Cross section of an accretionary wedge: Barbados Ridge complex

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ABSTRACT

Many major geological terranes are interpreted as accretionary complexes, and there are several speculative models for their structure and mode of formation. The seismic reflection section across the Barbados Ridge complex at lat 16°12′N presented here shows, for the first time, the entire cross-sectional shape of a large accretionary wedge and its forearc basin. Atlantic oceanic crust underlies 122 km of the wedge and then passes beneath the crust of the forearc of the Caribbean plate, where it can be traced 15 km farther; it dips landward at 9°. The forearc basement dips seaward to meet the ocean crust. The maximum thickness of the wedge is about 10 km. A layer of sediments, 1 km thick, is drawn beneath the accretionary wedge on the surface of the oceanic crust, with little disturbance, for a distance of 70 km, and some sediments still appear to adhere to the ocean crust to where it passes beneath the forearc basement. It is not clear whether sediment is subducted deeper, but it appears probable. The principal resistance to landward motion of the accretionary wedge is provided by the weight of up to 6 km of forearc-basin sediments on the seaward-dipping forearc basement. Both the forearc sediments and the basement have been deformed as a consequence of the horizontal compression produced by the subduction of ocean crust.

INTRODUCTION

The Barbados Ridge accretionary complex lies along the eastern margin of the Caribbean plate. The geology of Barbados indicates that subduction accretion has occurred here since at least the early Eocene (Speed and Larue, 1982). The complex is very wide in the south, where a thick sequence of Pliocene-Pleistocene turbidites from the Orinoco submarine fan is being accreted, and it narrows toward the north, where sediments on the Atlantic ocean floor are predominantly pelagic.

Models of crustal structure derived principally from gravity and seismic refraction data indicate that the complex sits above westward-dipping ocean crust and eastward-dipping crystalline crust that forms the edge of the Caribbean plate and is thickest where the ocean crust passes beneath the Caribbean crust (Westbrook, 1975; Speed et al., 1984). Earlier multichannel seismic profiles have shown that sediments on the ocean crust are thrust horizontally tens of kilometres beneath the accretionary complex (Westbrook and Smith, 1983, 1984).

The seismic section described in this paper comes from the most northerly of three wide-aperture (5 km) seismic reflection lines run across the accretionary complex in April 1985 by the R/V *Robert D. Conrad* and the RRS *Charles Darwin*. The line follows, in its eastern half, the seismic reflection line shown by Westbrook et al. (1982). Both ships had similar airgun arrays of about 2500 in^3 capacity which were fired alternately. Recording was made by the *Conrad*, which towed a 48-channel streamer. Two expanding seismic profiles (ESPs) (Stoffa and Buhl, 1979) were shot across the line to provide deep velocity information (Fig. 1). Questions that the experiment addressed were, What is the cross-sectional shape of the accretionary wedge? What is the velocity structure of the wedge and what information does this give concerning compaction and the presence of overpressured pore fluids? Is sediment subducted? How is the wedge restrained from being pushed backward by the shear stresses imparted to it by the subducting ocean crust?

SEISMIC SECTION

Basement

The most striking feature of the seismic section (Fig. 2*) is that reflections from the surface of igneous or metamorphic rocks can be seen beneath the whole of the accretionary complex. The basaltic top of igneous ocean crust has a rough surface that gives it a distinctive appearance on the seismic section with many diffraction hyperbolae. This surface can be followed beneath the complex 122 km from its toe to a point where it passes beneath a rough reflector that dips eastward from the island arc. The top of oceanic crust can be followed westward 15 km farther; it dips at about 9°. Velocity data from an ESP (at point A in Fig. 2) show that the material beneath the eastward-dipping reflector has an average seismic velocity of 4.7 km/s. Beneath the oceanic basement reflector, velocity rapidly rises to 6.8 km/s and is 7.2 km/s just above the Moho, at a depth of 26 km, making the thickness of oceanic crust 10 km at this point. The rough eastward-dipping reflector rises to a ridge, dips westward for 10 km, and then rises again toward the island arc. Above this reflector lie tilted and gently folded sediments of a forearc basin. These sediments show well-developed folds where they merge into the accretionary wedge at their eastern margin (Fig. 3). Small segments of the forearc-basin reflector are visible within the accretionary complex, showing that the westernmost part of the complex is formed, at least in part, from deformed forearc-basin sediments. The uplift and tilting of the forearc-basin sediments has led to the restriction of the current forearc basin to a small (9 km) width at the base of the slope from the island arc.

Decollement

The most prominent feature in the frontal part of the complex is the strong reflector that is at the decollement (detachment surface) between the accretionary wedge and the underlying, comparatively undeformed rocks. From its parallelism with the underlying sequence, it is clearly stratigraphically controlled, but it is not a strong, distinctive reflector in the ocean-floor sequence in front of the complex. The brightness of this reflector increases westward away from the front of the complex, indicating that the production of a strong acoustic impedance contrast at this horizon must be related to a process associated with the formation of the wedge. Beyond 40 km from the front of the wedge, the reflector becomes less distinct beneath a zone of dipping hyperbolic reflectors, indicating some structural disturbance of unclear character in the wedge. Two westward-dipping reflectors in the west of this zone appear to be thrusts cutting through the wedge and lifting the sea floor into a local ridge. Farther west,

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*Figure 2 is a loose insert accompanying this issue.

to a distance of 70 km from the front of the wedge, the reflector at the top of the sediments underlying the wedge is bright again for 9 km, and it terminates where it is intersected by the upper and more westerly of the two thrusts. If the brightness of the reflector is related to the development of the decollement and its efficiency, then the formation of the thrusts is a consequence of the breakdown in the efficiency of the decollement in the interval 40–60 km from the toe of the wedge, breaking the wedge and locally increasing its surface slope in response to the increased shear stress along the decollement at its base. Between 70 and 120 km, no continuous bright reflector occurs at the top of a layer of sediment on the ocean crust, but in many places, faint, layerlike reflectors occur a little way above the oceanic basement reflector, indicating the presence of some relatively undeformed sediments that might be attached to the ocean crust. A bright reflector is locally developed between 85 and 90 km, and a crossing seismic line at this position shows that, to the north of the section, the reflector, which is apparently at the decollement, is well developed over 20 km.

Sediment Subduction?

Beneath the thickest part of the complex the oceanic basement appears to have the form of a ridge and a trough (Fig. 4). This coincides with the position of a transform fault predicted from inspection of magnetic anomalies (Fig. 1; Westbrook, 1984). The unambiguous identification of reflectors is difficult in this region because of the low ratio of signal to noise, but there appear to be sediments in the trough of oceanic basement. The crest of the ridge lies at the point where the oceanic crust passes beneath the forearc basement; there are no obvious reflections that could be from sediments here or farther west beneath the forearc basement. The high interval velocity of 4.7 km/s between the forearc basement and the underlying ocean crust also appears to preclude the presence of any substantial amount of sediments, unless they are strongly metamorphosed: the sediments would be at a depth of 10 km, in a region with a low geothermal gradient, so that degree of metamorphism is unlikely. It is therefore not possible to show that sediments are subducted deeper beneath the island arc rather than being retained within the accretionary complex. However,

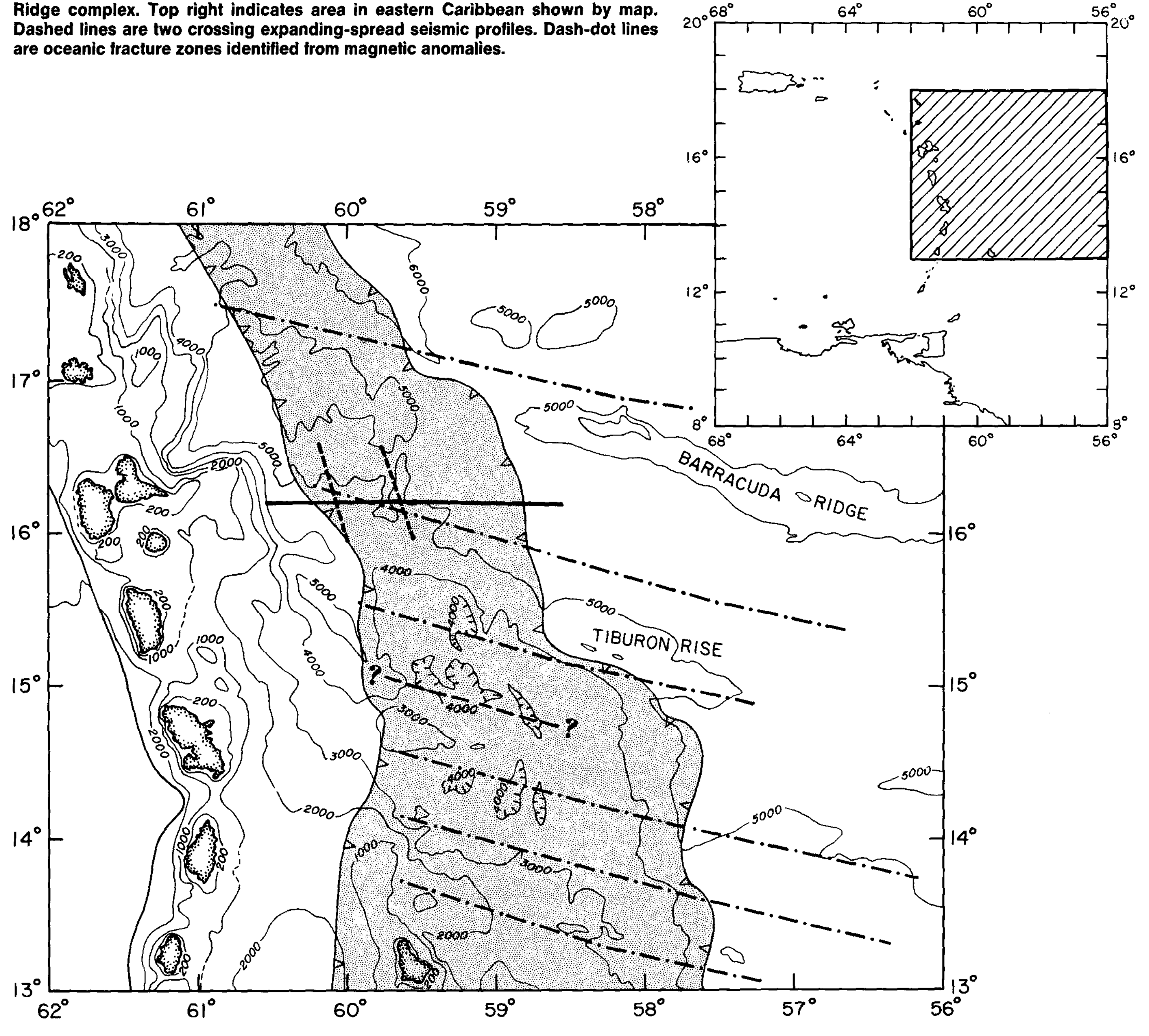
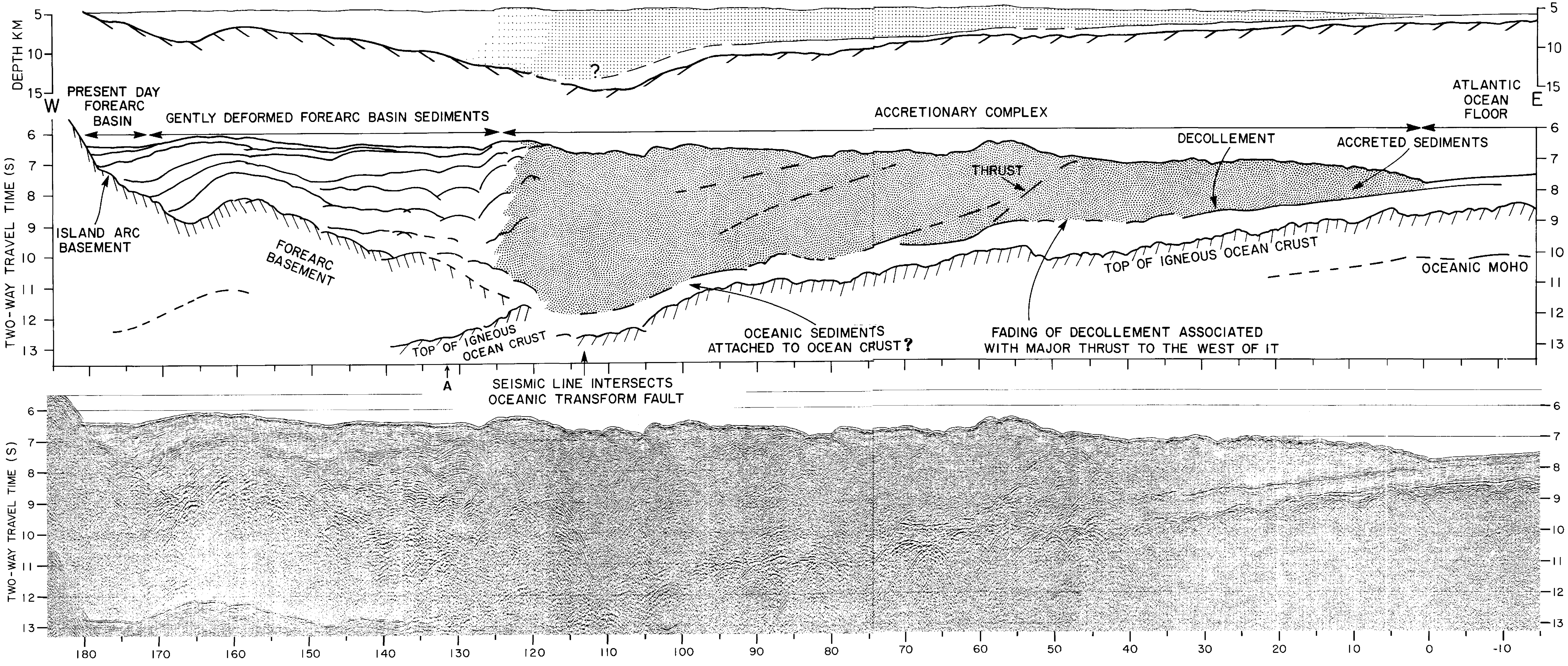


Figure 1. Map showing position of seismic section (heavy line) across Barbados Ridge complex. Top right indicates area in eastern Caribbean shown by map. Dashed lines are two crossing expanding-spread seismic profiles. Dash-dot lines are oceanic fracture zones identified from magnetic anomalies.



Westbrook et al., Figure 2. *Geology*, v. 16, no. 7

Figure 2. Seismic section across Barbados Ridge accretionary complex at lat 16° 12′N. Section is stacked at common depth point interval of 50 m, with nominal 48-fold coverage. Data have undergone *predictive deconvolution*, *band-pass filtering* (6–45 Hz), and equalization.

it seems likely that some of the sediments in the trough in the oceanic basement will be carried farther beneath the forearc basement in the lee of the flanking transform ridge.

Dipping Reflectors

At the toe of the wedge, only 250 m (the top quarter) of the sedimentary section is accreted to the wedge. This leads to the development of short-wavelength structures that are difficult to resolve in a seismic section of this scale. Even so, layered sequences of reflectors from the sedimentary bedding of accreted sediments can be seen just above the decollement as far as 15 km from the toe. They dip at about 5° toward the west (Fig. 5). Longer, westward-dipping reflectors passing through the wedge are presumed to be thrusts. These and other thrusts such as those already mentioned, between 50 and 70 km from the toe, are too long to be the original thrusts on which slices of the thin layer of ocean-floor sediment became accreted to the wedge at the toe. These later thrusts have developed as so-called "out-of-sequence" thrusts, to allow the wedge to adjust its shape to maintain its equilibrium profile, as predicted by models such as those of Davis et al. (1983) and Zhao et al. (1986).

DISCUSSION

The shape of the base of the accretionary complex is close to that predicted from gravity and seismic refraction data (Westbrook, 1975), in that the island-arc basement dips eastward beneath the accretionary complex, unlike common models of forearc structure which have the accreted sediments contained beneath an arcward-dipping leaf of basement rock (e.g., Dickinson and Seely, 1979), but in accord with some of the observations of Silver et al. (1985).

The mean surface of the accretionary wedge west of 55 km from the toe is virtually horizontal, and the basement beneath the wedge dips westward at an average angle of 2.7°. This requires shear stresses to remain very low along the whole of the bottom surface of the wedge, because an increase in shear stress would lead to deformation of the wedge and production of topography on its surface. If shear stress on the base is proportional to the overburden (i.e., thickness of the wedge), as predicted by a frictional model, the surface of the wedge should maintain a constant slope (Davis et al., 1983), but as it does not, the strength of the material forming the wedge must increase landward (Westbrook et al., 1982; Zhao et al., 1986). Seismic velocities in the wedge increase westward away from the toe, reflecting increased compaction and presumably increased strength. An alternative is that shear stress is transmitted across the decollement in a viscous manner. If so, it would not be linearly depth dependent in the same way as a frictional model. In the region between 40 and 60 km from the toe, there appears to be increased resistance to slip along the decollement, resulting in the development of major thrusts and a local increase in the seaward slope of the complex. At 33 km, the decolle-

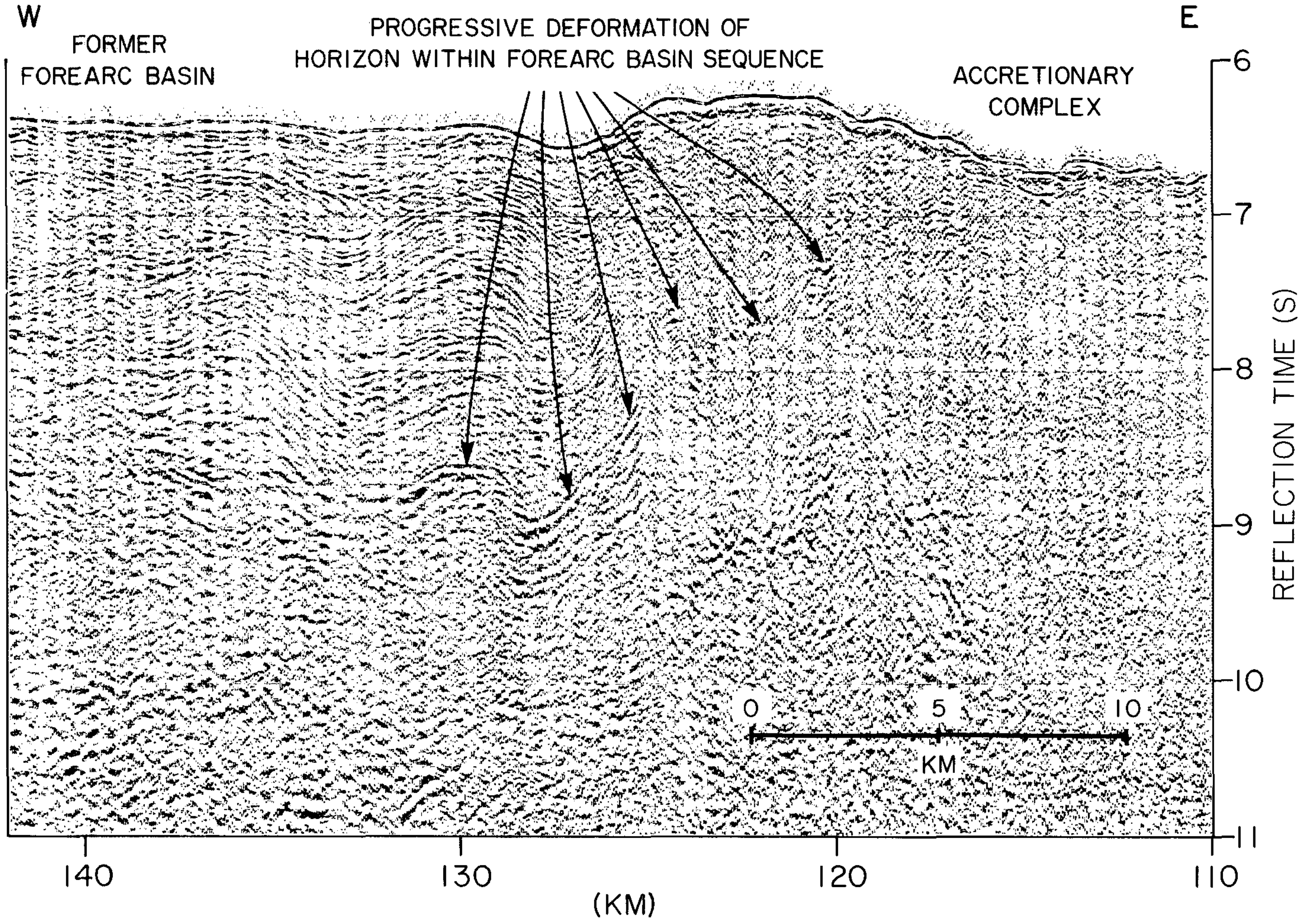


Figure 3. Migrated part of seismic section showing gradational deformational boundary between accretionary complex and forearc-basin sediments. Complex incorporates deformed forearc-basin sediments; odd prominent horizon can be seen within complex. Complex is growing toward arc by translation of rocks accreted from ocean-floor sequence and by incorporation of sediments from forearc basin. Sediments of forearc basin appear at times to have overstepped accretionary wedge, only to be subsequently deformed.

ment reflector is broken and displaced. This may represent the beginning of large-scale overthrusting and the temporary cessation of motion along the decollement seaward of it, until the shear stresses have been increased sufficiently by the increase in the seaward slope of the surface of the wedge to move the wedge forward again. The development of such features suggests that deformation of the wedge may propagate in waves along it.

The brightness of the decollement reflector, especially its westward increase in amplitude, could be produced by (1) the development of a thick zone of sheared clays, which may increase in thickness landward with increasing age of the decollement, or (2) it may be a consequence of a progressive change in the physical properties of the rocks on either side. The rocks immediately beneath the decollement have been under the same

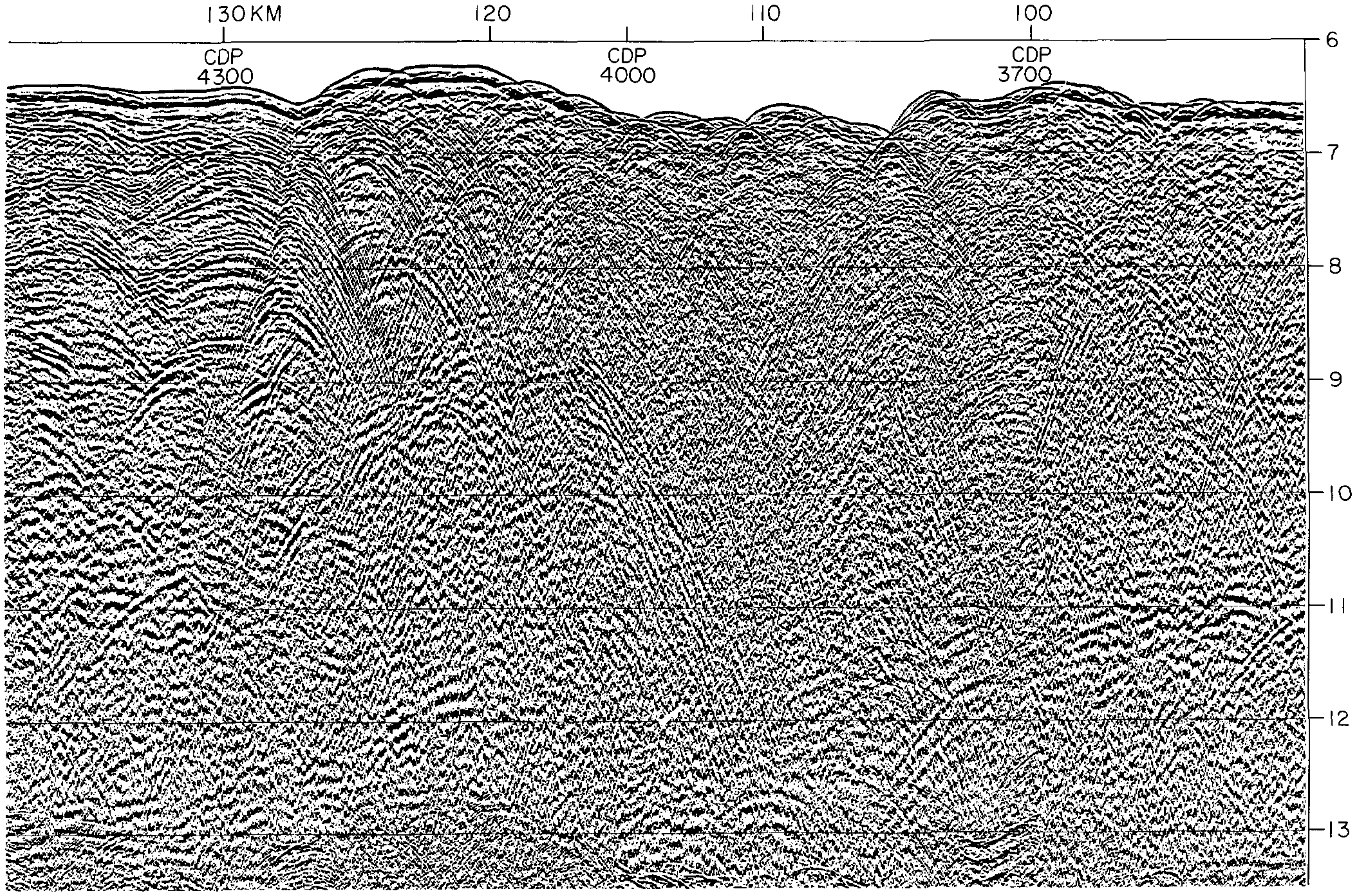


Figure 4. Part of section showing region where accretionary complex is thickest and ocean crust passes beneath leading edge of crust of Caribbean forearc. This is position where ship's track crosses trace of oceanic fracture zone; trough in oceanic crust and ridge west of it are presumably related to fracture zone.

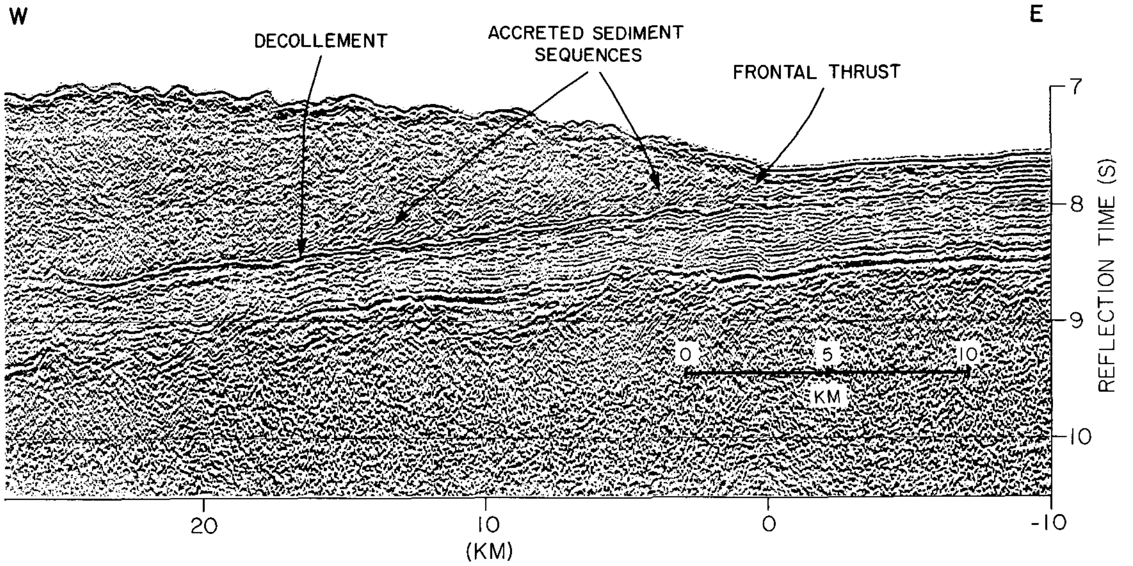


Figure 5. Migrated part of section showing toe of wedge. Decollement at base of wedge is evident. It is predominantly stratigraphically controlled, but it appears to cut down through section in places and truncates some underlying horizons. Above decollement, patches of finely layered reflectors may represent bedding of accreted sediments.

overburden pressure for a shorter time than the rocks above and will be relatively less consolidated, with higher porosity, lower density, and lower seismic velocity. The loss of the bright reflector at 70 km could be because it is intersected by a thrust that soles out at a lower stratigraphic level and the old decollement is deformed in the hanging wall. At 58 km, a thrust cuts down into the underlying sequence without a loss of brightness on the decollement behind it. The thrusts could also be acting as conduits for pore water (Cloos, 1984), and so the loss of brightness may result from dewatering of the underlying sequence through pathways provided by the thrusts. Furthermore, the brightness of the decollement and thrusts may be caused by localized dilatancy in the thrust zones produced by overpressured water flowing through them. High pore-water pressures were measured at the decollement during Leg 78A of the International Phase of Ocean Drilling, 80 km south of the seismic line (Biju-Duval, Moore, et al., 1984), and subsequently methane anomalies in pore water sampled during Leg 110 of the Ocean Drilling Program have been used to demonstrate that the decollement acts as a conduit for fluids.

A significant aspect of the landward margin of the wedge is that it appears to come into direct contact with only about 10 km of the surface of the forearc basement. Consequently, the stresses exerted by the basement *directly* upon the wedge form only a minor component of the resistance to landward motion of the wedge induced by the motion of the oceanic crust. Most of the resistance to landward motion is provided by the forearc-basin sediments, which would have to be thickened and/or driven up the slope of the forearc basement. These sediments, therefore, act as a so-called "backstop" to the accretionary wedge, although it is clear that they are deformed where they adjoin the wedge and are incorporated within it to some degree. They may be thought of as more of a "brake" than a "stop." Stresses are transmitted into forearc basement beneath the sediments; the forearc basement is also subject to shear stresses arising from the oceanic crust subducted beneath it. The arching of the forearc sediments over the basement high at 160 km shows that this high has formed through deformation of the basement, which is, therefore, not a rigid tectonic element. Although there is no clear indication of the mechanism of deformation, it seems that thickening of the forearc basement is its consequence. This forearc basement high is possibly the equivalent of the outer-arc high or trench-slope break of some western Pacific island arcs such as the Tonga-Kermadec and the Mariana, which have comparatively small forearc basins. It is possible that the forearc basement has grown by the accretion of flakes of ocean crust at its forward edge. The scope for this is limited because forearc basin sediments, only gently deformed, overlie all but 10 km of the basement surface, and the oldest overlie the deepest and most seaward part of the basement. Consequently, any significant seaward growth of the forearc basement by accretion of ocean crust would have had to precede the formation of the forearc basin.

The development of the forearc basin has been dependent upon the growth of the wedge that forms its seaward margin. When the wedge did not thicken as rapidly as the basin filled, then sediments overstepped the seaward margin onto the wedge. When the converse was true, the wedge attained a higher relative relief and formed a barrier to sediments. During the mutual growth of the wedge and the basin, the overstepping sequences have been deformed and are almost indistinguishable on the seismic section from parts of the wedge that were accreted at the front of the complex.

CONCLUSIONS

The following generalizations concerning the behavior of accretionary wedges may be made from the interpretation of this seismic section of a complete wedge.

1. The wedge does not require a "backstop" formed by a landward-dipping basement surface to constrain its landward surface.
2. The sediments of the forearc basin over a seaward-dipping basement surface can act as the backstop to the wedge.
3. Sediments of the forearc basin are deformed by landward motion of the wedge and by deformation associated with its thickening, and can themselves be accreted to the wedge.
4. Sediments on the ocean crust are drawn beneath the wedge as far as the leading edge of the crystalline basement of the overriding plate and are probably subducted beneath it.
5. The nature of the seismic reflection from the decollement at the base of the wedge appears to show a dependency upon the strain history of the decollement and the presence of overpressured pore fluids.

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ACKNOWLEDGMENTS

Supported by the National Science Foundation Grant OCE 83-17040 and Natural Environment Research Council (NERC) Grant GR3/5540. G. J. Tiley was supported by a NERC research studentship. We thank the masters and crews of the R/V *Robert D. Conrad* and the RRS *Charles Darwin* for their contributions to the success of the seismic experiment. Lamont-Doherty Geological Observatory Contribution no. 4318.

Manuscript received June 22, 1987
Revised manuscript received March 24, 1988
Manuscript accepted April 14, 1988

Reviewer's comment

This paper represents a major improvement in the understanding of the Barbados Ridge Complex, and provides considerable food for thought. It is an important paper—the section illustrates many fundamental processes (including accretion, underplating, and "backstopping").

Dan Davis