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14. MECHANISMS OF ACCRETION AND SUBSEQUENT THICKENING IN THE BARBADOS RIDGE ACCRETIONARY COMPLEX: BALANCED CROSS SECTIONS ACROSS THE WEDGE TOE[1]

K. M. Brown,[2] A. Mascle,[3] and J. H. Behrmann[4]

ABSTRACT

Detailed analysis of ODP Leg 110 cores provides evidence for a complex structural evolution of the frontal thrust system of the Barbados Ridge accretionary wedge. Thrust faulting and back rotation are the dominant thickening mechanisms within 5 km of the toe of the wedge. Folding and duplex formation are only secondary thickening processes at this point. Estimates of shortening across the frontal 5 km of the wedge vary depending on the balancing technique used. Ignoring the affects of compaction, line-balanced sections suggest 26–36% tectonic shortening, whereas simple volume balanced sections indicate 32% shortening. When a potential average 14% volume loss is considered, the volume-balance estimates of shortening rise to nearer 40%.

By 12 km from the front (Site 673), large-scale folding, with the development of overturned sections, becomes a significant thickening process. This folding is followed by the development of low-angle faults that cut out stratigraphic section at around 18 km from the toe (Site 674). These faults are interpreted as out-of-sequence thrusts that cross-cut and dismember an already complexly deformed wedge. The out-of-sequance thrusts are found in a region of the wedge where arc-dipping, low-angle reflectors become prominent on seismic reflection profiles.

The current basal décollement zone (to the east of Site 674) lies in the lower Miocene section. Oligocene and Eocene strata are thrust undeformed beneath the wedge for at least 12–l8 km (and perhaps farther). The presence of Oligocene and Eocene material within the wedge is, therefore, evidence of a different basal décollement geometry in the past. This different geometry could have entailed either: (1) an earlier phase of frontal off-scraping, with a décollement zone at a lower stratigraphic level; or (2) duplex formation and underplating of part of the Oligocene and Eocene section. We suggest that a mechanism of underplating is the best explanation for the general structural configuration observed at Site 674. If this is the case, then on ODP Leg 110 we made the first penetration of an underplated section in ODP or DSDP history.

The overall progression in structural style across the accretionary wedge reflects the need for continuous shape adjustments to maintain a stable critical taper during progressive accretion. Erosion of material from the slope of the wedge at Sites 673 and 674 may have had an important affect on the structural development of the wedge. It is important to note that erosion becomes significant in the region of the wedge where underplating and out-of-sequence thrusting is proposed to have occurred.

INTRODUCTION

Seismic-reflection profiles across the forearc region of the Barbados Ridge system provide evidence for considerable deformation of accreted sedimentary sequences (see Peter and Westbrook, 1976; Biju-Duval et al., 1982; Westbrook, et al., 1982; Westbrook and Smith, 1983; Speed et al., 1984; Valery et al. 1985; Mascle et al., this volume). The combined results of DSDP Leg 78A (Biju-Duval, and Moore, et al., 1984) and ODP Leg 110 (Mascle, Moore, et al., 1988) provide an unprecedented amount of information about the details of accretion and allow the verification of seismic interpretations. In particular, structural fabrics and geometries associated with the initial accretion of sediments are now relatively well documented (at Sites 541, 542, 676, 675, 671), with the first penetration of the active basal detachment surface and underthrust section of an accretionary system completed at Site 671. These structural data allow us to present line-balanced cross sections that further constrain the form of the initial accretionary structures.

In the following discussion, we will assume that structural lineament trends are close to north–south in the region of the wedge where we have constructed our balanced cross sections (i.e., in the first 5 km of accretion). This allows us to orthogonally project our borehole data onto CRV 128 (Fig. 1).

The assumption of north–south structural trends is backed up by evidence from the GLORIA long-range side-scan sonar and Seabeam data in the region (Brown and Westbrook, 1987). Farther up the accretionary slope, in the region of Site 674, trends are less clear but we have little reason to suspect that they differ widely from those nearer the front.

Numerically based models of wedge development (e.g., Davis et al., 1983; Davis 1984; Dahlen et al., 1984) suggest that deformation wedges have geometries governed by the balance between compressional and extensional forces, with a resulting characteristic critical taper or angle developing between the basal décollement and surface of the wedge. Extending the concepts proposed by these models of quasi-static systems to an actively growing wedge leads to the conclusion that progressive frontal accretion must be balanced by additional thickening in the more interior regions of the wedge. During Leg 110, we found evidence for such continued thickening at Sites 673 and 674. Of particular importance in later wedge thickening are out-of-sequence thrusts, large asymmetric folds with overturned limbs, and possible underplated material consisting of Oligocene and Eocene strata. The out-of-sequence thrusts may partly explain the nature of the landward-dipping reflectors that are common in many seismic reflection sections across accretionary

[1] Moore, J. C., Mascle, A., et al., 1990. *Proc. ODP, Sci. Results*, 110: College Station, TX (Ocean Drilling Program).
[2] Earth Sciences Board, University of California at Santa Cruz, CA 95064.
[3] Institut Francais du Pétrole, 1-4 Avenue Bois-Preau, BP 311, 92506 Rueil Malmaison Cedex, France.
[4] Institut für Geowissenschaften und LithosPharenforschung Universität Giessen, D-6300 Giessen, Federal Republic of Germany.

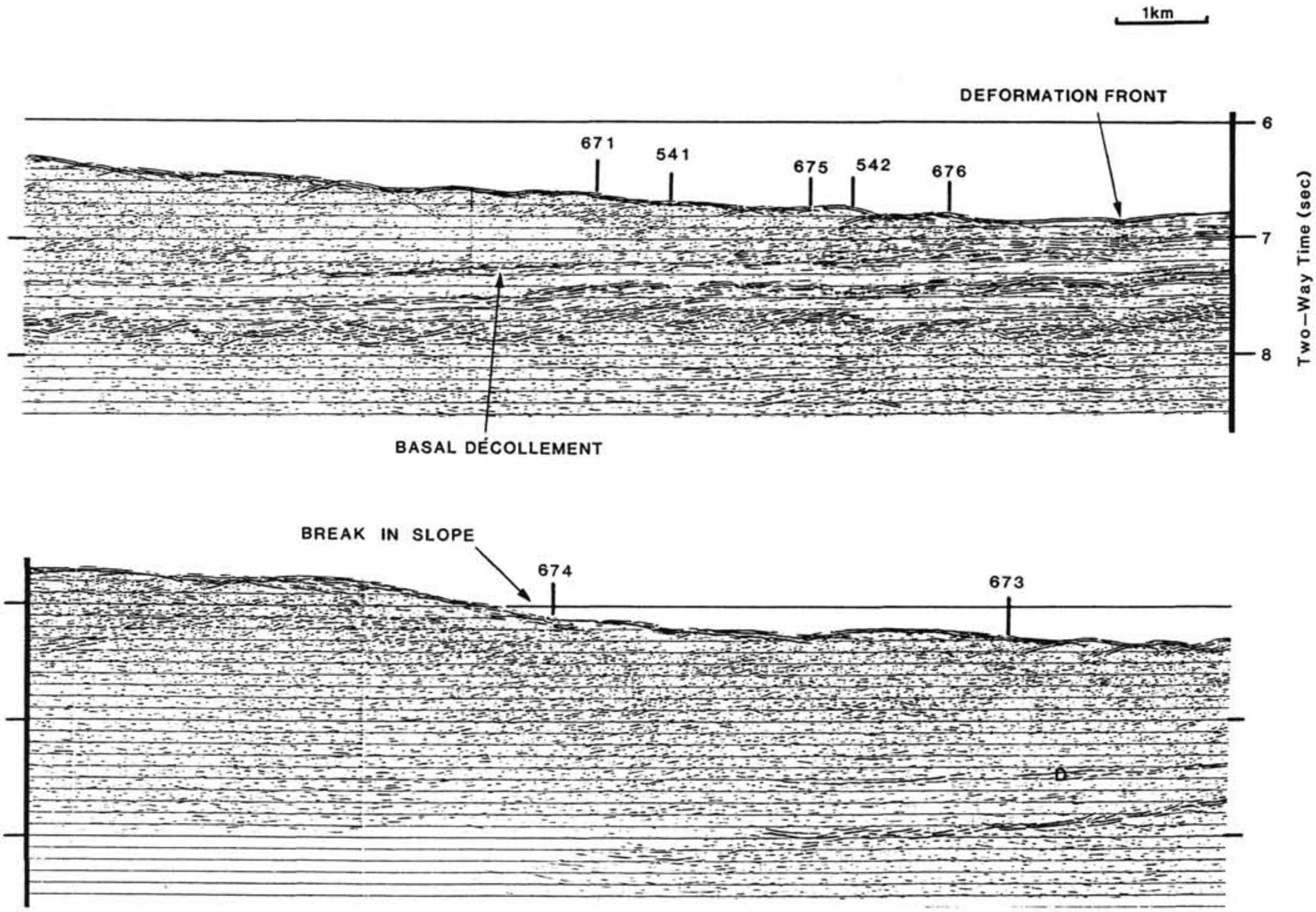


Figure 1. Seismic line CRV 128 with the approximate positions of DSDP Leg 78A and ODP Leg 110 holes orthogonaly projected onto the section (see track chart in Chapter 1 of Mascle, Moore, et al. (1988).

wedges (Cloos, 1984). It is also important to note that, in the same region of the wedge where these structures are developed, there is evidence for significant erosion by mass-wasting processes. We may, therefore, have sampled part of a complex system in which wedge thickening and thinning processes are in some sort of dynamic equilibrium.

LOCAL TECTONIC SETTING

The Barbados forearc is an active accretionary wedge to the east of the Lesser Antilles island arc and forms the leading edge of the Caribbean Plate. Currently the Atlantic oceanic crust subducts westward beneath the Antilles at between 2- and 4-cm/yr (Minster and Jordan, 1978; Sykes et al., 1982). The most recent period of wedge growth probably began in Eocene time (Westbrook, 1982).

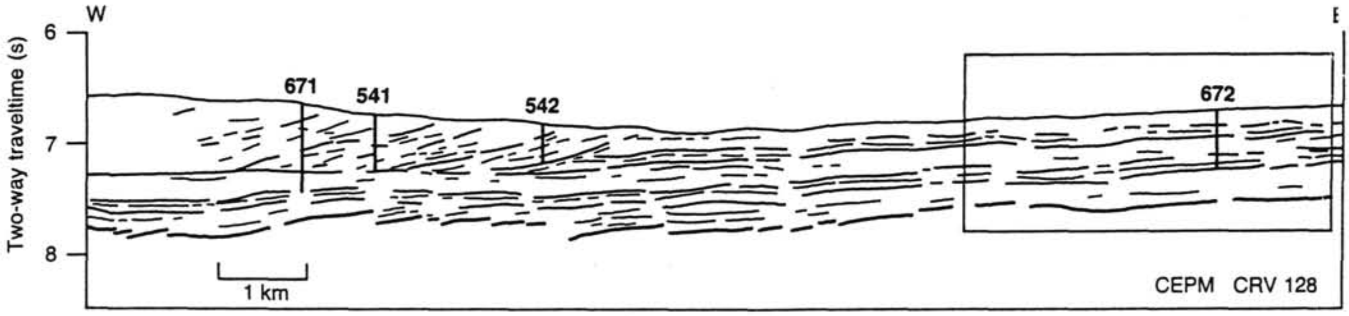
The drilling area lies on the northeast flank of the Tiburon Rise (see Mascle, Moore, et al., 1988). At present, the east northeast-trending Tiburon Rise ponds northward-flowing Orinoco fan turbidites (Wright, 1984). Consequently, few terrigenous turbidites occur in the current abyssal section north of the rise where the post-Oligocene section is composed predominantly of muds, marls, and local ash beds (see Site chapters, Mascle, Moore, et al., 1988). However, some terrigenous and locally derived carbonate turbidites do occur in the Oligocene and Eocene sequences (Dolan et al., this volume). This area was chosen because the incoming sedimentary section is 1 km thick and the associated portion of the accretionary wedge is anomolously thin relative to other areas of the Barbados Ridge (see isopach maps in Speed et al., 1984). It enables the basal décollement of the wedge to be penetrated. Data from previous DSDP Leg 78A (Biju-Duval and Moore et al., 1984) and seismic-reflection profiles (Fig. 1; also see better sections in Chapter 1 of Mascle, Moore, et al., 1988 and Westbrook and Smith, 1982) reveal that only the uppermost 200 m of the sedimentary section is off-scraped at the outer macroscopic deformation front, with the basal detachment lying in the lower Miocene section. The bulk of the abyssal plain section, comprising Oligocene to Senonian strata (see Site 543 chapter in Biju-Duval, Moore, et al., 1984), is underthrust as an undeformed unit beneath the toe of the accretionary wedge.

As a result of only 200 m of section being offscraped at the toe, the structural grain of the accretionary wedge in the Leg 110 area is exceptionally fine and thrust spacings are generally less than 1.5 km. This has allowed us to sample a large number of structures in a relatively small region of the wedge.

PRE-ACCRETION STRUCTURES IN THE ABYSSAL PLAIN SECTION (SITE 672)

Observations

Seismic reflection (Fig. 2) and borehole data (Fig. 3) both indicate that the abyssal plane sediments have experienced a certain amount of structural disturbance prior to accretion at the macroscopic deformation front. Numerous high-angle normal



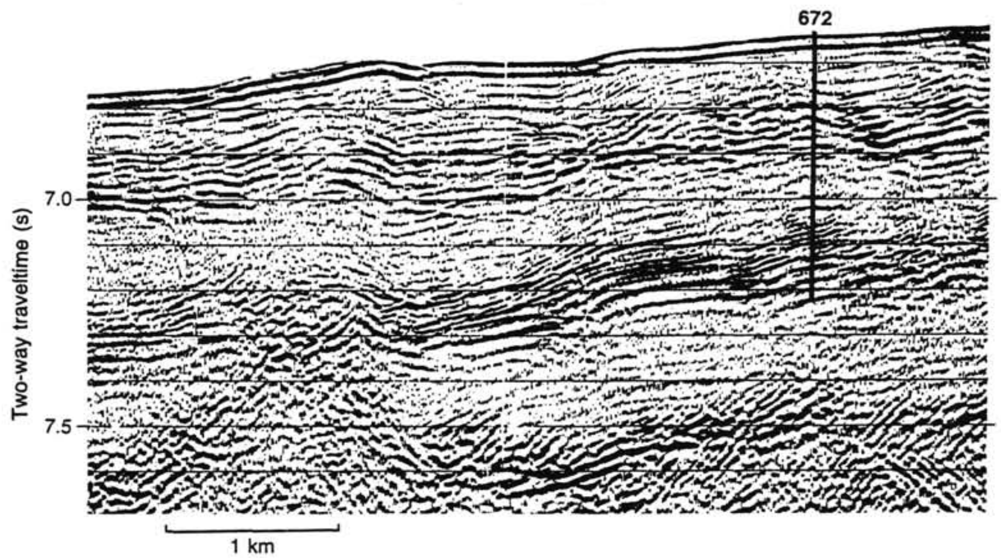


Figure 2. Top: Line drawing of migrated high-resolution multichannel line CRV 128 (taken from Site 672, Mascle, Moore, et al. (1988). Bottom: Detailed seismic section and location of Site 672. Note breaks at seafloor along the traces of some of the normal faults.

faults are the most obvious structures affecting the abyssal plane sequence. The lack of any major changes in the thickness of seismo-stratigraphic units younger than middle to upper Eocene times suggests that most of the activity on these faults ceased before these times. However, seafloor disturbances along some of the fault traces (Fig. 2) suggest that they have recently been locally reactivated. A number of steeply dipping normal faults were also observed in the cores of Site 672 (Fig. 3). These occur in sediments as young as upper Pliocene and are particularly evident at around 180–110 m sub—bottom (Fig. 3) where a small normal fault zone appears to have been intersected.

A different structural style was observed in the cores through the lower Miocene horizon at approximately 190 m sub-bottom (Fig. 3). Around this horizon bedding dips are very disturbed and both sigmoidal arrays of mud-filled vein structures and low-angle shear zones are developed (see Brown and Behrmann, this volume for detailed discussion of small-scale structures). The low-angle sheet dip of the arrays and occasional low-angle discrete shears suggest that this horizon has been affected by approximately bedding-parallel shear. Unfortunately, structures in most of the cores could only be oriented in respect to the vertical axis and so the direction of displacement cannot be determined.

Significance

Two contrasting styles of structure appear to affect the abyssal plain sequence some 5 km in front of the megascopic deformation front of the accretionary wedge. First, high-angle normal faults are locally reactivated, perhaps as a consequence of the loading of the oceanic plate by the encroaching accretionary wedge. Second, and perhaps more significantly, there is evidence for a low-angle shear along the lower Miocene horizon. The origin of the shear couple is not certain, but this lower Miocene horizon is also associated with the basal décollement of the frontal portion of the accretionary wedge (see below and synthesis chapter in Mascle, Moore, et al., 1988). This is particularly intriguing in the light of geochemical anomalies that also occur along this horizon (see Site 672 chapter in Mascle, Moore, et al., 1988 and Gieskes et al., this volume). These anomalies have been interpreted to result from the expulsion of exotic fluids out from the deeper regions of the accretionary wedge and into the abyssal plane sediments (Gieskes et al., this volume; Shipboard Scientific Party 1987). It appears likely, therefore, that a coupling exists between the propagation of the basal décollement zone into the incoming abyssal plain section and the location of conduits along which fluids are preferentially expelled from the thickening accretionary wedge.

STRUCTURAL EVOLUTION IN RESPONSE TO INITIAL ACCRETION (SITES 676, 542, 675, 541, AND 671)

Structural Development During Initial Accretion and Thickening

The frontal 5 km of the accretionary wedge can be divided into two principal structural domains comprising the accreted and underthrust sequences. The division is based on the amount of deformation and style of structures that are observed in the

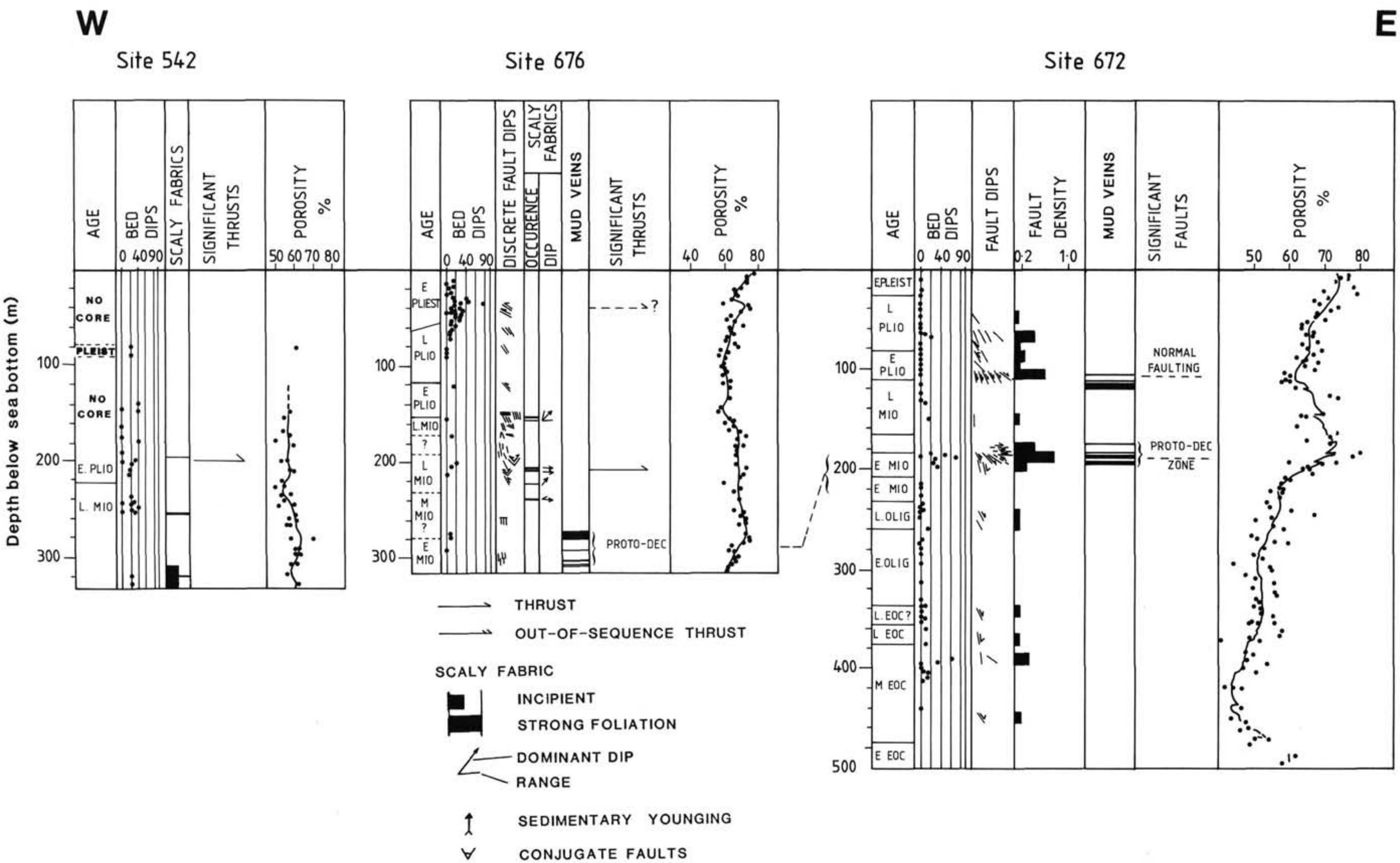


Figure 3. Composite structural logs of Sites 672, 676, and 542, drilled during DSDP Leg 78A and ODP Leg 110.

cores and correlatable features on seismic reflection sections. The basal décollement zone marks the boundary between these two structural domains.

The accreted sequences are typified by variable bedding dips and zones of scaly fabric development that can commonly be demonstrated to correlate with biostratigraphic defined age inversions. These zones of scaly fabrics, therefore, are considered to be the sites of thrusts. The major biostratigraphically and structurally defined thrusts can be demonstrated, in places, to be associated with small porosity inversions most probably resulting from the emplacement of the older and more compacted sections onto younger sections. This is particularly evident at Site 671B where a major thrust emplaces upper Miocene strata over lower Pleistocene material (120 mbsf, see Fig. 4). In the accreted sequences, bedding dips become more variable and generally steepen westward away from the accretionary front (Fig. 5). However, no overturned sections were identified in the frontal 5-6 km of the complex. Part of this increase in dip is consistent with back-rotation of imbricate thrust packets, but there appears to also be a general increase in the intensity of small-scale folding. The minor folding is concentrated in the regions just above the major biostratigraphically defined thrusts and the basal décollement (see bed dips logs in Fig. 4).

The basal déollement zone marks the boundary between the accreted and underthrust domains. On the seismic reflection sections (e.g., see Fig. 1 and 6), the décollement corresponds to the boundary between the complex and commonly seismically opaque accreted sequences and the relatively undisturbed subhorizontal reflectors of the underthrust sediments below. On CRV 128, the basal décollement is also marked by a fairly strong and occasionally discontinuous reflector (Fig. 1). The basal décollement was penetrated at Sites 671, 675, and 541 (Fig. 4). It is associated with the lower Miocene horizon and, at Site 671, is marked by a 40-m wide zone of scaly clays and local stratal disruption (See Brown and Behrmann, this volume). This décollement zone also coincides with apparent lows in porosities in Sites 676, 541, and 671. Considering that porosities in the lower Miocene sediments are initially high (Site 672, Fig. 3) it seems that tectonic deformation causes partial collapse of pore space. As discussed in Brown and Behrmann (this volume), the zone of scaly fabrics that makes up the basal décollement also thickens with increasing distance back in the wedge. When compared with displacement estimates derived from the balanced cross sections (see also Brown and Behrmann, this volume) it appears that this thickening may be correlated with increasing strains on the basal detachment.

The underthrust sequences of Oligocene and older sediments below the basal décollement zone were really only penetrated to any depth at Site 671 (see Fig. 4). From Site 671 it can be demonstrated that these sequences experience only minor low-angle brittle faulting in their upper parts. Bedding dips are generally horizontal (and never exceed 10°-20°). No significant zones of scaly fabric development or biostratigraphically defined thrusts were observed from about 20 m below the décollement, and the sediments below the basal décollement are interpreted to be relatively undeformed. The borehole observations are entirely consistent with the apparent undeformed character of the reflectors below the seismically defined décollement (Fig. 1).

Balanced Cross Sections

A rough estimate of the shortening across the toe of the Barbados accretionary wedge in the region of DSDP Leg 78A and ODP Leg 110 can be obtained using line and volume balancing techniques. The maximum density of information exists in the frontal 5 km of the wedge across Sites 676, 542, 675, 541, and 671 (Figs. 3 and 4). The multichannel seismic reflection section CRV 128 also runs approximately along the line of the transect (Fig.1) and was particularly useful in defining the basal décollement geometry. Although the transect is slightly displaced with respect to line CRV 128 (Lallement et al., pers. commun., 1988), along strike projections of the borehole data do tie in reasonably well (a small amount of relative adjustment is required) with some of the internal structure observed on the reflection section (see Fig. 6).

Two possible endmember versions of line-balanced cross sections are presented in Figure 7 using the borehole data as a principal constrain, with some useful additional input being obtained from CRV 128. Some of the main assumptions in the construction of the balanced section are; that there is no out-of-plane movement of material, and that total bed length and thickness do not appreciably change as a result of tectonic strains. It must also be assumed that thickness variation due to original across-strike sedimentary facies variations are also minimal. We were also, unfortunately, not able to take into account the affects of the numerous small conjugate high-angle reverse faults that occur in the off-scraped section (See Brown and Behrmann, this volume), as these are generally too small for the scale of these sections.

There are differences in the style and geometries used in the two sections in Figure 7. Section A predominantly builds the wedge along low-angled but relatively simple imbricate thrusts that generally ramp straight up through the off-scraped sequences. It also maximizes the extent and thickness of lower Pleistocene material in slope basins. There is some evidence that the Pleistocene section does show variations in thickness of between 25-90 m on the complex, with particularly thick accumulations at Sites 541 and 671 (see Fig. 4). Consequently, the net tectonic shortening in Section A is low, being on the order of 25%.

Section B (Fig. 7) makes more use of secondary flats and thrust imbricates developed within the Pliocene and locally in the Miocene. This allows a greater variety of structures to be developed in the wedge, maximizes the component of tectonic thickening, and keeps the development of the Pleistocene filled slope basins to a minimum. Figure 8 is an illustration of a data compilation and interpretation right at the toe of the wedge. The small thrust at approximately 215 m sub-bottom at Site 676 (See Fig. 3) appears to correlate with the cut off of a series of subhorizontal reflectors on CRV 128. The interpretation is that this thrust must continue as flat along the base of the Pliocene section, with the implication that this may have been a common frontal geometry in the past. Also shown on the interpretation is a small backthrust noted during recent submersible dives by S. Lallemant and others on the toe of Barbados Ridge (Lallemant et al., unpublished data). In addition to the above, some representation has been made in Section B (Fig. 7) of the relatively abundant minor folds and duplex structures that may be developed just above the basal décollement in the lower and middle Miocene section. Evidence for these comes from the variations in bedding dips and the numerous minor scaly clay zones developed 40-50 m above the basal décollement. These features are particularly evident at Sites 541 and 671 (see Fig. 4). Tectonic shortening in Section B, using the geometries and assumptions described above, is on the order of 36%. However, even in this solution borehole data requires the inclusion of thick sequences of Pleistocene section in the region of Sites 671 and 542.

In summary, the main features that come out of the borehole data and line-balancing analysis are the following.

1. Within the frontal regions of the accretionary complex major thrust spacings are on the order of 1-1.5 km (see Fig. 7).

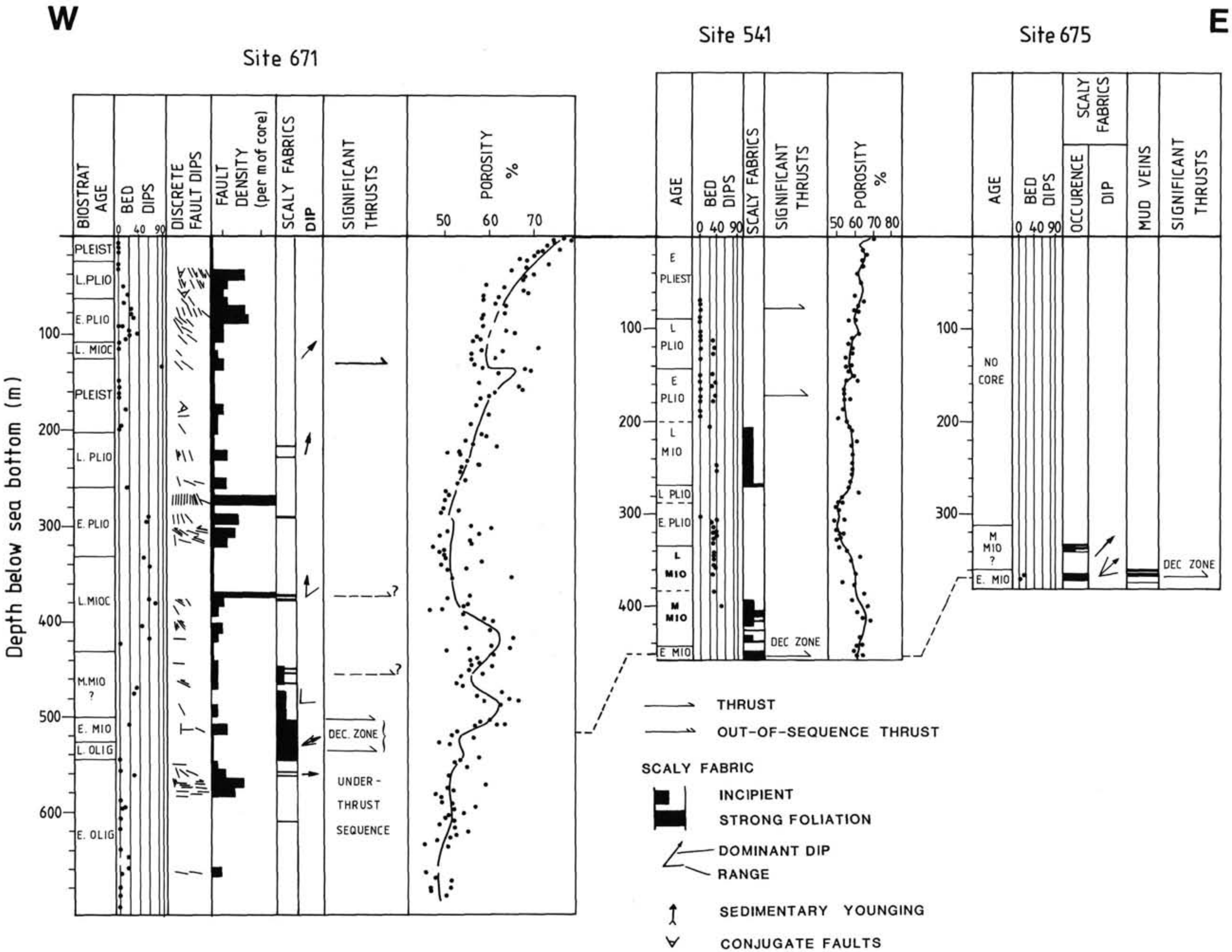


Figure 4. Composite structural logs of Sites 675, 541, and 671B, drilled during DSDP Leg 78A and ODP Leg 110. Site 675 is to the west of Site 542. Note westward increase in structural complexity.

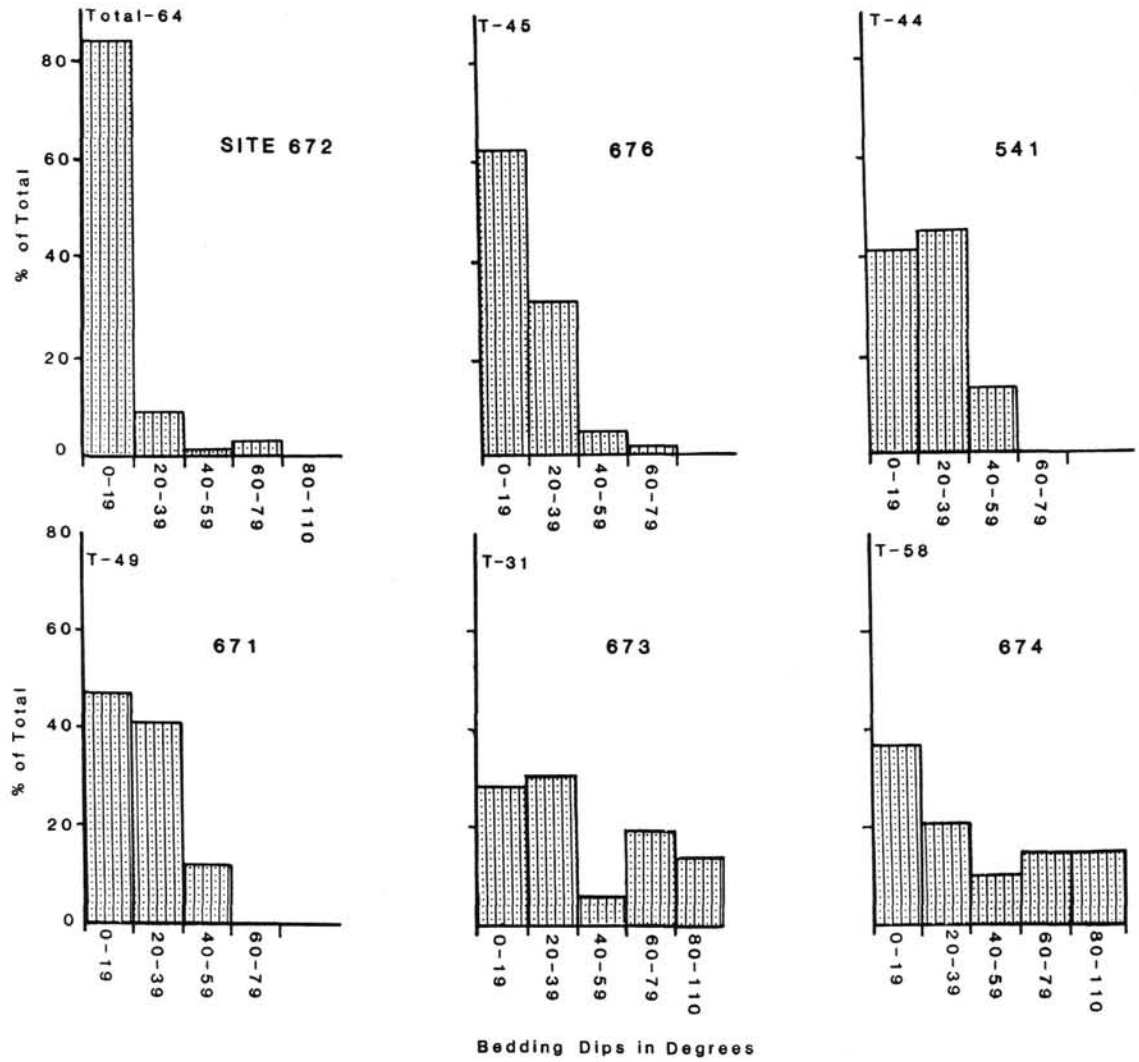


Figure 5. Histogram illustrating the general increase in bedding dips across the wedge from Site 672 to Site 674 (see Fig. 1 for relative locations.) All overturned bedding has been grouped into the 80°–110° category.

2. Thrust repetition is the dominant mechanism whereby significant shortening and structural thickening occurs in the wedge.

3. On the basis of line balancing (Fig. 7) there is approximately 25–36% shortening across the first 4–5 major imbricate packets.

Line-balancing techniques can usefully be compared to volume balances across the same region of the complex. To simplify the volume balance calculations, relatively simple geometries were taken for the major imbricate thrusts (see Fig. 9A). The volume of each thrust slice can be estimated and the original basal length restored individually. The initial thicknesses of the Miocene and Pliocene sections were taken from the reference Site 672. The Pleistocene section, however, appears to be generally thicker in parts of the section accreted to the wedge. To account for this, average values of the thickness of Pleistocene in the wedge were estimated from borehole data (see Figs. 3 and 4). As a result an original sedimentary thickness of 230 m was taken for the first three thrust sheets (TSO to TS2, see Figs. 9A and 9B). As there is a greater thickess of Pleistocene material in thrust slice TS3 (at Sites 541 and 671), a 260-m original sedimentary thickness was used in this case. The calculated parameters and notation are presented in Figure 9B. The total displacement along the basal décollement is 140 m east of branch point 1 (Bl), 590 m east of branch point 2 (B2), 1900 m east of branch point 3 (B3), and 3050 m east of branch point 4 (B4). Assuming that no compaction has occurred during deformation and tectonic loading, we calculate a total shortening of approximately 32%.

SUMMARY AND SIGNIFICANCE OF RESULTS

Cores from Site 671, 675, 676, and 542 demonstrate that the affects of the lateral compressive stresses resulting from plate convergence are confined to the off-scraped sequences above the basal décollement. Significant lateral compressive stresses do not appear to affect the sequences below the décollement in the first 5 km of underthrusting. Near the deformation front, initial shortening in the off-scraped sequences is primarily taken up by thrusting, with folding being confined mainly to the regions near the base of the hanging wall sequences (Fig s. 3, 4, and 7). Back rotation of the thrust packets during imbrication probably accounts for a large part of the westward increase of the bed dips in the frontal 5 km of the accretionary wedge. Unfortunately, there are problems in constraining the overall timing of accretion at the toe of the wedge by looking at the slope

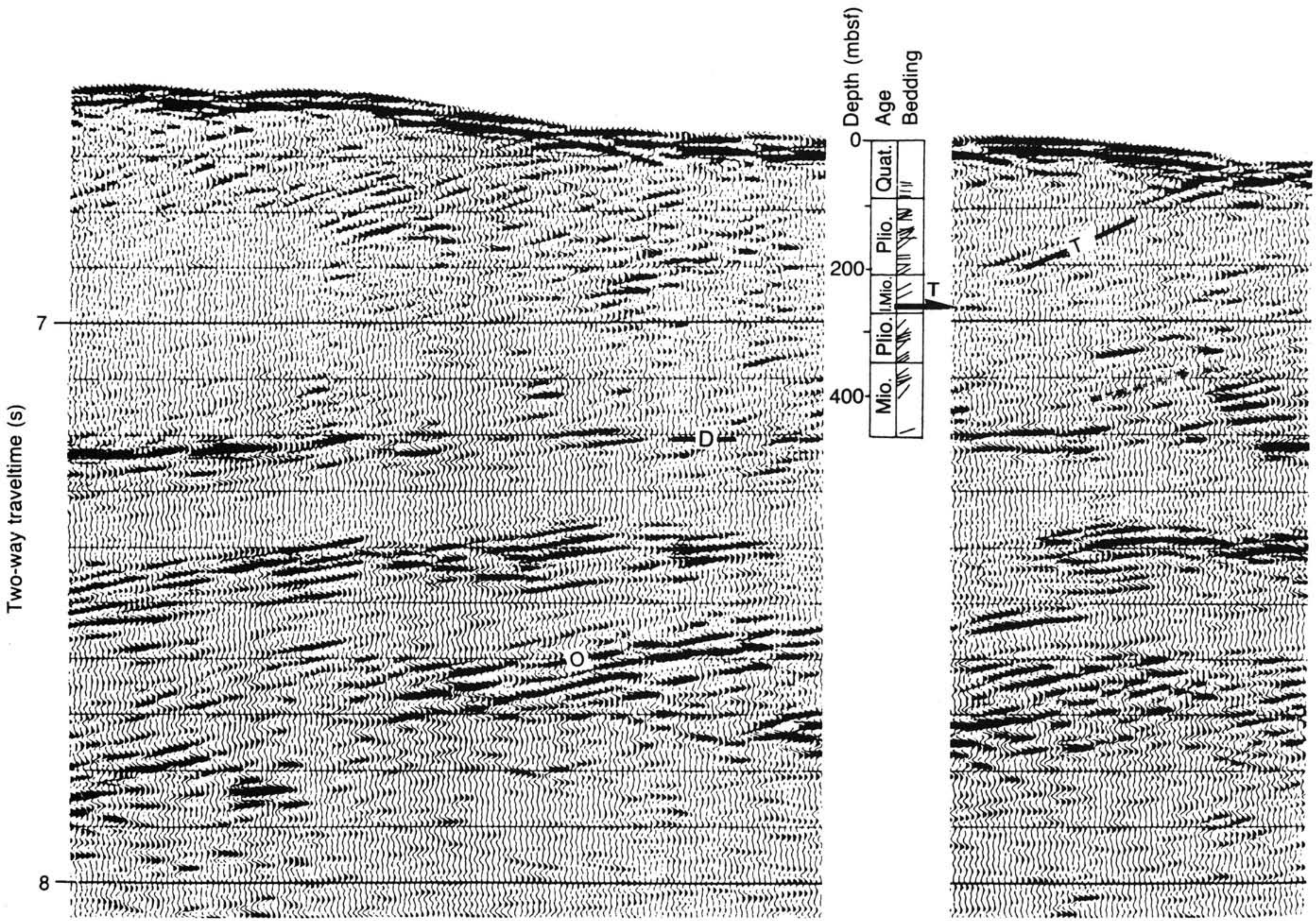


Figure 6. Seismic reflection line CRV 128 (shotpoints 350 to 450) and projection of DSDP Leg 78A Hole 541 (see Fig. 4). T: thrust; D: Décollement; Top of Oceanic Crust is at zero. Figure adapted from Mascle, Moore, et al. (1988).

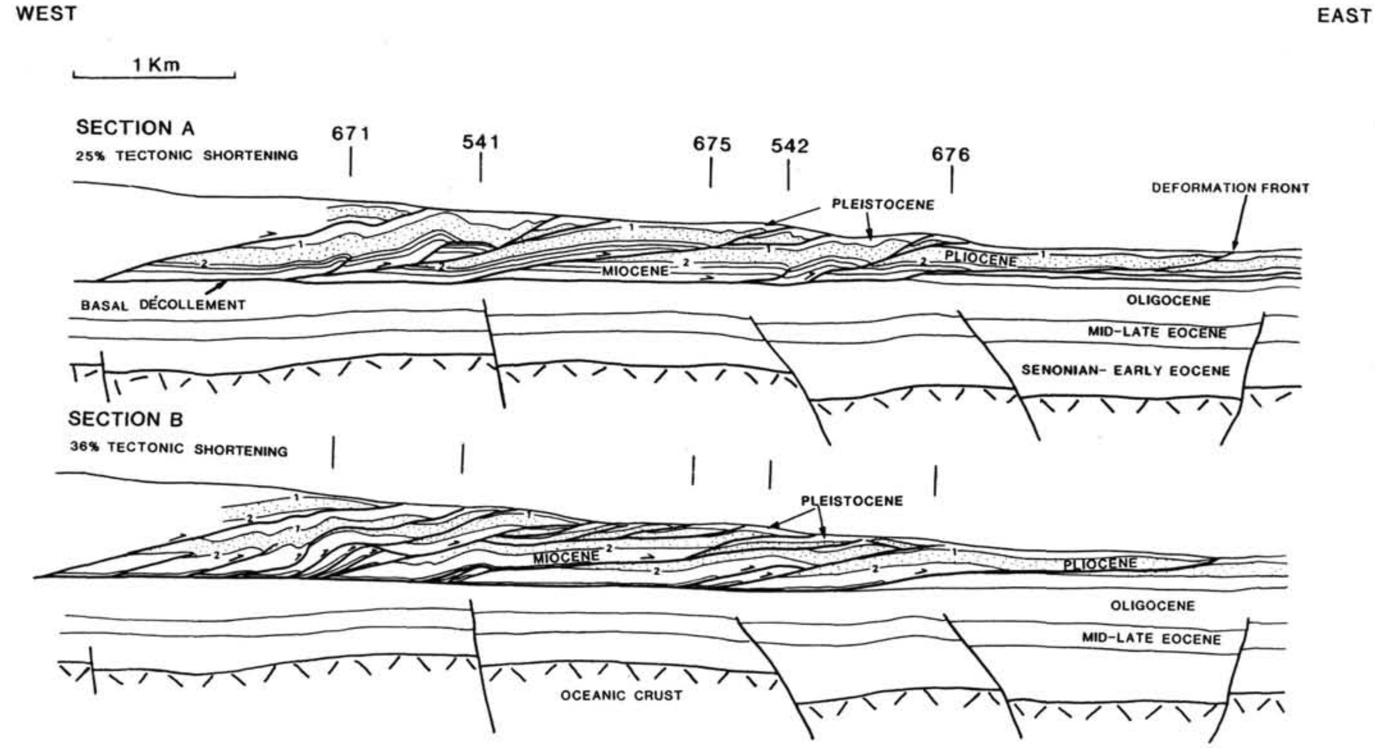


Figure 7. Two possible end-member versions of line-balanced sections that can be constructed using borehole data from DSDP Leg 78A and ODP Leg 110, and seismic line CRV 128. Vertical and horizontal scales are equal.

cover basal unconformity. These are due to a lack of a upper Pleistocene or Quaternary section (see Figs. 3 and 4). Most probably, the wedge between the toe and Site 671 has been accreted in mid-upper Pleistocene to Holocene times but we cannot be sure.

There is insufficient data on the internal geometries in the wedge to completely constrain the line-balanced sections (Fig. 7). Consequently, the resulting shortening estimates are not the only possible solutions to the data represented by the boreholes and seismic section. For example, with the present data the effects of bulk deformation are harder to assess but should not be ignored. Conjugate sets of steeply inclined reverse faults and minor folds are relatively common (Figs. 3 and 4). Taken together they may account for significantly more horizontal bulk shortening and vertical thickening than can be easily represented by our line-balanced sections. However, we believe (bearing in mind that we have ignored compaction affects) that it would be difficult to define a reasonable cross section that has a significantly greater shortening than either the maximum line-balancing estimate of 36% (Section B of Fig. 7) or the volume-balancing estimate of 32% (Fig. 9).

The only poorly defined variable that may affect these shortening estimates is the volume loss occurring as a result of pore-fluid expulsion and resulting compaction of the sediments in the wedge. A large volume loss could significantly drive up the maximum estimate of shortening in the wedge. Volume could also have been lost as a result of erosion of the surface of the wedge. However, there is no evidence for significant erosion in the region of the balanced sections. In contrast, there is evidence that significant compaction occurs during accretion. Shipboard Scientific Party (1988) used the porosity data from the ODP holes to estimate that, on average, a 22% volume loss has occurred in the post lower Miocene section at Site 671 relative to the sediments at the reference Site 672. The bulk of the compaction apparently occurred in response to tectonic thickening and increased vertical loads. A small amount of additional compaction also appears to have resulted from lateral compressive stresses (Moore, 1989). However, these lateral compressive effects appear to be relatively small and, given the large scatter in the porosity data, it is hard to judge their significance. It must be noted at this point that Site 671 is in the thickest part of the wedge covered by the balanced sections. Consequently, the average volume loss throughout the toe of the wedge will be less than 22%. For instance, the compaction at Site 676, right at the toe of the wedge, is negligable when compared to Site 672. We propose that an average volume loss of 14% would be closer for the toe of the wedge as a whole. Taking a volume loss of 14%, the original volume-balance estimate of 32% shortening (Fig. 9) can be increased to a corrected value of nearer 40%.

We have not tried to draw line-balanced sections that have been corrected for compactional affects because of the lack of constraints on where and how such porosity loss actually occurs in the wedge. Different lithologies, for example, do not volumetrically compact at the same rate, and it would be a major project in itself to derive reasonable two-dimensional volume-loss data from the borehole and porosity logs (even if this could be done with the required accuracy). By ignoring volume loss our line-balancing estimates should, therefore, also be on the low side by an amount similar to that of the volume-balancing estimates.

SUBSEQUENT THICKENING OF THE ACCRETIONARY WEDGE (SITES 673 AND 674)

There are significant developments (see below) in both the stratigraphy of the accreted section and its deformation style between the region within 5 km of the toe of the accretionary wedge (Sites 676–671) and the region that is some 12–18 km west of the deformation front (Sites 673–674). The following features

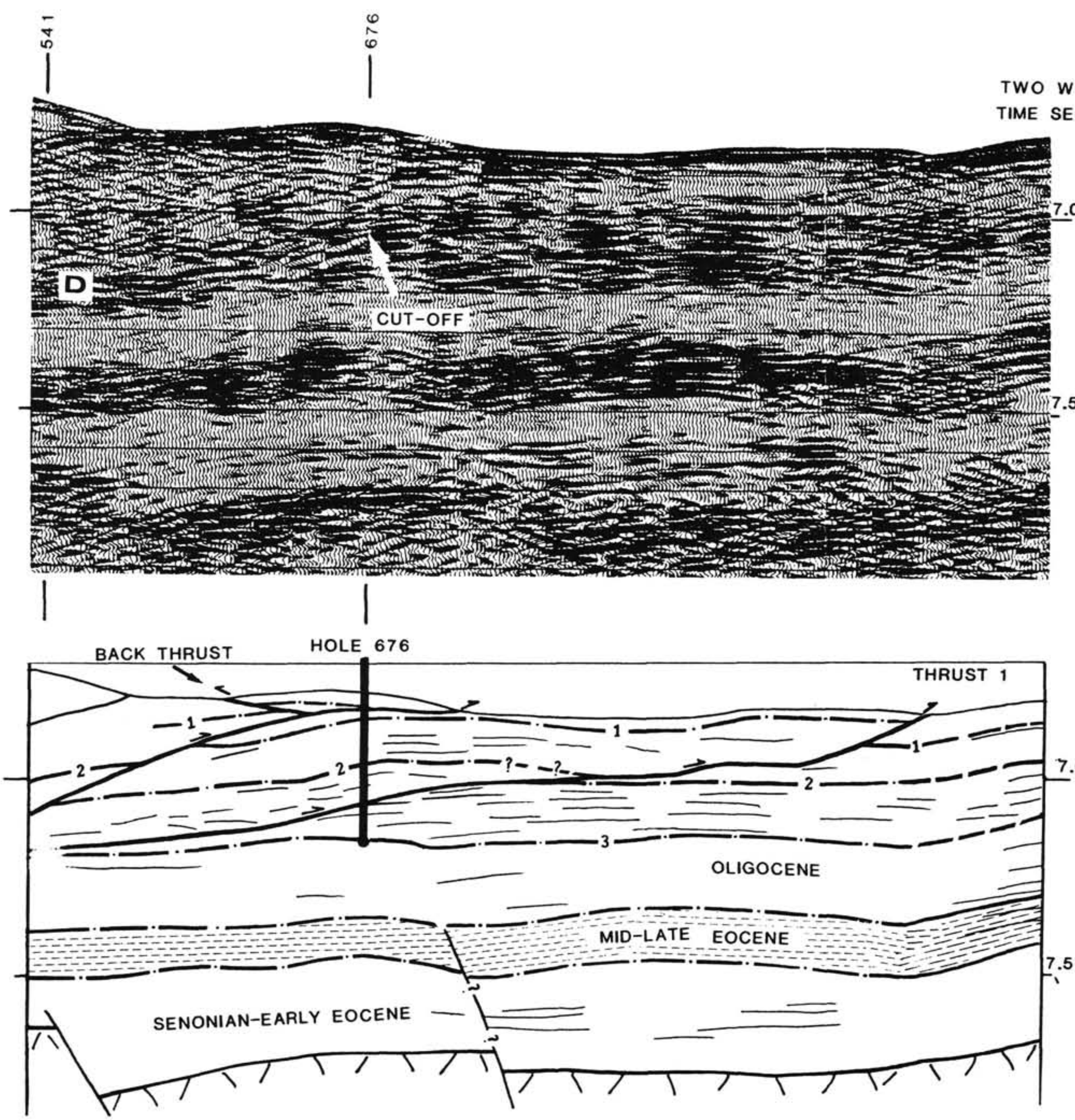


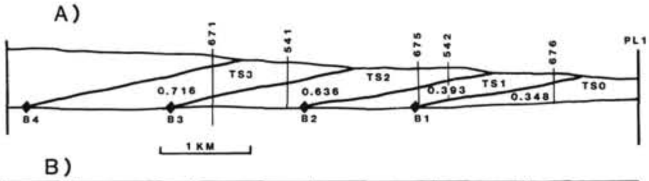
Figure 8. Portion of seismic reflection section CRV 128, and corresponding interpreted line drawing. Note the seismic cut-off that matches closely with a thrust at approximately 210 mbsf at Site 676 (Fig. 3). We propose that the small thrust continues as a flat along the base of the Pliocene section and cuts to the surface at the position denoted by thrust 1. (1: Pliocene-Pleistocene boundary; 2: Miocene-Pliocene boundary; 3: approximate position of lower Miocene unit associated with basal detachment).

will be discussed in some detail below: (1) significant erosional unconformities associated with slumps and debris flow deposits, (2) development of both large and small folds associated with overturned bedding, and (c) secondary thickening by out-of-sequence thrusts. Behrmann et al. (1988) and Brown and Behrmann (this volume), provide a more detailed account of small-scale structures and additional structural development.

Erosional Unconformities and Debris Flows

The nature and age of the slope deposits are important for two reasons. First, it may be possible to constrain the age of accretion of different portions of the wedge and so determine its rate of growth. Second, it may be possible to document whether significant volumes of the accretionary wedge have been re-

A)



B)

Thrust Slice No.	Undeformed Basal Length (km)	Deformed Basal Length (km)	Basal Displacement (km)	Cross Sectional Area (km²)	Original Sedimentary Thickness (km)
TS0	2.300	2.160	0.140	0.530	0.230
TS1	1.700	1.250	0.450	0.393	0.230
TS2	2.820	1.510	1.310	0.636	0.230
TS3	2.750	1.600	1.150	0.716	0.260

Figure 9. A. Schematic representation of model used for volume-balance estimates across the toe of the Barbados Ridge complex. B. Table of values pertinent to the volume-balance calculations.

moved by erosion. Erosion is important because it may unroof the deeper regions of the wedge, affect porosity profiles, and expose regions of the wedge that would otherwise be too deeply buried to sample with the drill bit. Large-scale erosion may also promote continued thrust faulting in the internal regions of the wedge as a consequence of the need to sustain a "critical taper" (See Dahalen et al., 1984; Davis et al., 1983). As a general point, the upper Pleistocene section at Sites 671 and 673 contain reworked Eocene and Oligocene radiolarians (see site chapters, Mascle, Moore, et al., 1988. Therefore, it would appear that these units were exposed and being eroded from the surface of the wedge during the Pleistocene.

At Hole 673B (Fig. 10) the lower Pleistocene section is relatively undeformed, contains debris flow deposits (see Chapter 6 of Mascle, Moore, et al., 1988) and is most probably of slope sediment origin. It is not possible to tell from sedimentary characteristics whether the upper Pliocene and indeterminate units (approx. 25–60 mbsf) that lie below this Pleistocene unit have likewise been deposited as slope sediments (as has been depicted in Fig. 10). However, the extremely variable bed dips and numerous faults strongly suggest that they are not *in situ*. At the base of this upper disturbed sequence (at approximately 75 mbsf) there is a sedimentary breccia (Mascle, Moore, et al., 1988, Chapter 6) with lower Miocene material below. This lower sedimentary boundary represents a stratigraphic break with potentially more than 100 m of missing section (comprising most of the Miocene and perhaps parts of the Pliocene). Unfortunately, no biostratigraphic dates were recovered from the matrix of the breccia. In contrast to Hole 673B, nearby Hole 673A (see Site 673 chapter of Macle, Moore, et al., 1988) was drilled down through 20 m of debris flow deposits straight into Miocene material below another potentially large stratigraphic break.

Farther up the accretionary wedge at Site 674 (Fig. 10), the upper 100 m of section contains lower Pleistocene debris flow deposits (see Site 674 chapter, Mascle, Moore, et al. 1988) and a relatively intact sequence of bedded upper Pliocene to lower Pleistocene sediments (40–60 mbsf). There may also be a Miocene section but it was not biostratigraphically dated. This upper 100 m of section is bounded on its base by a major low-angle fault at 100 mbsf. This fault is associated with intense scaly fabrics and contains Oligocene material. Just below this fault is another Pliocene section (100–130 mbsf). It differs from the Pliocene sequences above the low-angle fault in being heavily deformed and having an appreciably lower porosity (see porosity at Site 674, Fig. 10).

Interpretation

At Site 673, sedimentary breccias and debris flow deposits coupled with the apparent stratigraphic break at 75 mbsf suggest that this break is a large erosional unconformity at the base of a slope cover sequance. The age of the basal contact is unknown. Although we are fairly sure that the Pleistocene section is of slope origin, we are not certain about the Pliocene unit at 125–130 mbsf. Judging from the deformation in this Pliocene unit, we propose that it has either been imbricated with the slope sediments on a thrust fault or slid in from farther up the slope on a shallow slump plane. In either case, this unit could have originaly been part of the accreted sequances.

At Site 674, the situation is even more complicated. The porosity jump across the low-angle fault at 100 mbsf suggests that the Pliocene section at 100–130 mbsf was buried much more deeply in the past than at present. The intense deformation suggests that it was probably part of the accreted sequances. Erosion is generally the simplest way of removing material from the top of the complex. However, the porosity discordance lies across the low-angle fault. Whether the upper 100 m of section are all slope sediments or not, the fault indicates that they are displaced relative to the complex below. We propose a thrust-faulted erosional unconformity (with several hundred meters of section missing) as the simplest geometry that would explain most of the features associated with the contact at 100 mbsf. The upper section could have been laterally displaced a considerable distance from an original position on an older portion of the wedge farther to the west (presumably accreted in pre-Pliocene times). As will be discussed further below, the structure at 100 mbsf may be an out-of-sequence thrust that has been relatively recently active.

Folding and Overturned Bedding

The bulk of the accreted section below the unconformity at Site 673 is composed of a lower Miocene sequence containing the stratigraphic horizon that is associated with the basal décollement in the frontal 5 km of the complex. As this horizon at Site 673 is relatively undeformed, the basal décollement appears to have been situated at a somewhat lower stratigraphic horizon during the accretion of this sequance. Although sedimentary younging evidence is lacking in this section, good biostratigraphic control (Clark et al., this volume; Chapter 6, Mascle and Moore, 1988) indicates that parts of the section at Site 673 are overturned. At least one, and possibly several, anticlinal and synclinal folds have been transected in this hole (Fig. 10). The bedding dips are consistent with either a recumbent open, anticline geometry or an overturned tight, isoclinal fold. As we only know the dips of the beds and not their strikes, we cannot further constrain the detailed geometry of the folds. We can say, however, that they probably have half-wavelengths on the order of 100 m. The approximate positions of the hinge zones in the lower folds are also marked by regions of scaly fabric development, suggesting that the hinges are faulted out.

Several small overturned folds with inverted limbs were also documented in the middle Eocene section at Site 674 (between 150–185 mbsf). The hinges of the folds are commonly faulted. The folds have half-wavelengths on the order of 10 m and were clearly defined on sedimentary younging evidence (cross bedding and grading). Brown and Behrmann (this volume) also described small symmetrically folded calcite veins and local isoclinally folded veins with boudinaged limbs and axial plane fabrics at Site 674.

Interpretation

Many of the same stratigraphic units are present in the upper and lower limbs of the folds at Site 673. However, porosities of

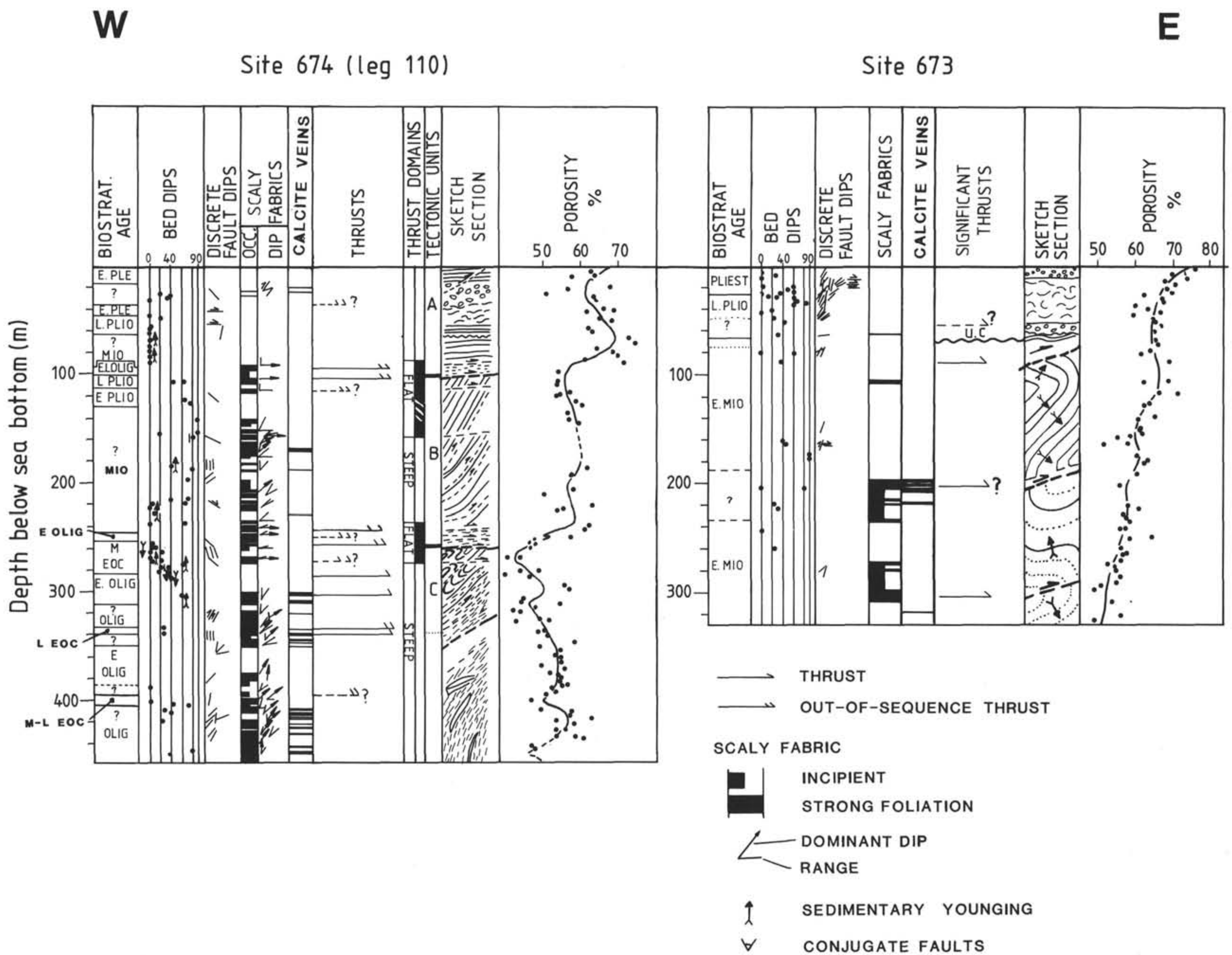


Figure 10. Composite structural logs of Sites 673 and 674 drilled during Leg 110. Site 673 is to the west of Site 671. Note westward increase in structural complexity. Ages denoted with a ? are correlated on lithostratgraphic evidence only, due to the absence of good biostratigraphic data.

the units in the folds show a steady downward decrease (see porosities on Fig. 10). This suggests that sufficient time has elapsed for the strata in the lower limb to have undergone compaction after folding had occurred. The folds at Site 673 are, therefore, probably not very recent structures.

The general increasing intensity and numbers of folds westward and the eventual occurrence of overturned bedding in asymmetric folds at Sites 673 and 674 are part of the continuing response of the wedge to tectonic compression. In the toe of the accretionary wedge, within 5 km of the accretionary front, discrete thrusts initially appear to be the dominant mechanism of shortening in the system. However, farther back in the system folding does appear to have become an increasingly significant additional thickening process.

Out-of-Sequence Faulting

Two main types of fault geometry were observed at Site 674 at a distance of 18 km from the accretionary front. There are large numbers of thrusts that emplace older strata over younger strata (see Fig. 10). Toward the base of the hole they become so numerous that scaly fabrics are developed throughout much of the section. In contrast to these are faults that place young material onto older material across a large stratigraphic break. The two best-documented examples are at 100 and 255 mbsf (Fig. 10). These faults are associated with intense sub-horizontal scaly fabrics. The fault at 100 mbsf contains dismembered sequences with a wide range of ages (e.g. upper and lower Oligocene) and lies below a Pliocene (and possible Miocene) units. As discussed above, this fault may be a faulted unconformity between displaced slope cover sequences and an eroded portion of the wedge below. The lower fault at 255 mbsf emplaces lower Oligocene and possible Miocene strata directly over a middle Eocene unit. The faults at 110 mbsf and 255 mbsf are also associated with a downward increase in porosity which is again consistent with the removal of section across them. Two deeper faults at 340 mbsf and 400 mbsf also cut-out section, but are different from the upper ones in being associated with steeply dipping scaly fabrics and not having clearly defined downward decreases in porosity across them.

Interpretation

The faults that anomolously cut-out section could be normal faults. If so, they are major features that indicate significant extension has occurred in this portion of the wedge (Fig. 11). Platt (1986) has proposed that normal faulting in orogenic wedges may occur in response to the destabilization of the critical taper of the wedge (see Dahalen et al., 1984) in response to large-scale underplating of material at depth. We cannot totally discount this possibility because underplated material, in the form of an Eocene and a Oligocene section, conceivably may have been encountered in the wedge at Site 674 (see below). However, several factors point to out-of-sequence thrusting as a more likely explanation:

1. Discontinuous, low-angle seismic reflectors begin to become abundant in this portion of the wedge (Figs. 12 and 13). The reflector geometries are consistent with thrusts but not with normal faults. The large porosity/density variations across the two low-angle faults at 100 and 255 mbsf may, for instance, provide a sufficient contrast in seismic velocities for the thrust zones to be directly imaged as seismic reflectors.

2. No grabens or normal fault scarps can be observed upslope from Site 674.

3. There is no small-scale structural evidence that is consistent with normal faulting, but there are abundant compressional features. These range from the thrusts that emplace older over younger material to the folds that are developed in the middle Eocene section immediately below the out-of-sequence fault at 255 mbsf.

4. Elsewhere in the Barbados Ridge complex, out-of-sequence thrusts are commonly associated with an obvious break in slope of the surface of the wedge. A good example in a nearby portion of the wedge is illustrated on a seismic reflection section in Westbrook et al. (1982). There is a similar break in slope imaged on CRV 128 (Fig. 1) at Site 674 (see also Fig. 5 in Chapter 1 of Maacle, Moore, et al. (1988). This lends credence to the view that out-of-sequence faulting may have been recently active in this region of the wedge.

Models that might explain both the geometry of the out-of-sequence thrusts and the presence of Oligocene and Eocene strata in the wedge are discussed in the following section (see Figs. 14 and 15). Out-of-sequence thrusts are one mechanism by which the interior regions of both accretionary wedges and orogenic belts can continue to thicken away from the deformation front. Previous deformation commonly rotates bedding and early thrusts to high angles (see Fig. 5). These are, consequently, not in favorable orientations for reactivation as thrusts. As a result, out-of-sequence thrusts are generally cross-cutting features and can juxtapose units of widely differing ages and geometries. We again emphasize that the proposed out-of-sequence thrusts are active in a region of the wedge where substantial erosion may have occurred (see previous section). Erosion would tend to thin the wedge, whereas out-of-sequence thrusting would tend to thicken it. Perhaps some dynamic balance is being struck between these two processes to maintain a stable critical taper (see Dahalen et al., 1984).

IS THE EOCENE-OLIGOCENE SECTION AT SITE 674 FRONTALLY ACCRETED OR UNDERPLATED MATERIAL?

Oligocene and Eocene strata form part of the underthrust series below the present basal décollement zone of the toe of the wedge to the east of Site 674. Approximately the same décollement geometry continues up until at least the region of Sites 673 and 674 (see Fig. 13 below). However, Eocene and Oligocene material is again encountered in the wedge at Site 674.

Two possibilities may account for the inclusion of the Oligocene-Eocene strata in the wedge. Either the basal décollement was deeper in the past (Fig. 14), or the strata were underplated at a position farther to the west of the deformation front (Fig. 15). Information from one borehole is not enough for a defini-

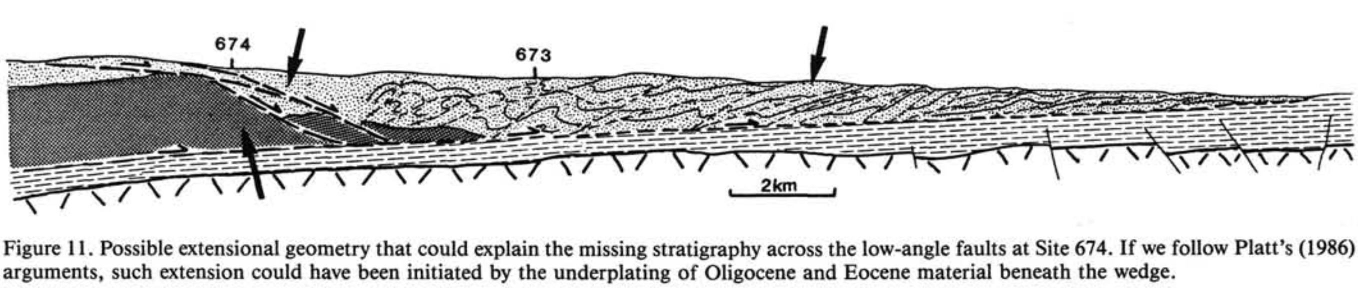


Figure 11. Possible extensional geometry that could explain the missing stratigraphy across the low-angle faults at Site 674. If we follow Platt's (1986) arguments, such extension could have been initiated by the underplating of Oligocene and Eocene material beneath the wedge.

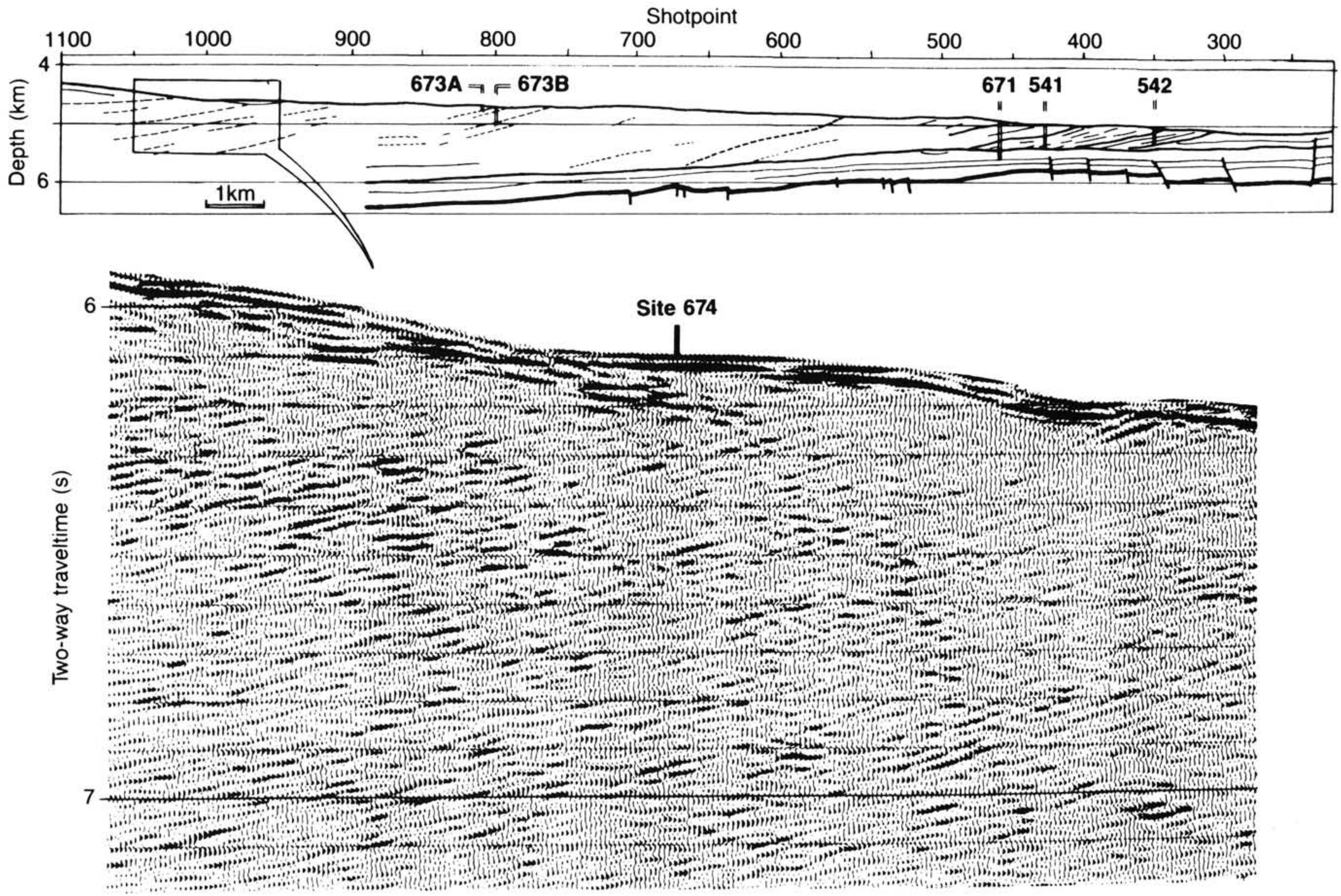


Figure 12. Line drawing and extracted portion of CRV 128 in the region of Site 674 (taken from Mascle, Moore, et al., 1988). Note the relatively low-angle, discontinuous, west-dipping reflectors that are abundant in this region of the wedge.

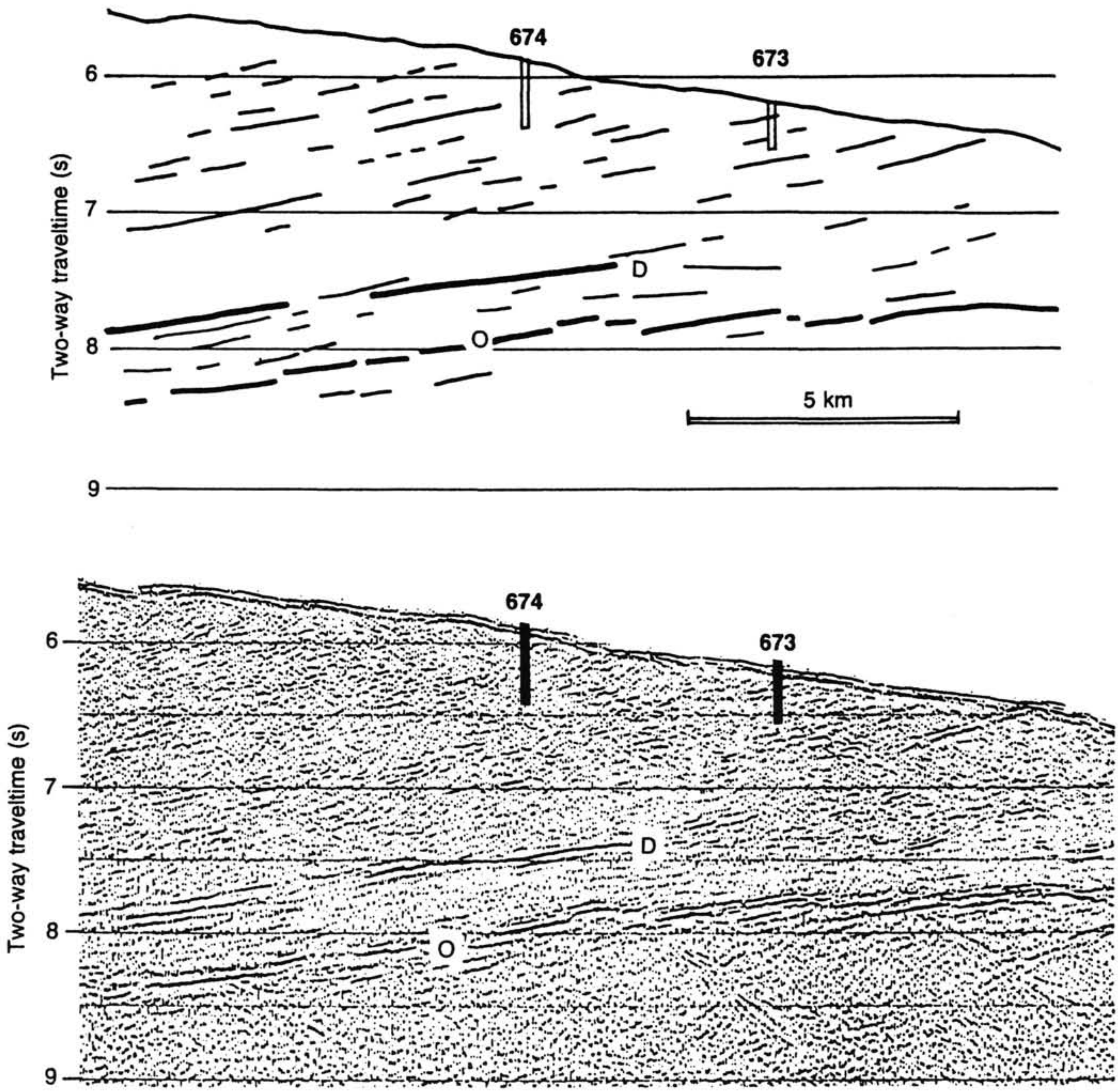


Figure 13. Line drawing and extracted portion of A1 in the region of Site 674 (taken from Mascle, Moore, et al., 1988). Note the relatively low-angle, discontinuous, west-dipping reflectors that are abundant in this region of the wedge. Line A1 runs at approximately 45° to the strike of deformation front (see track chart, Mascle, Moore, et al., 1988) and so is an oblique section. The approximate along-strike positions of Sites 673 and 674 have been projected onto the sections. D: décollement; O: top of oceanic crust.

tive answer, but a general consideration of the geometries observed at Site 674 leads us to favor the latter solution.

At Site 674 the cored sequence can be divided into three major tectonic units (Tectonic Units A, B, and C on Fig. 10). The unit boundaries are placed at the major, low-angle, out-of-sequence structures and porosity discordances at 110 and 255 mbsf. Each tectonic unit also contains a major stratigraphic grouping. Tectonic Unit A contains probable slope sediments of Plio-Pleistocene age. Tectonic Unit B contains accreted sediments of probable Miocene and Pliocene age. Tectonic Unit C contains Eocene-Oligocene strata. Note that essentially the out-of-sequence structures have crudely reconstructed the original stratigraphic order (although the middle and upper Oligocene is missing) of these sediments and that this is reflected in the porosity logs (Fig 10). Note also the general moderate to steep dips of the scaly fabrics, thrusts, and bedding in Tectonic Units B and C. It seems unlikely that these more steeply dipping thrusts are in a favorable orientation to be active at present.

The main feature to which we draw attention is that, apart from the sheared material in the out-of-sequence fault zones

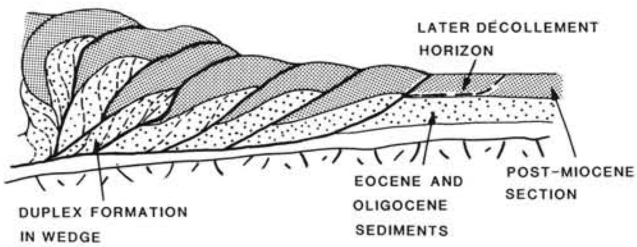


Figure 14. Sketch showing a possible model where the décollement was lower in the sedimentary section during initial frontal off-scraping at some point in the past. The model also illustrates how the Oligocene and Eocene could have formed a duplex within the wedge during the early phases of accretion.

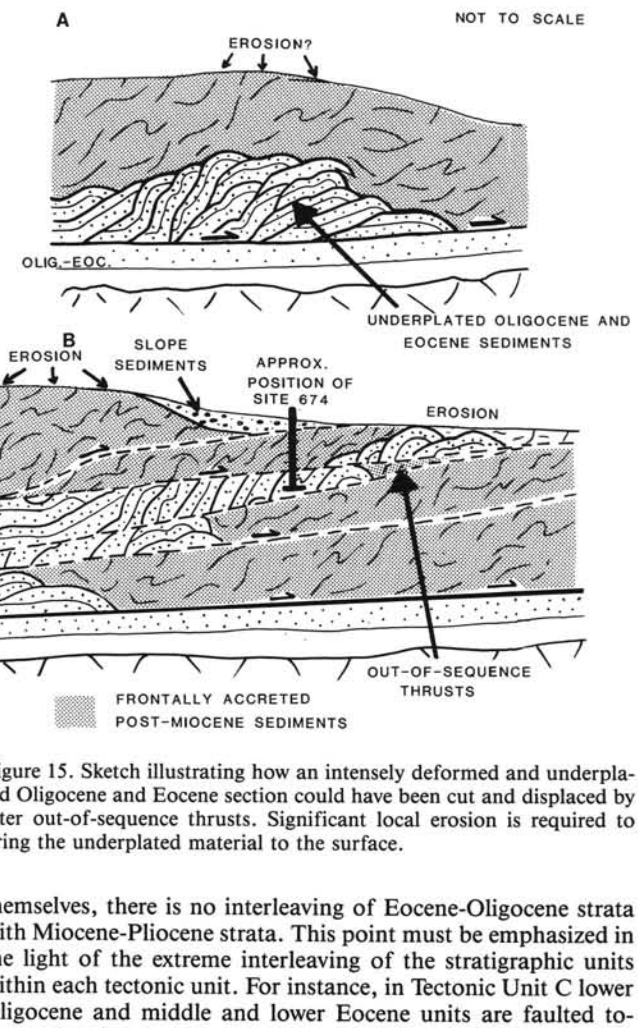


Figure 15. Sketch illustrating how an intensely deformed and underplated Oligocene and Eocene section could have been cut and displaced by later out-of-sequence thrusts. Significant local erosion is required to bring the underplated material to the surface.

themselves, there is no interleaving of Eocene-Oligocene strata with Miocene-Pliocene strata. This point must be emphasized in the light of the extreme interleaving of the stratigraphic units within each tectonic unit. For instance, in Tectonic Unit C lower Oligocene and middle and lower Eocene units are faulted together in almost every combination on both probable in-sequence, and out-of-sequence thrusts. However, no part of the Miocene and Pliocene sequence is found in this Unit.

Interpretation

It seems to us that the simplest way to derive this geometry is to complexly deform each tectonic and stratigraphic grouping in widely separate regions of the wedge and thrust them together only at the last moment along the out-of-sequence thrusts.

Figure 14 illustrates an off-scraped geometry that may conceivably allow the development of the features seen at Site 674. This sketch shows the Oligocene-Eocene section somehow being interleaved in a duplex within the wedge without involving the post-Miocene section. The out-of-sequence thrusts then cut up this already complex sequence.

Figure 15 shows an alternate solution where the post-Miocene section could have been deformed as a separate unit during initial off-scraping, with the Eocene-Oligocene section experiencing more intense deformation during duplex formation and underplating (Fig 15A). These completely separate tectonic elements could then be juxtaposed during subsequent out-of-sequence thrusting (Fig. 15B).

Both models illustrated in Figures 14 and 15 can explain the missing section and mixture of ages in the out-of-sequence thrusts. However, we suggest that the underplating model (Fig. 15) has a simpler overall geometry. In addition, we do not see why the denser and stronger Oligocene and Eocene units undergo intense duplex formation and thrusting in the wedge (Fig. 14) without including the weaker Miocene and Pliocene sediments. It seems to make far more sense that the Oligocene and Eocene strata were underplated at depth beneath an already thickened, dewatered, and stronger post-Miocene section (Fig. 15). There is also some independent evidence for more recent underplating from seismic reflection line CRV 128 (Fig. 16). A sub-horizontal reflector is imaged above the décollement zone near Site 673 (Fig. 15). The thickness of the unit between the reflector and the basal décollement zone below is very similar to that of the correlatable underthrust Oligocene to middle Eocene section. This reflector could represent the easternmost extent of a large body of underplated material in the wedge.

SUMMARY

The combined results from DSDP Leg 78A and ODP Leg 110 provide a good basis for constraining the progressive change in structural style that occurs within 18 km of the deformation front (Fig. 17). Initial off-scraping occurs predominantly by thrust repetition (Fig. 17). The Seismic reflection and borehole data allow the construction of two endmember line-balanced sections across the frontal 5 km of the wedge. In the line-balance section that uses significant sedimentary thickening of the lower Pleistocene on the wedge, tectonic shortening may be as low as 25%. Alternatively, 36% tectonic shortening can be accommodated where slope sediment thicknesses are kept to a minimum. This larger tectonic shortening estimate compares well with the general volume-balance estimate of 32% shortening. However, these estimates do not take into account the volume loss that has occurred in the wedge due to compaction. When an average 14% volume loss is considered the volume-balance estimate rises to nearer 40% shortening.

With increasing distance back in the wedge, bed dips steepen and thickening by large- and small-scale folding becomes increasingly prominent (Site 673). Asymmetric folds continue to develop until overturned bedding is observed in the wedge at Site 673, some 12 km from the accretionary front (Fig. 17).

Perhaps some of the most exciting structural discoveries of Leg 110 were made in the western region of the wedge (at Site 674). They are vital insights as to the kinematics of continuing wedge thickening, and a possible interrelationship with mass-wasting effects (Fig. 17). The balance of the evidence points to the development of out-of-sequence structures in the region of Site 674. An underplated section comprising Oligocene and Eocene strata may also have been encountered at this site (Fig. 17). In the same region, there is much evidence for significant erosion of material from the wedge. Erosion would tend to counteract the affects of the thickening processes and thus enhance

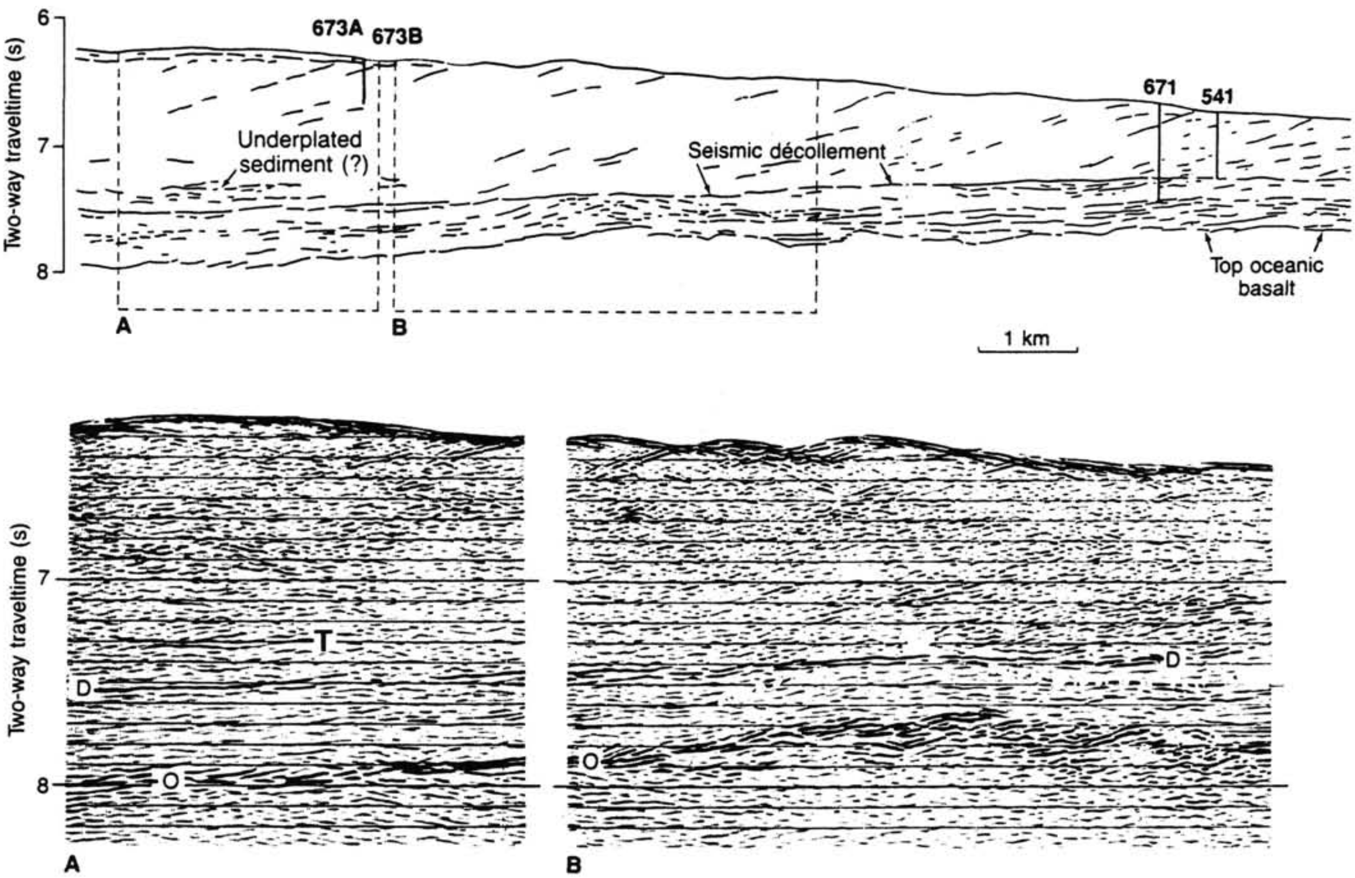


Figure 16. Line drawing and portions of CRV 128. Note the fairly strong reflector (T) just above, and parallel to, the basal décollement (D) below Site 673 (inset A). The reflector T may be the top of an underplated Oligocene and Eocene section. O: oceanic crust.

the prospects for continued out-of-sequence thrusting in this region and reduce the chances that underplating might initiate extension in the deformation complex.

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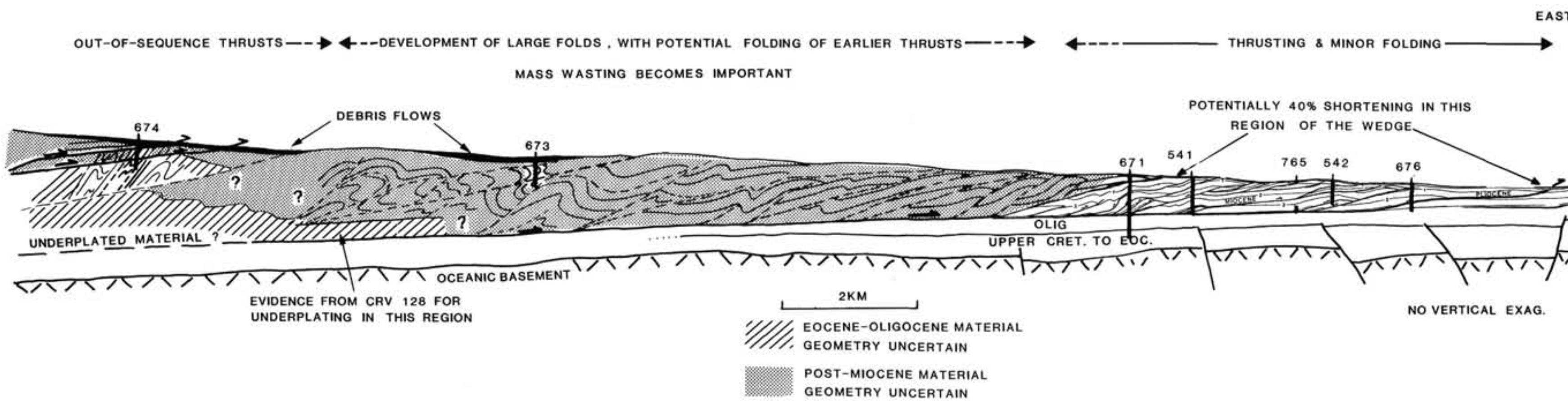

Figure 17. Schematic summary cross section illustrating the main mesoscopic structural features associated with the initial off-scraping and subsequent thickening of the toe of the Barbados Ridge accretionary wedge in the region of ODP Leg 110.