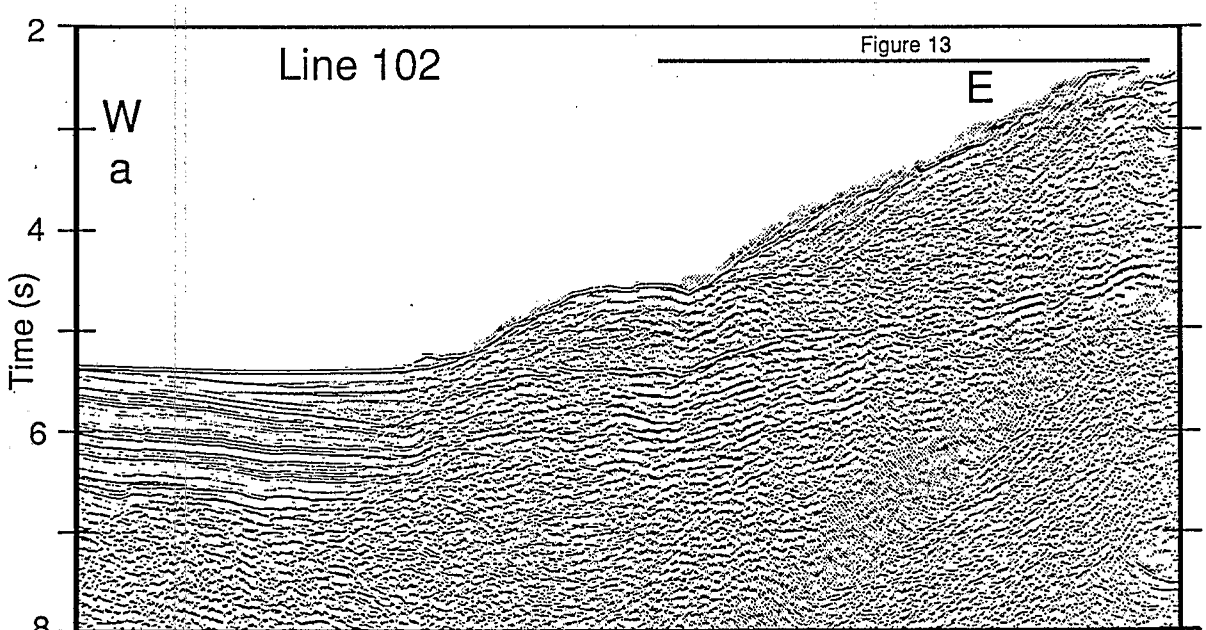

Fig. 9. (*a*) Migrated multichannel seismic section 102. (*b*) Line drawing of the time section. (*c*) Velocity structure derived from stacking velocities superimposed over the line drawing of the time section. Vertical zig-zag line indicates sharp horizontal velocity gradient. Velocities in km/s. (*d*) Depth converted line drawing.

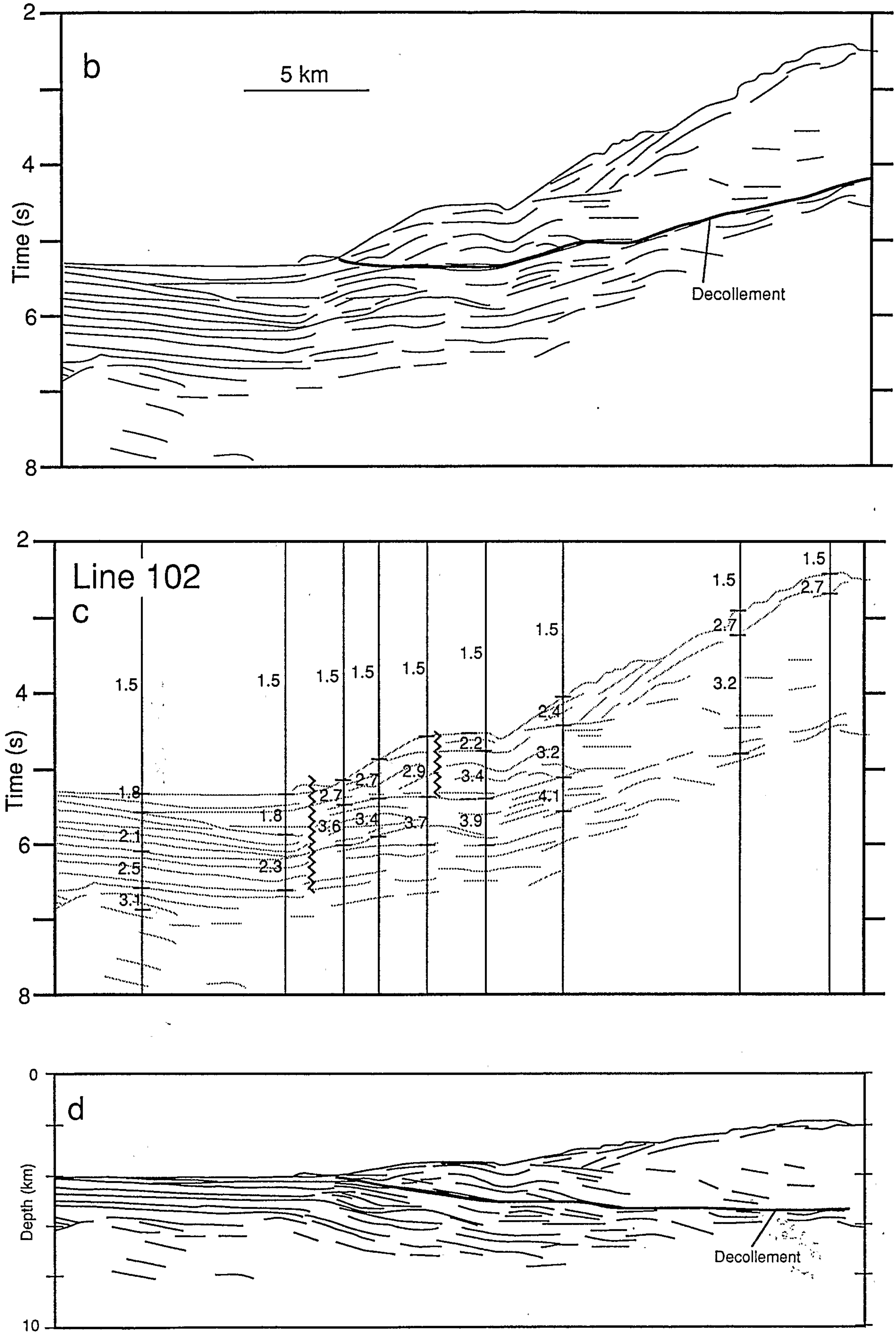

Fig. 9. (continued)

toe, reflections from ridge rocks gain amplitude and continuity, and some of them rise eastward to end updip at a prominent angular discordance formed along a strong, nearly flat horizon that seems to mark the base of the accretionary wedge. Overall, seismic reflection data indicate that a heterogeneous rock assemblage makes up the ridge.

The seismic stratigraphy of the West Santo basin was derived from a dense grid of single-channel seismic reflection sections [*Collot and Fisher*, this issue]. This basin abuts the north flank of the ridge (Figure 2), and indicates that most units of the basin fill thin northward and northeastward from the ridge. Furthermore, basin fill that returns parallel, strong, continuous reflections is more common around the northern and northeastern periphery of the basin, whereas poorly reflective fill lies adjacent to the ridge.

Interpreted Evolution of the North Ridge

We believe that coalesced volcanos form the north ridge. The contrasting seismic response of ridge rocks implies a heterogeneous rock assemblage; in particular, the locally strong reflections from deep within the ridge could be from crystalline rocks that contrast greatly in acoustic impedence with their encasing rocks. Furthermore, the dredged mixture of fine-grained, siliciclastic rock and MORB suggests that the ridge is composed of sedimentary, probably volcaniclastic, rocks that interfinger with or overlie basalt. Velocity information and reflection geometry suggest that sedimentary rocks are more common shallow in the ridge and that high-velocity, possibly crystalline ridge rocks lie at moderate depth (1-2 km). Although the calculated 2.65 gm/cm^3 density of ridge rocks is appropriate for this rock mixture, the calculated 0.0015 G magnetic susceptibility appears low for MORB, unless the basalt is altered or only comprises a small fraction of the ridge volume.

The northward and northeastward thinning and facies gradation of the fill within the West Santo basin point to sediment transport away from the ridge toward the West Torres plateau and the now adjacent New Hebrides arc. This transport direction implies that the ridge was a source for most of the basin fill. We are unable to pinpoint the sediment source because we cannot document westward thinning of the fill; the source, however, seems to have been a part of the ridge that lies somewhere west of the part of the basin that we surveyed. West of the New Hebrides arc the DEZ appears to include horsts of oceanic crust [*Maillet et al.*, 1983]; this Eocene MORB is approximately coeval with Eocene andesite conglomerate that was recovered from below the deep-water North Loyalty basin, at Deep Sea Drilling Project (DSDP) site 286 [*Andrews, et al.*, 1975] (Figure 1). Seismic stratigraphic analysis of deposits near this site suggests that the south ridge of the DEZ was the source for the andesite conglomerate [*Fisher*, 1986]. This volcanic activity as well as the seismic stratigraphy of the north ridge and West Santo basin suggest that near the New Hebrides arc the north ridge of the DEZ is a coalesced string of submarine volcanos. If so, this origin of the ridge is important to understanding the collision zone because a massive horst of oceanic crust and a ridge containing a mixed volcanic lithology would have substantially different mechanical properties within the collision zone. Specifically, water entrained within ridge sediment could facilitate subduction of the ridge.

Shape of the North Ridge Under the Accretionary Wedge

Sea Beam and multichannel seismic data indicate that the subducted and unsubducted parts of the north ridge differ considerably in shape; these data reveal three distinctive morphologic and structural features of rocks near the ridge. First, most of the unsubducted part of the ridge has a rounded top and steep upper flanks, but Sea Beam bathymetry shows that near the toe of the accretionary wedge, the rounded ridge top decreases in relief, veers southward, and is replaced progressively eastward by a flat summit area (Figure 5). Second, these data show that the base of the steep north flank of the ridge is marked by an abrupt break in slope; below this break the ridge flank is covered by horizontal fill within the West Santo basin. Third, seismic section 103 (Figure 7) shows that along the south flank of the ridge, strata filling the Central d'Entrecasteaux basin thin sharply onto this flank.

These three morphologic and structural features are evident in seismic reflections from rocks below the accretionary wedge. In particular, multichannel seismic section 104 (Figure 8) shows that the reflection from the ridge crest extends beneath events from the accretionary wedge as a horizontal, low-frequency reflection that forms an angular discordance with events from within the ridge. The depth converted version of section 104 (Figure 8*d*) indicates that the ridge crest under the accretionary wedge has low relief and dips shallowly toward the arc. Depth converted section 106 (not shown here) shows that the top of the ridge also has low relief in north-south cross section. Hence the small, flat, summit areas evident in Sea Beam data widen and coalesce beneath the accretionary wedge to occupy nearly all of the crest of the subducted part of the ridge.

Northeast dipping reflections that are evident along seismic sections 105 (Figure 6) and north dipping ones on section 106 (Figure 10) probably mark the flank of the north ridge under the accretionary wedge. On section 105, rocks that cause these dipping events extend far enough to the northwest that, below the toe of the accretionary wedge, they merge in a confusing pattern with subducted ocean sediment. We used partial prestack migration and prestack migration in separate processing schemes to try to clarify this structure along seismic section 105. The prestack-migrated section yielded the better structural image (Figure 11) and shows that the shallow fill within the West Santo basin onlaps southward onto the deep basin fill, and the deep fill downlaps northward onto the basin bottom (Figure 11*b*). A single-channel seismic section obtained west of the accretionary wedge shows that in north-south cross section the downlapping, deep basin fill borders the north flank of the north ridge. Hence we believe that beneath the accretionary wedge along line 105, rocks of the north ridge form the southeastern limit of the downlapping, deep basin fill and that the northeast dipping reflections delineate the ridge flank. These ridge-flank reflections appear similar to north dipping reflections on seismic section 106 (Figure 10), and we infer that these north dipping reflections are also from the ridge flank.

Seismic section 106 (Figure 10) shows that the north edge of the flat ridge summit underlies a steep seafloor scarp, which on the time section, induces a false scarp in the buried ridge flank. The edge of the ridge summit is associated not only with

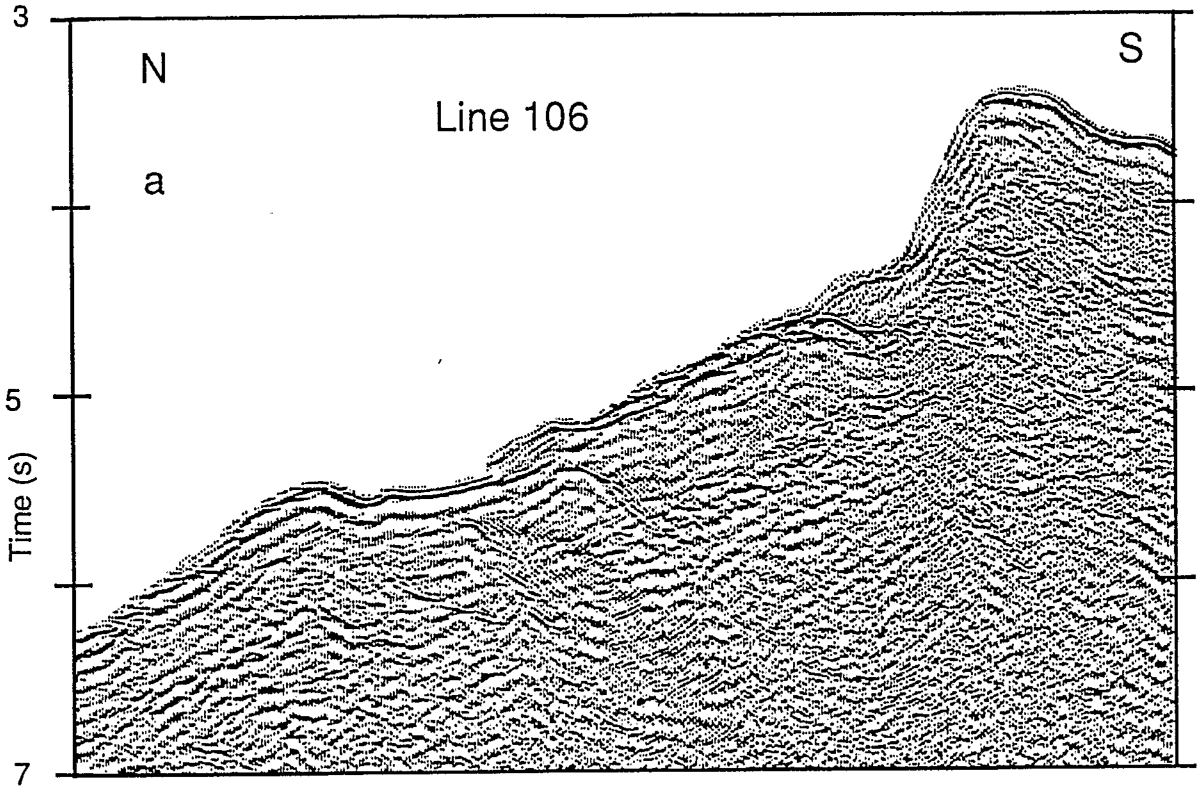

Fig. 10a. Detail of migrated multichannel seismic section 106.

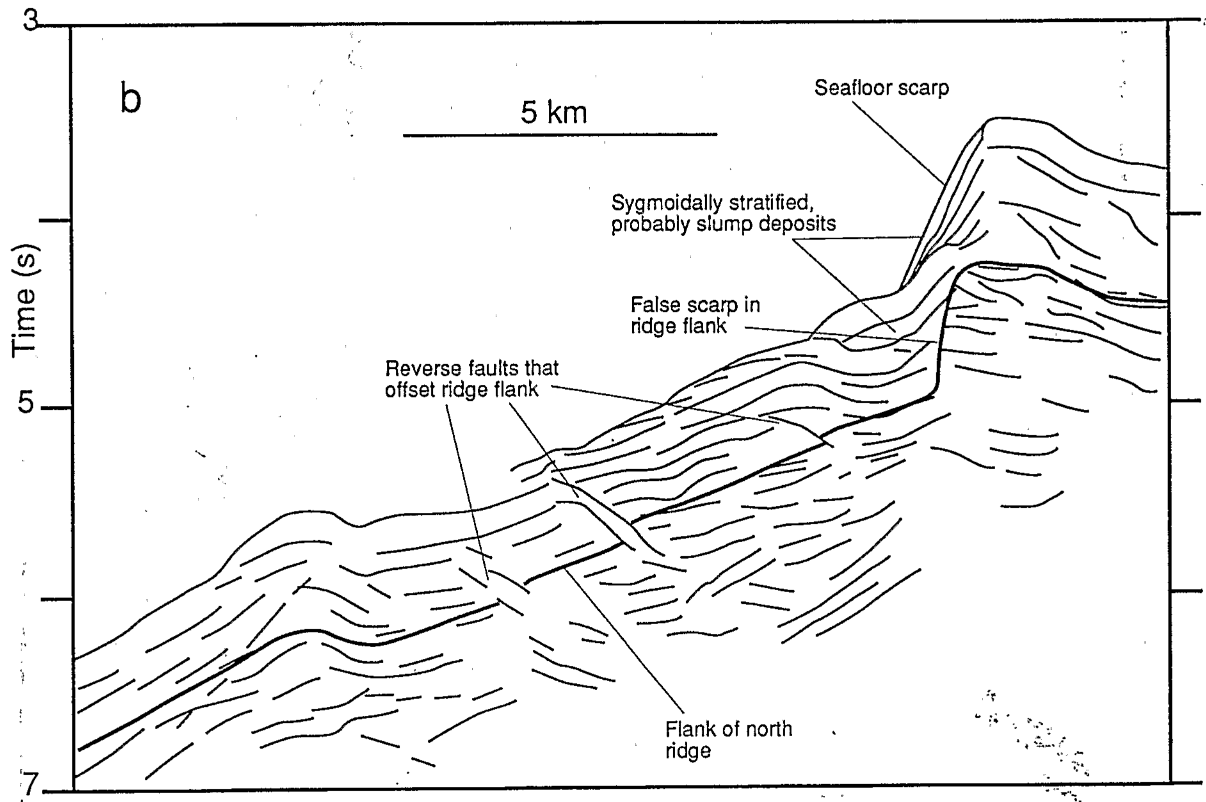

Fig. 10b. Interpretive line drawing showing the subducted flank of the north ridge and the steep reverse faults that pierce this flank. Location shown in Figure 5.

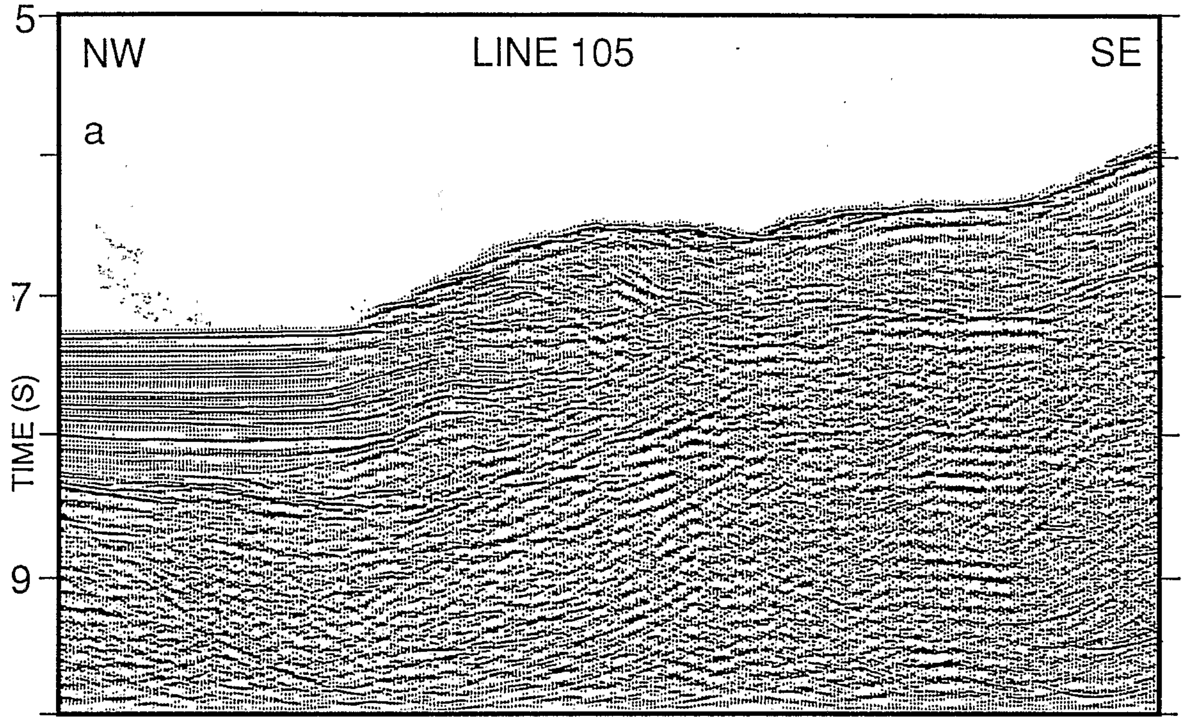

Fig. 11*a*. Prestack migrated multichannel seismic section 105.

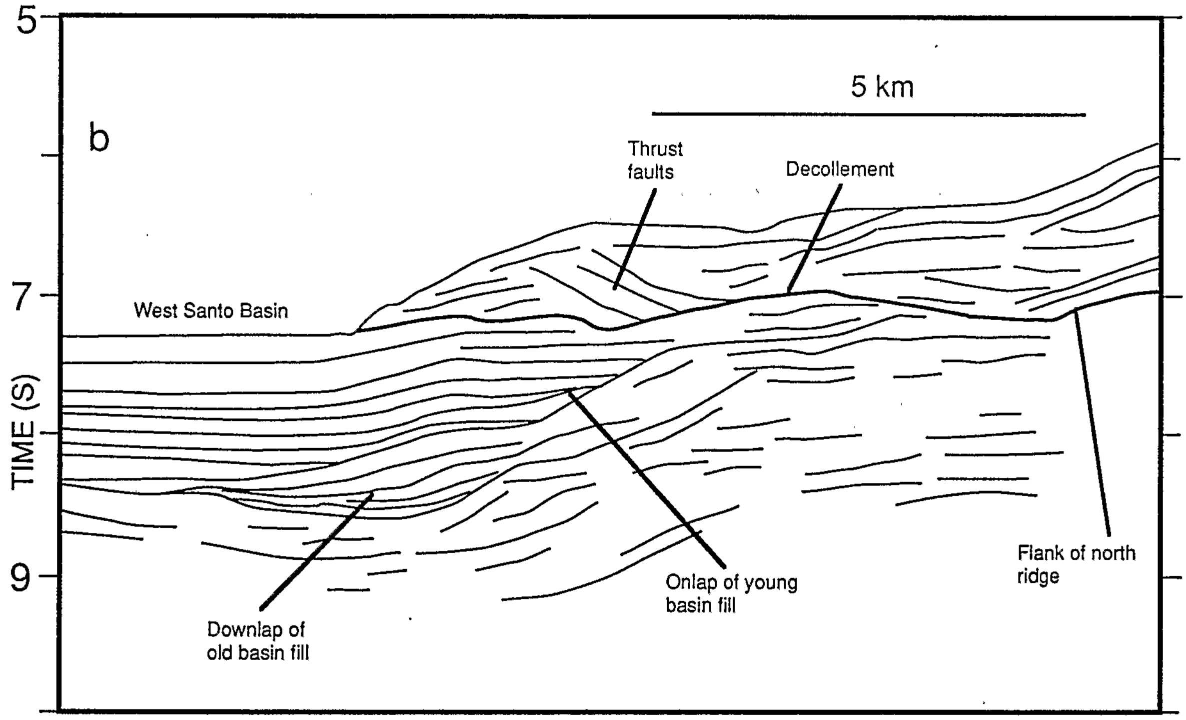

Fig. 11*b*. Interpretive line drawing of these data showing the subducted flank of the north ridge and the West Santo Basin. Line location shown in Figures 5 and 7.

the steep seafloor scarp but also with sygmoidally stratified rock, probably slump deposits (Figure 10). However, on seismic section 105 (Figures 7 and 12) neither seafloor scarp nor obvious slump deposits mark the summit edge. Instead the subducted ridge seems to have more subdued, rounded topography than do the unsubducted or shallowly subducted parts of the ridge.

Reflections from the subducted south flank of the ridge are not evident in our seismic data. However, beneath the accretionary wedge the subducted fill of the Central

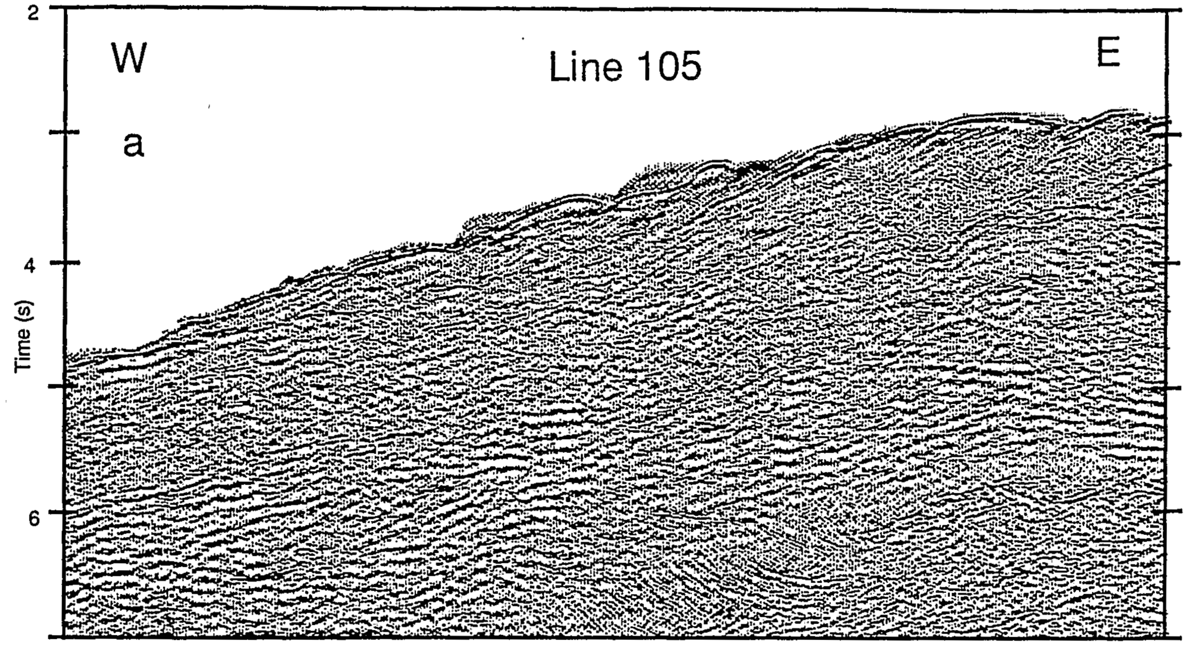

Fig. 12*a*. Detail of migrated multichannel seismic section 105 showing mass-wasting deposits that dip and shift trenchward.

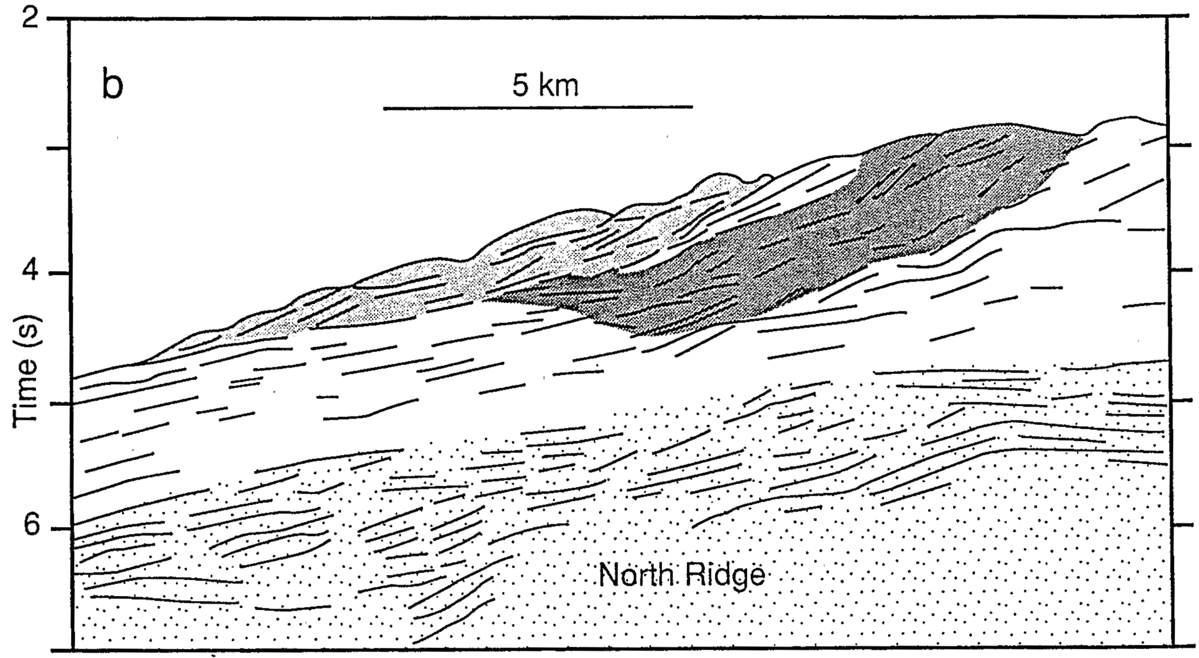

Fig. 12*b*. Interpretive line drawing of these data. Stippling indicates ridge rocks. Gray shades indicate units of downlapping sequences in the accreted rocks. Location of seismic section shown in Figures 5 and 7.

d'Entrecasteaux basin appears to thin eastward from the trench, as shown by seismic section 102 (Figures 9 and 13). Interpreting the geologic meaning of this apparent thinning is difficult; one possibility is that it results from poor seismic imaging that was caused by complex structure within the accretionary wedge or subducted fill. However, we interpret the thinning to indicate where the basin ends and where relatively high topography of the subducted part of the DEZ begins.

Seismic reflection data from both flanks of the ridge indicate that the ridge changes shape beneath the accretionary wedge. Eastward beneath the wedge, the crest of the ridge appears flatter and the edge of the ridge summit seems more rounded than do corresponding parts of the unsubducted ridge. Furthermore, the subducted part of the DEZ may have greater bulk beneath the arc than it does west of the arc.

GEOLOGY OF THE ACCRETIONARY WEDGE

Location and Structure of the Interplate Decollement

Seismic reflection data indicate that the interplate decollement warps upward to the south to accommodate the subducted part of the north ridge Below the accretionary wedge that lies north of the ridge, the decollement follows the

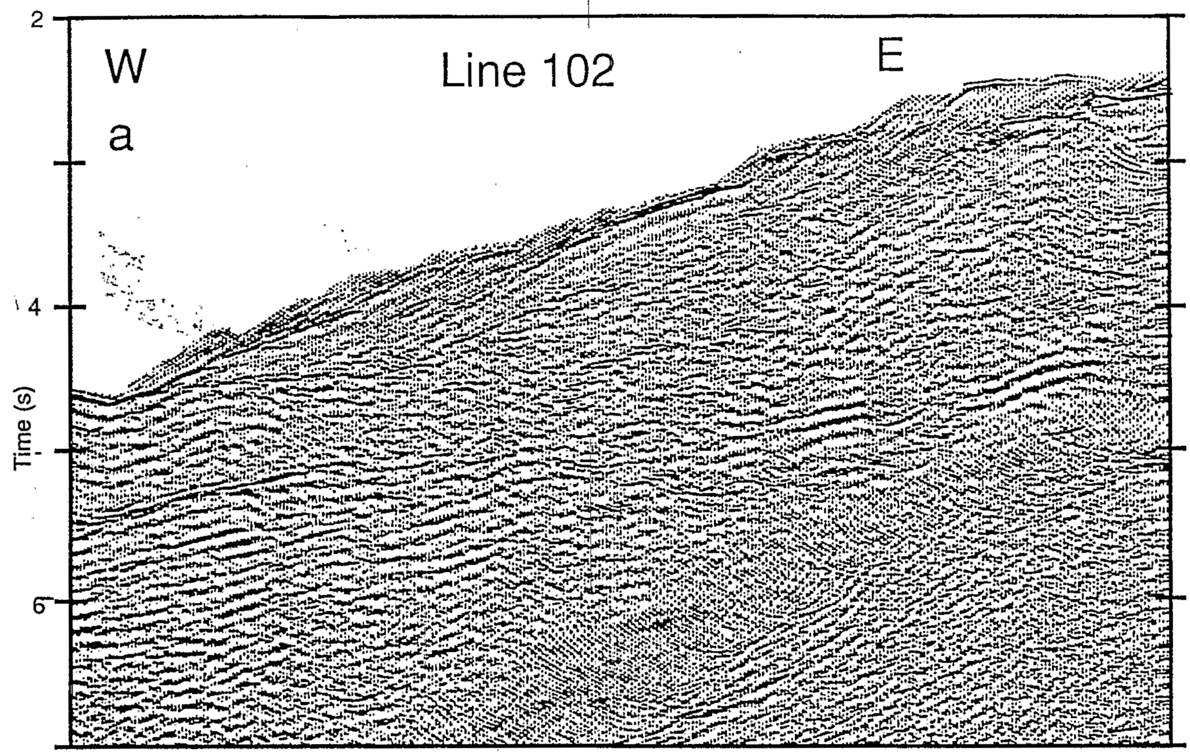

Fig. 13*a*. Detail of migrated multichannel seismic section 102 showing the mass-wasting deposits that dip and shift trenchward.

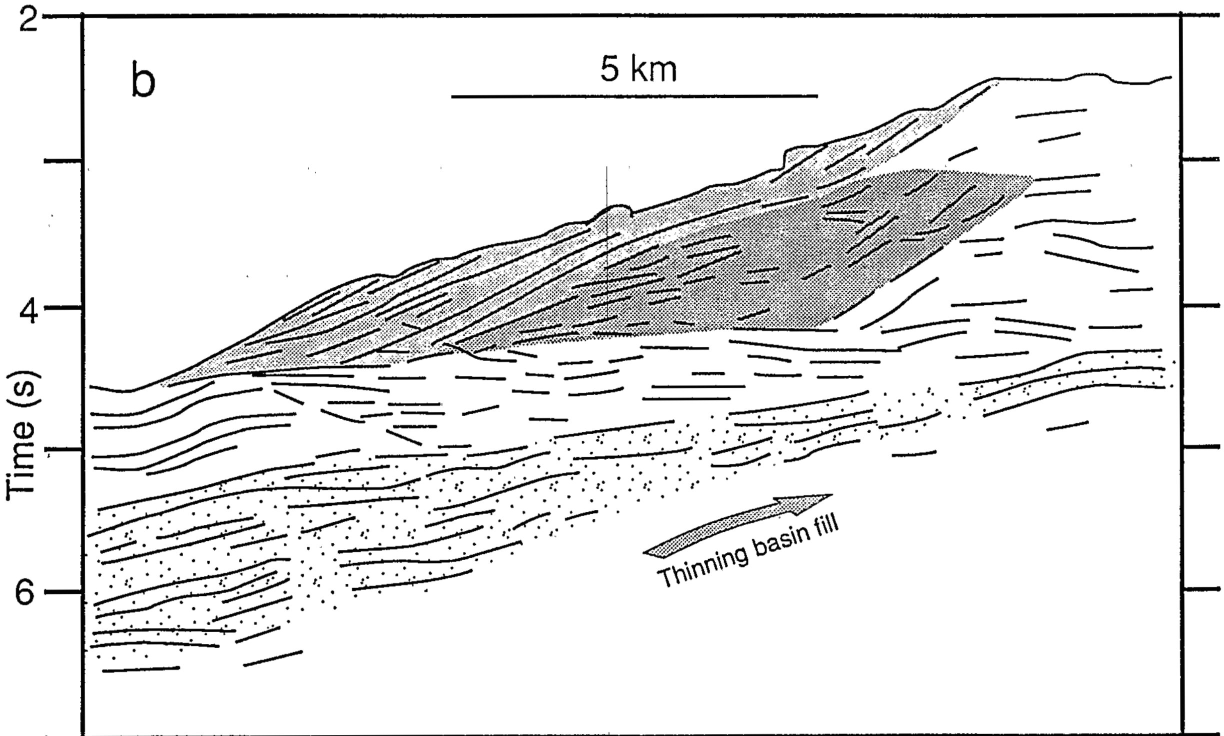

Fig. 13*b*. Interpretive line drawing of these data. Stippling indicates subducted fill within the Central d'Entrecasteaux basin. Gray shades indicate units of downlapping sequences in the accreted rocks. Location of seismic section shown in Figures 5 and 9.

top of the fill within the West Santo basin, as suggested by reflections from several thrust faults that merge downward against the top of this fill (Figure 11). Near the north flank of the ridge, however, the West Santo basin pinches out against the flank of the ridge, and rocks juxtaposed at the decollement change abruptly from accretionary wedge over basin fill to wedge over ridge rocks. This lithologic transition in the footwall of the decollement could be accompanied by an abrupt change in shear stress or in rock mechanical properties. This footwall transition, in fact, is associated not only with a deep cusp in the leading edge of the accretionary wedge, as shown by Sea Beam data (Figure 5) [*Collot and Fisher*, this issue] but also with a steepening of faults that cut this wedge. The steep faults, shown by seismic section 106 (Figure 10), lie south of the footwall transition, over the ridge flank. Thus north of the transition in footwall lithology, low-angle thrust faults sole out at shallow depth, whereas south of the transition, reverse faults pierce the ridge flank, meaning that the interplate decollement must locally lie within the ridge.

Near the ridge crest, however, the decollement emerges from within the ridge as suggested by seismic section 104 (Figure 8), which does not show any thrust faults that emerge through the ridge crest west of the toe of the accretionary wedge. We believe, therefore, that the decollement emerges at this toe and that the decollement lies along an angular discordance of reflections from near the subducted ridge top. The position of the decollement is also known at scattered locations along the ridge crest from singlechannel seismic sections, which show reflections from thrust faults that merge downward with the inferred top of the ridge. These inferences and the fault geometry suggest that the decollement lies along the subducted ridge crest.

South of the subducted north ridge the interplate decollement appears to lie along the top of the fill within the Central d'Entrecasteaux basin. Seismic section 102 (Figure 9) shows a prominent reflection that separates low-frequency, coherent reflections below from less coherent reflections above. The lower reflections probably correlate with the well-bedded ocean basin fill evident west of the toe of the accretionary wedge. Disharmonic rock structure is also evident across the prominent reflection. We propose that the prominent reflection is from the interplate decollement.

Another abrupt lithologic transition probably occurs in the footwall of the interplate decollement where the fill of the Central d'Entrecasteaux basin pinches out against the south flank of the ridge. However, we have too few data to delineate the structural consequences of this transition.

From north to south across the ridge the subduction zone apparently accommodates the subducting ridge by warping the interplate decollement to follow a path upward from the top of the fill in the west Santo Basin, through the north flank of the ridge, to the ridge crest. The decollement then follows an unknown path downward from this crest to lie along the top of the fill within Central d'Entrecasteaux basin. Because part of the path lies within the ridge, rocks from this feature have been or are being accreted onto the arc.

Evidence for Mass Wasting of the Accretionary Wedge

Collot and Fisher [this issue] describe in detail evidence from Sea Beam bathymetric and single channel seismic reflection data that indicates that mass-wasting deposits form a widespread blanket within the shallow part of the accretionary wedge. Sea Beam data show numerous scarps that are concave downslope as well as isolated hillocks that are convex downslope, and single-channel seismic data show rock masses that form rounded bumps in the seafloor but have a nearly flat base at shallow depth within the wedge. We believe that these features in bathymetric and and single-channel seismic data evidence mass-wasting deposits.

On multichannel seismic sections 105 and 102 (Figures 12 and 13), rocks beneath the upper part of the accretionary wedge and lap downslope; they form vertical successions in which beds high within a succession begin progressively farther downslope and extend nearer to the trench than do underlying beds. Correlating features in multichannel seismic and Sea Beam bathymetric data reveal that the downlapping successions tend to underlie the upper arc slope, both north and south of the ridge. Seismic section 105, obtained north of the ridge, suggests that the upper part of the accretionary wedge can be subdivided into three successions, which have divergent bedding dip and are outlined by reflections that are somewhat stronger and more continuous than are reflections from within the successions (Figure 12). The downlapping successions make up a substantial proportion of the accretionary wedge. Similarly, seismic section 102 (Figure 13), collected south of the ridge, shows that downlapping successions make up much of the thickness of the wedge.

We believe that the downlapping successions result from large-scale mass wasting of the accretionary wedge. The bedding geometry suggests that slumps are redeposited to form acoustically definable bodies. These separate bodies may indicate episodic mass wasting, which could result as major earthquakes trigger large slumps.

In this collision zone, accreted rocks commonly dip trenchward, but in general, the continuity of reflections is commonly too poor to reveal the progressive trenchward shift of bedding that is typical of the downlapping sequences. Trenchward dip of beds deserves special mention because this dip is opposite to the landward dip commonly imposed on accreted deposits by active dewatering passages [*Cloos*, 1984] or by imbricate thrust faults. Trenchward dip suggests that a process like sedimentary accretion, rather than compressive, structural accretion, predominates within large parts of the accretionary wedge within the collision zone. This sedimentary accretion, we believe, involves material derived from mass wasting of slope deposits that were unsettled by the ridge. Trenchward dips indicate that sedimentary accretion predominates along seismic section 104 (Figure 8*a*), recorded along the the crest of the subducted north ridge, and along seismic section 12 [*Fisher et al.*, 1986], which was obtained between the two ridges of the DEZ. Neither section, however, reveals the trenchward shift that is typical of the downlapping beds.

Stratigraphic Implications of the Velocity Structure

Preliminary indications from interval velocities derived from seismic reflection data are that rocks forming the accretionary wedge have velocities over 3 km/s, and rocks characterized by this velocity range underlie areas on both sides of the north ridge. Furthermore, the velocities measured in wedge rocks are substantially higher than are those in ocean basin sediment, just west of the accretionary wedge, which suggests either that the lower part of the accretionary wedge does not include much material accreted from the ocean basins or that such material dewaters and consolidates over a short distance arcward of the trench, as suggested by *Shipley and Moore* [1986] and *Bray and Karig* [1985]. The high velocities could be due to (1) probably altered, igneous basement of the volcanic arc, (2) indurated, possibly volcanic rocks accreted from the DEZ, or (3) multiply deformed, strain-hardened, accreted sedimentary rock. The high velocities do not necessarily mean that the accreted rocks are competent because fractures, closed by the weight of overburden, could pervade and thus weaken the rocks. Some accreted rocks, however, are probably competent as indicated by the locally steep (20°-30°) seafloor dips of the accretionary wedge, as measured from Sea Beam data [*Collot and Fisher*, this issue].

TECTONIC SYNTHESIS AND CONCLUSION

Two attributes of the north ridge, namely, its direction of movement and shape, exert primary influence over the structural and stratigraphic evolution of the accretionary wedge within the collision zone. At about 2 cm/yr, the component of relative arc-ridge motion that parallels the trench is small; nonetheless this relentless motion forces the north ridge beneath the accretionary wedge that lies north of the ridge and withdraws the south flank from beneath the southern wedge. In our view, the accretionary wedge is uplifted by the shallowly tapered north flank of the ridge; these rocks steepen until they fail under the influence of gravity and cascade downflank to blanket areas of low topographic relief. Progressive northward ridge movement results in continuous remobilization of previously unsettled wedge material; eventually, much of the wedge that overlies the ridge flank becomes remobilized deposits. This remobilization could account for the accumulation of downlapping successions that locally make up most of the accretionary wedge. Mass wasting probably involves progressive movement of material depending on its strength. As the subducted ridge begins to uplift part of the accretionary wedge, weak layers at shallow depth within the wedge slough first. Eventually wedge rocks that overlie the north flank of the ridge could become a residue of relatively strong, strain-hardened rock. Such a residuum could cause the high acoustic velocities measured in rocks at shallow depth within the wedge.

Slumping of rocks in the upper part of the wedge and possible erosion of the base of the wedge by irregular subducted features are two styles of tectonic erosion that could be active in reducing the structural relief of accreted rocks as they are uplifted on the ridge flank. *Fisher* [1986] described the absence from the collision zone of large anticlines and thrust faults having large vertical throw, that might be caused by the insertion of the ridge beneath the accretionary wedge and consequent displacement of accreted material. We believe that the structure related to ridge insertion is manifested by mass wasting deposits.

Abrupt pinchouts of fill in oceanic basins cause frictional or mechanical discontinuities in the footwall of the interplate decollement. As the ridge moves northward, rocks of the accretionary wedge are deformed at the base of the ridge flank, where the West Santo basin pinches out. From north to south the discontinuity causes the interplate decollement to rise upward from the top of ocean basin sediment to the ridge crest and then to plunge downward from this crest to the top of the ocean basin that lies south of the ridge. Steep reverse faults along the north side of the ridge pierce the ridge flank, indicating that the decollement at least locally lies within the ridge. This piercement may result because the ridge is not a stiff, monolithic indenter but contains a mixture of volcanic lithologies. In the collision zone the interplate decollement might cut downward into the sedimentary cap, so that material collected by the ridge in its journey across the southwest Pacific Ocean and exotic to the New Hebrides arc may be incorporated into the accretionary wedge. The great extent of the DEZ and its possible volcanic origin means that, during the collision, the ridge is not likely to possess constant mechanical properties over large distances.

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