Shipley, T.H., Ogawa, Y., Blum, P., et al., 1995
Proceedings of the Ocean Drilling Program, Initial Reports, Vol. 156

1. INTRODUCTION[1]

Shipboard Scientific Party[2]

For more than 30 yr, long-distance transport of large blocks on subhorizontal faults has been known to be aided by overpressured pore fluids that reduce fault shear strength (Hubbert and Rubey, 1959). Modeling of accretionary prism shapes as Coulomb wedges near failure requires that accretionary prisms and their basal detachments be weak (Davis et al., 1983; Dahlen, 1990). However, few in situ observations of fluid pressures, which strongly influence strength, exist within modern accretionary margins (e.g., Moore and Vrolijk, 1992; Westbrook and Smith, 1983). The evolution of the pore-pressure system is poorly understood. Evidence from multiple episodes of fracturing and vein filling in accreted rocks demonstrates that fluid flow is episodic, but time scales are difficult to estimate accurately (e.g., Knipe et al., 1991). In fine-grained, muddy accretionary prisms, such as the northern Barbados Ridge, fault zone fracture-induced permeability begins to dominate early (e.g., Moore et al., 1991; Moore, 1989). Thus, both temporal and spatial effects complicate the dynamics of fluid flow. Yet, dynamic hydrologic models must rely on few in situ observations of intergranular and fracture permeability and on estimates of the dimensions of pathways (e.g., Screaton et al., 1990; Shi and Wang, 1988).

Recognition of the significance of fluids in accretionary prism tectonics has spurred innovative experiments and new techniques (Langseth and Moore, 1990). Study of fluids requires close coordination of many specialties using geochemical signatures and structural, and physical property observations (e.g., Fisher and Hounslow, 1990; Vrolijk et al., 1991). The drilling program for Barbados brings together all these disciplines to combine in situ measurements of permeability and fluid pressures, long-term monitoring of temperature and pressure, and studies of fluid and solid chemistry, tectonic fabrics, and physical properties in an integrated program. While this is not the ultimate experiment, it is a large step for evaluating the role of faults in fluid transport and the episodicity of fluid flow and its relationship to seismicity. Understanding the fate of subducted and accreted fluids will contribute to the definition of geochemical cycles (Kastner et al., 1991).

REGIONAL SETTING

The northern Barbados Ridge is the leading edge of the Caribbean Plate, which is being underthrust by Atlantic Ocean floor at rates estimated between 25 and 40 km/m.y. (Dorel, 1981; Jordan, 1975; Sykes et al., 1982). The Lesser Antilles to the west defines the volcanic arc, while the island of Barbados east of the arc is an outcrop of the forearc accretionary prism (Fig. 1). Frontal structures south of the Tiburon Rise are long wavelength folds, widely spaced ramp faults, and long décollement reflections (e.g., Bangs and Westbrook, 1991; Westbrook and Smith, 1983). To the north, the thickness of the trench sediment is much thinner, and prism thrusts are more closely spaced (Biju-Duval et al., 1982; Westbrook et al., 1984). From the Deep Sea Drilling Project/Ocean Drilling Program (DSDP/ODP) drilling transect and northward, the Barbados accretionary complex is at least 10 km thick and 120 km wide, in addition to a 50-km-wide forearc basin (Bangs et al., 1990; Westbrook et al., 1988). The prism forms a wide, low-taper wedge.

Previous Drilling and Site-specific Geology and Geophysics

During DSDP Leg 78A, the length of the drill string limited site choices for exploratory drilling to the flank of the Tiburon Rise (Biju-Duval, Moore, et al., 1984) (Fig. 1). Legs 78A (Biju-Duval, Moore, et al., 1984) and 110 (Mascle, Moore, et al., 1988; Moore, Mascle, et al., 1990) produced a transect of nine sites that span about 15 km (Fig. 2). This drilling transect is on the boundary between two provinces, where the Tiburon Rise partially dams along-axis trench transport of turbidites to the north. Geophysical and geological observations of the northern Barbados Ridge are extensive. Reviews of previous work are found in the *Initial Reports* volume for DSDP Leg 78A (Bouysse, 1984; Westbrook et al., 1984) and the *Initial Reports* and *Scientific Results* volumes for ODP Leg 110 (Ladd et al., 1990; Westbrook et al., 1988) and references therein. In the vicinity of the drilling transect, several data sets have been collected; these include SeaBeam, Gloria side-scan, deep-tow 3.5 kHz, and heat flow. Bottom-navigated heat-flow and deep-tow 3.5-kHz and side-scan surveys document a correlation between thrust faults and heat-flow anomalies, allowing one to infer fluid flow paths (Lallemant et al., 1990).

A seismic line trending east-west crosses through ODP Hole 671B, illustrating the main structural features of the toe region (Shipley et al., 1994; Fig. 3). These data are consistent with earlier data and with interpretations that show an extraordinary fault reflection extending at least 70 km westward of the trench (e.g., Biju-Duval et al., 1982; Westbrook and Smith, 1983). Brown and Behrmann (1990) thought that the prism grows near the toe by imbrication of thin fault blocks, based on drilling and seismic data (Fig. 4). In addition, they indicated that west of Hole 671B, the prism deforms by large-scale folding, out-of-sequence thrusting, and, probably, underplating.

Geochemical signatures, heat flow, and direct observations were used to detect focused fluid flow in the toe region (e.g., Vrolijk et al., 1991; Langseth et al., 1988; Fisher and Hounslow, 1990) (Fig. 5). The Barbados prism apparently has two distinct and active fluid regimes that are separated by the décollement and that communicate only near the toe of the slope (Vrolijk et al., 1991). Both the décollement and several other faults show chemical and temperature anomalies that require active fluid advection. Hole 671B (Leg 110) cored through what has been identified as a 40-m-thick décollement and 151 m into the underlying underthrust section (Moore et al., 1988). Because of unsuccessful measurements of in situ fault-zone fluid pressures during Leg 110, the assertion of near-lithostatic pressure at the décollement at Site 542 remains unverified ("the inadvertent packer experiment," Moore et al., 1982).

Three-dimensional Seismic Reflection Data

In June 1992, a three-dimensional seismic reflection survey imaged the detachment fault between the Caribbean and American plates within the Leg 156 area (Shipley et al., 1994). Previous work had linked waveform characteristics of this fault to porosity and fluid

[1] Shipley, T.H., Ogawa, Y., Blum, P., et al., 1995. *Proc. ODP, Init. Repts.,* 156: College Station, TX (Ocean Drilling Program).

[2] Shipboard Scientific Party is as given in list of participants preceding the contents.

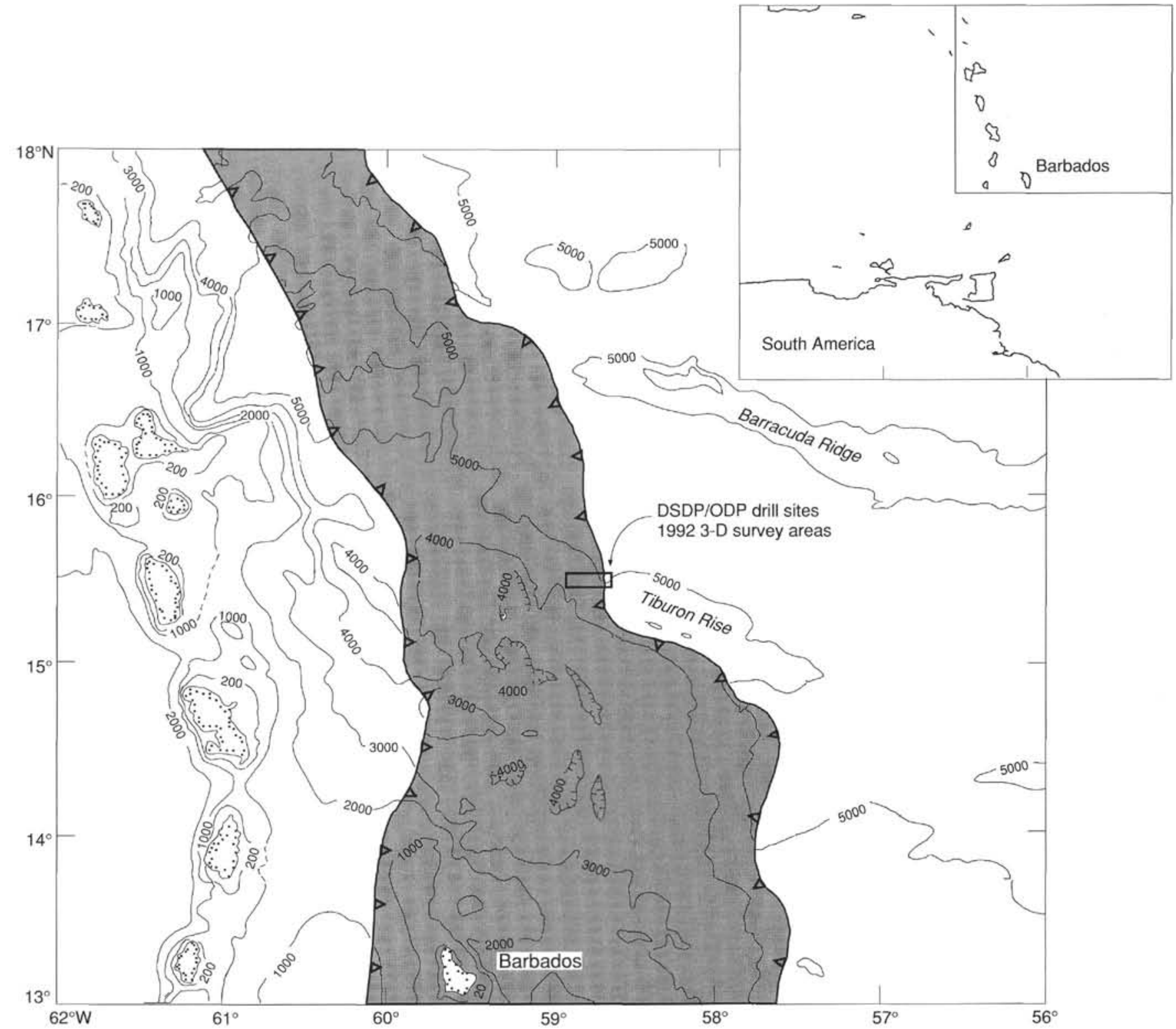

Figure 1. Index chart of the Lesser Antilles. Shaded zone is the extent of the northern Barbados Ridge accretionary prism. The Tiburon Rise dams along-axis trench transport, partly explaining the reduction in width of the prism to the north. The box illustrates the location of the DSDP/ODP drilling transects and is approximately the size of the three-dimensional seismic survey that identified the drilling locations during Leg 156 (modified from N.L. Bangs, pers. comm., 1994). Bathymetry in meters.

pressure (Bangs and Westbrook, 1991). In the drilling area, the fault-zone reflection is usually a compound reversed-polarity reflection that has been modeled as a low-velocity, high-porosity zone 10 to 14 m thick, which is significantly thinner than the drilling-defined, 40-m zone of deformation at Hole 671B, located within the survey. A few areas of the fault surface have positive polarity and represent increasing impedance across the fault, including Hole 671B. This is consistent with the drilling results from Hole 671B. This hole penetrated through the fault zone and 151 m into the underlying section without initial difficulty before a core barrel became stuck in a sandy layer, suggesting a much thinner or stronger fault zone. A map of the reflection amplitude associated with the fault plane reflection illustrates the variability of the fault properties (Fig. 6). Represented on the map is the peak amplitude associated with the fault reflection (Shipley et al., 1994). Structural contours overlain on the amplitude map indicate that neither the high-amplitude compound negative- nor positive-polarity sections correspond to structural closure on the fault surface. The areas of the fault having the largest negative amplitudes in Figure 6 align along an east-northeast-trending band 2 km wide. The areas where the fault reflection has positive polarity are small in proportion to the compound negative reflection area but are noteworthy, such as near Hole 671B.

Relatively high fluid content and porosity imply undercompaction and high fluid pressures, and high fluid pressures produce low shear strength (Brown and Moore, 1993; Brown et al., 1994; Tobin et al., 1994). Thus, the negative-polarity reflection suggests a weak fault throughout the surveyed region (Fig. 6). The few areas of positive polarity could be stronger regions of the fault surface and may have produced a noticeable change in the local stress pattern. The negative-polarity sections may be dilatant zones within the fault. Because per-

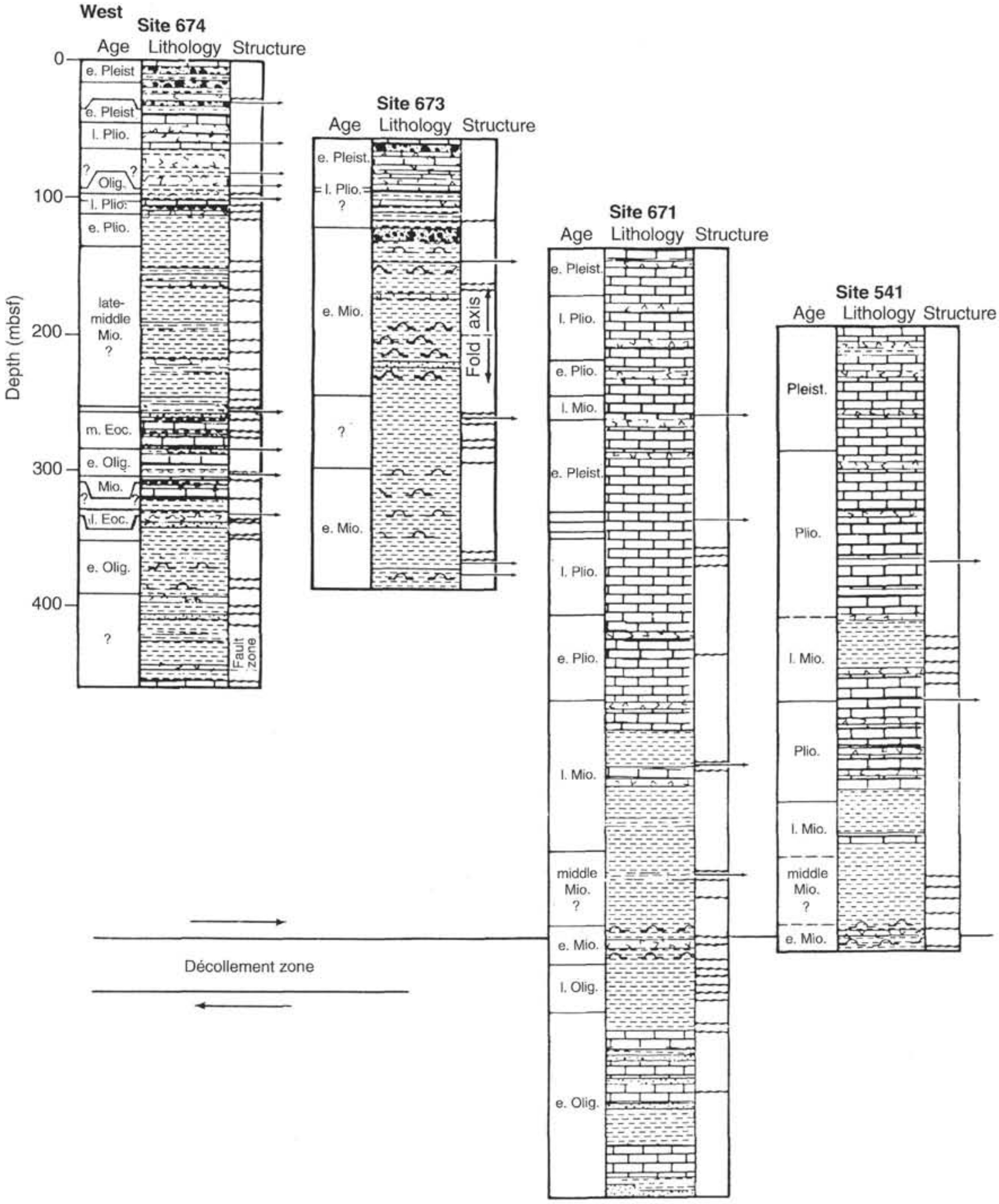

Figure 2. Lithostratigraphy of the DSDP Leg 78A and ODP Leg 110 transects (Mascle and Moore, 1990, Leg 110 *Scientific Results*, p. 414–415).

meability correlates with porosity, the dilatant zones may be locations of channelized fluid flow (Brown and Moore, 1993). The Leg 156 drilling program was designed to answer some of these speculations.

SCIENTIFIC OBJECTIVES AND METHODOLOGY

Leg 156 constitutes a drilling and experimental program for evaluating the effects, rates, and episodicity of fluid flow in an accretionary prism environment. The program focuses on fluids in the décollement zone of the Barbados accretionary prism. It includes measuring fluid flow through the accretionary prism and sediments underthrust beneath the décollement zone. Leg 156 planning used the geologic and hydrogeologic framework developed from previous drilling here, as well as the three-dimensional seismic reflection survey.

The Leg 156 program included the sealing of cased holes using the CORK system (Davis et al., 1992). A wire-screened interval of casing was placed across the décollement. These CORK holes will monitor changes in temperature (a proxy for fluid flow) and pressure within the fault zone for at least 2 yr. One hole includes a long-term fluid sampler. Submersibles will allow for additional experimentation and transfer of data from long-term monitoring. The elementary objectives of this drilling program (to measure permeability and to monitor both the temporal and spatial fluid pressures along an active detachment fault) are fundamental observations, but have remained elusive

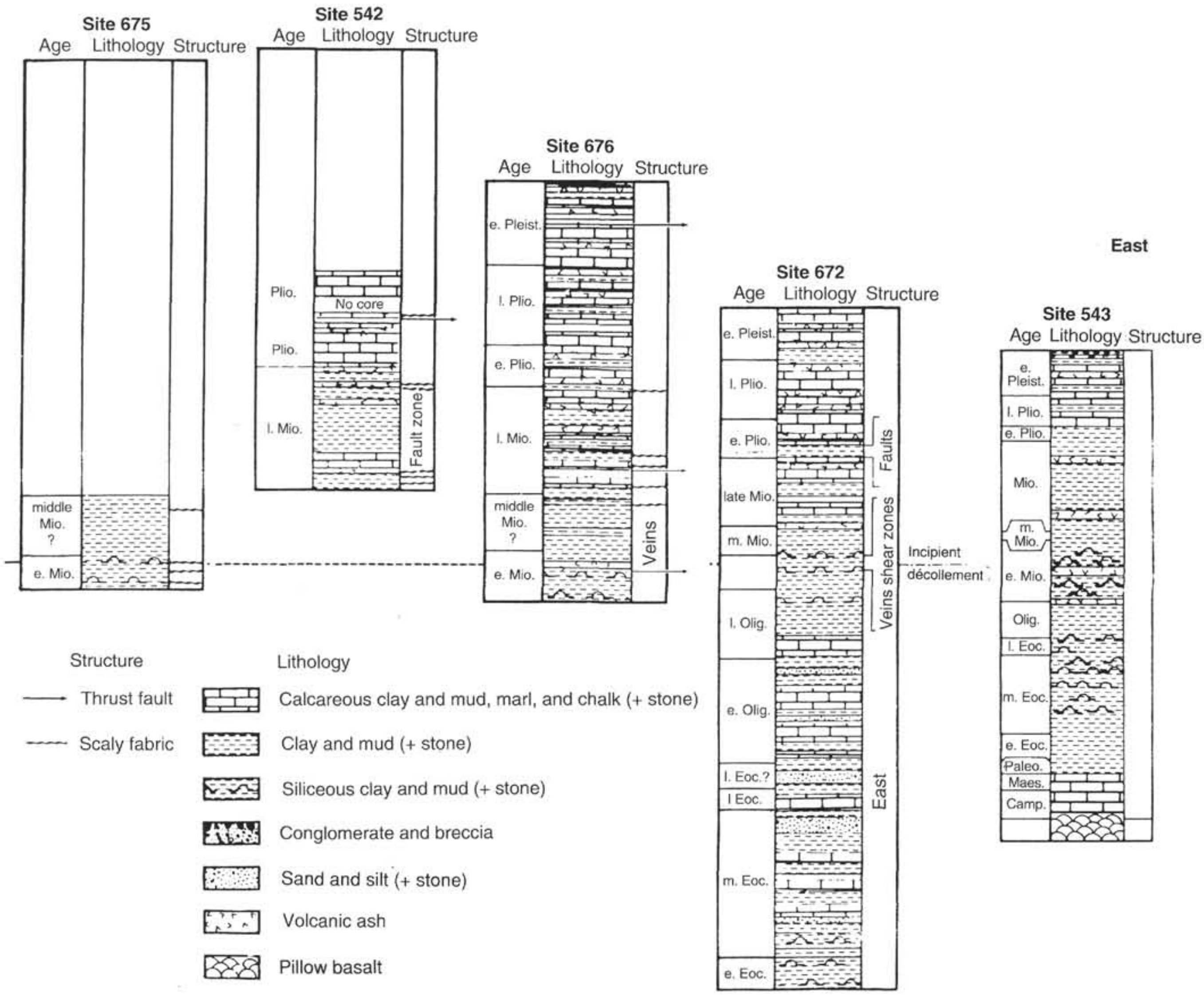

Figure 2 (continued).

because they are technically challenging. The main objectives of Leg 156 were as follows:

1. Fluid pressure in and around the décollement zone. No reliable fluid-pressure measurements exist for the frontal area of accretionary prisms, even though several attempts (inadvertent or otherwise) have been made (Biju-Duval, Moore, et al., 1984; von Huene, 1985). Fluid pressure is the driving force for fluid flow and must be known to create any reasonable model of fluid expulsion and to evaluate structural models of prism tectonics.

2. Permeabilities of prism sediments and associated fault zones. Although measurements on recovered core samples provide estimates of matrix permeability (e.g., Taylor and Leonard, 1990), in situ measurements are essential for determining permeability at the scale of the flow system. Some models suggest that fault zones may be three to five orders of magnitude more permeable than the matrix (Screaton et al., 1990). Obviously, information about permeability will dramatically influence the understanding of the dynamics of fluid flow.

3. Reflection amplitude and polarity anomalies along faults. Dilatant zones may explain high-amplitude, reversed-polarity reflections in seismic reflection data from the northern Barbados Ridge (Bangs and Westbrook, 1991). Similar reflection reversals in the Oregon accretionary prism correlate with surface vents and have been interpreted as dilatant zones (Moore et al., 1991). Seismic data from the new three-dimensional survey in the area of the Leg 110 cruise show a large negative-polarity amplitude anomaly along the décollement zone (Shipley et al., 1994). Site 947 was placed so as (1) to investigate this amplitude anomaly, (2) to monitor its fluid pressure, and (3) ultimately, to measure its migration.

4. Continuous or episodic flow? Although groundwater systems driven by semiconstant water tables tend to flow continuously, structural and seismologic intuition suggests that tectono-hydrologic systems are episodic. The nature of the earthquake cycle (Kanamori, 1986) and related fluid flow (Sibson, 1981), and the ubiquitous crack-seal textures of deformed rocks (e.g., Ramsay, 1980), support this view. Accordingly, the temporal and spatial variability of fluid flow along a convergent plate boundary is fundamental.

5. Space and time variations in fluid composition and comparison with veins and authigenic mineral phases. The variability of fluid composition in space and time will provide information about potential fluid sources and will allow for modeling of solute fluxes and temporal rates.

6. What controls the location of the décollement? What is the relationship between the specific locations of the fault and lithology

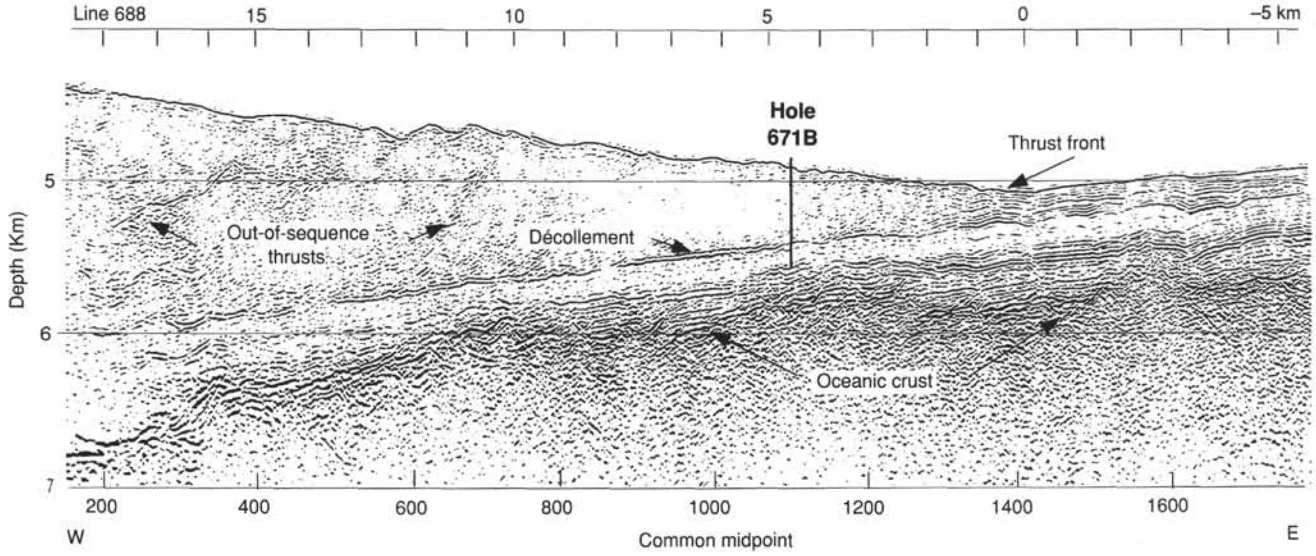

Figure 3. Relative true-amplitude depth section of east-west seismic Line 688 (passing through Hole 671B) is an example of seismic data. Even at this scale, the décollement reflection clearly stands alone, separated by reflection-free intervals above and below, simplifying its study. Out-of-sequence thrusts become seismically identified 10 km west of the frontal thrust. The zone of transparency in the prism 5 to 8 km from the thrust front trends is parallel to the trench and thus is not everywhere coincident with the northeast-trending high-amplitude décollement reflection. The velocity function used in migration and depth conversion began with DSDP/ODP data and then was modified by trial migration velocity studies (Shipley et al., 1994; see "Structural Setting" chapter, this volume).

and physical properties? Do paleoceanographic, environmental, or sedimentological histories control physical properties?

DRILLING PLAN AND STRATEGY

The two-month ODP program planned for three CORK holes; however, only two were deployed. Figure 7 is a schematic cross section of the margin and seismic line illustrating the relative positions of the sites. The high-amplitude compound negative-polarity reflection may result from dilation of the fault zone. Site 947 (NBR-3) was to test this hypothesis but did not reach the décollement. Site 948 (NBR-2) is where the fault-plane reflection has a positive polarity, and the fault may not have significantly high fluid pressures or be of significant thickness. Site 949 (NBR-7), about 2 km arcward of the thrust front, was an alternate for Site 947. The CORK holes, 948D and 949C, were instrumented with a string of temperature sensors and several pressure sensors in the well and at the seafloor. At Site 949 the tool string was similar to those used successfully in the Juan de Fuca and Cascadia drilling programs (Westbrook, Carson, Musgrave, et al., 1994). A digital string was deployed at Site 948 (see "Explanatory Notes" chapter, this volume). These strings are capable of monitoring changes in temperatures (a proxy for fluid flow) and pressures within the fault zone for at least 2 yr. A chemical sampler will collect a time series of samples to be retrieved during later ODP or submersible operations at Site 949 (see "Explanatory Notes" chapter, this volume). The packer experiments were designed to estimate permeability through both pulse and flow tests. Other experiments included vertical seismic profiles (VSPs) at Sites 948 and 949 and a bottom-shot (shear-wave anisotropy) VSP experiment at Site 949 (see "Explanatory Notes" chapter, this volume). Logging-while-drilling (LWD) at Sites 947 and 948 (see "Explanatory Notes" chapter, this volume) was an essential element of the Leg 156 program, given the importance of measuring in situ physical properties of the accretionary prism near failure and the active plate-boundary fault. LWD is open-hole logging accomplished with the tools mounted in the rotating bottom-hole assembly. This technique improves the possibility for logging in inherently unstable accretionary prisms. Unlike that used for earlier VSP work, we used the array seismic imager tool (ASI). Its use within cased holes assures that hole conditions do not preclude the experiment. However, a cased hole must have good coupling to the formation for the ASI tool to be successful. A cement-bonding tool (CBT) evaluated the cementing quality that was critical for both the ASI tool and hydrologic isolation of the décollement. A complete fluids-geochemical sampling and analysis program was performed. The elementary objectives of this drilling program (to measure permeability and to monitor both temporal and spatial fluid pressures along an active detachment fault) are fundamental observations, but have remained elusive because of their technical challenge. Our challenge was to implement CORK systems at record water depths to produce a compelling record of fluid activity along faults.

Safety and Pollution Prevention

The main issue related to safety and pollution was that of the fault zones. During Legs 78A and 110, both out-of-sequence thrusts and the décollement were cored so as to sample all stratigraphic sections. No hydrocarbons were discovered above background. No free gas was detected. No abnormal fluid pressures were measured. This was a good preview for planning that was confirmed by our safe operations during Leg 156.

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* Abbreviations for names of organizations and publication titles in ODP reference lists follow the style given in *Chemical Abstracts Service Source Index* (published by American Chemical Society).

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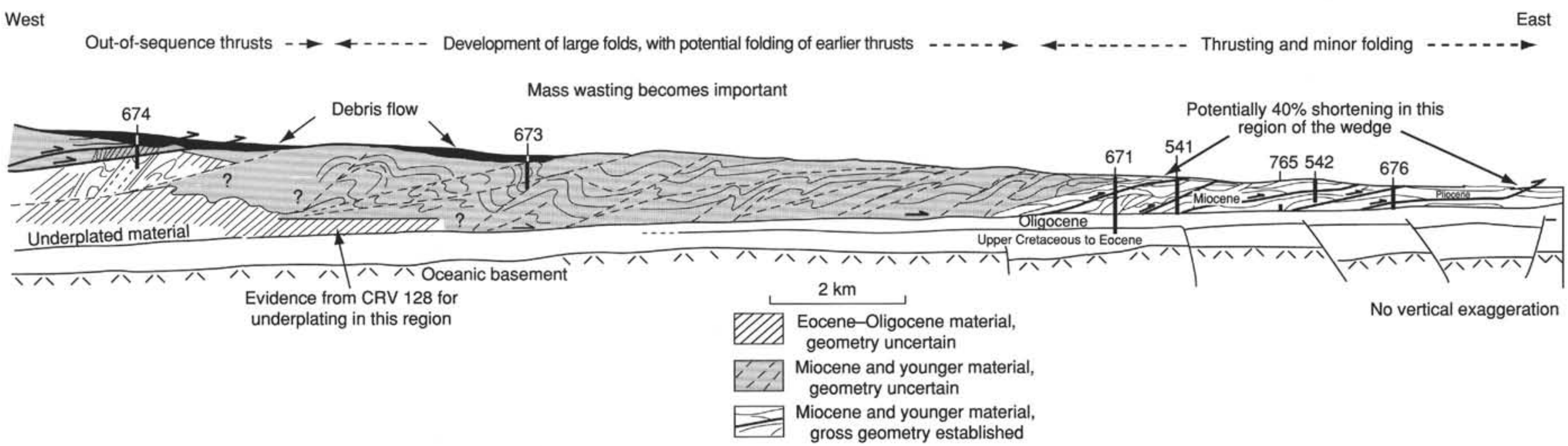

Figure 4. Schematic representation of the structural setting from seismic data and drilling during Leg 110 (modified from Brown et al., 1990, Leg 110 *Scientific Results,* p. 227).

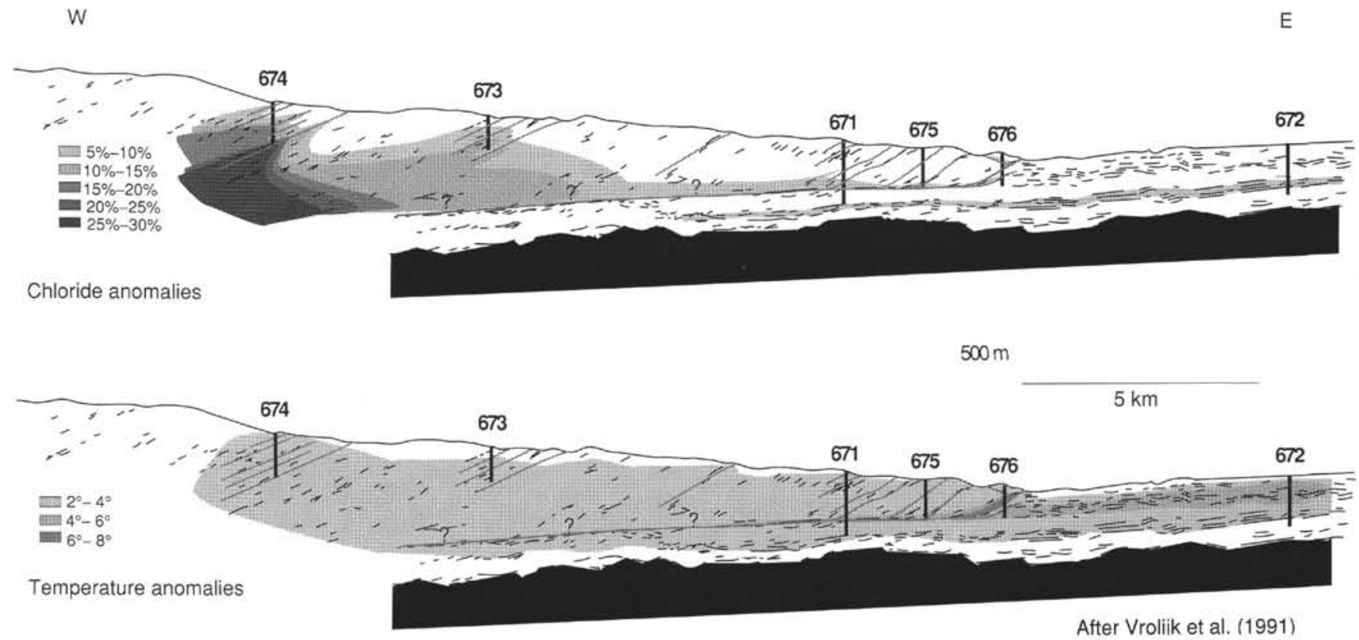

Figure 5. Synthesis of some of the geochemical results from Leg 110, illustrating the relationship between chemical anomalies and faults (after Vrolijk et al., 1991).

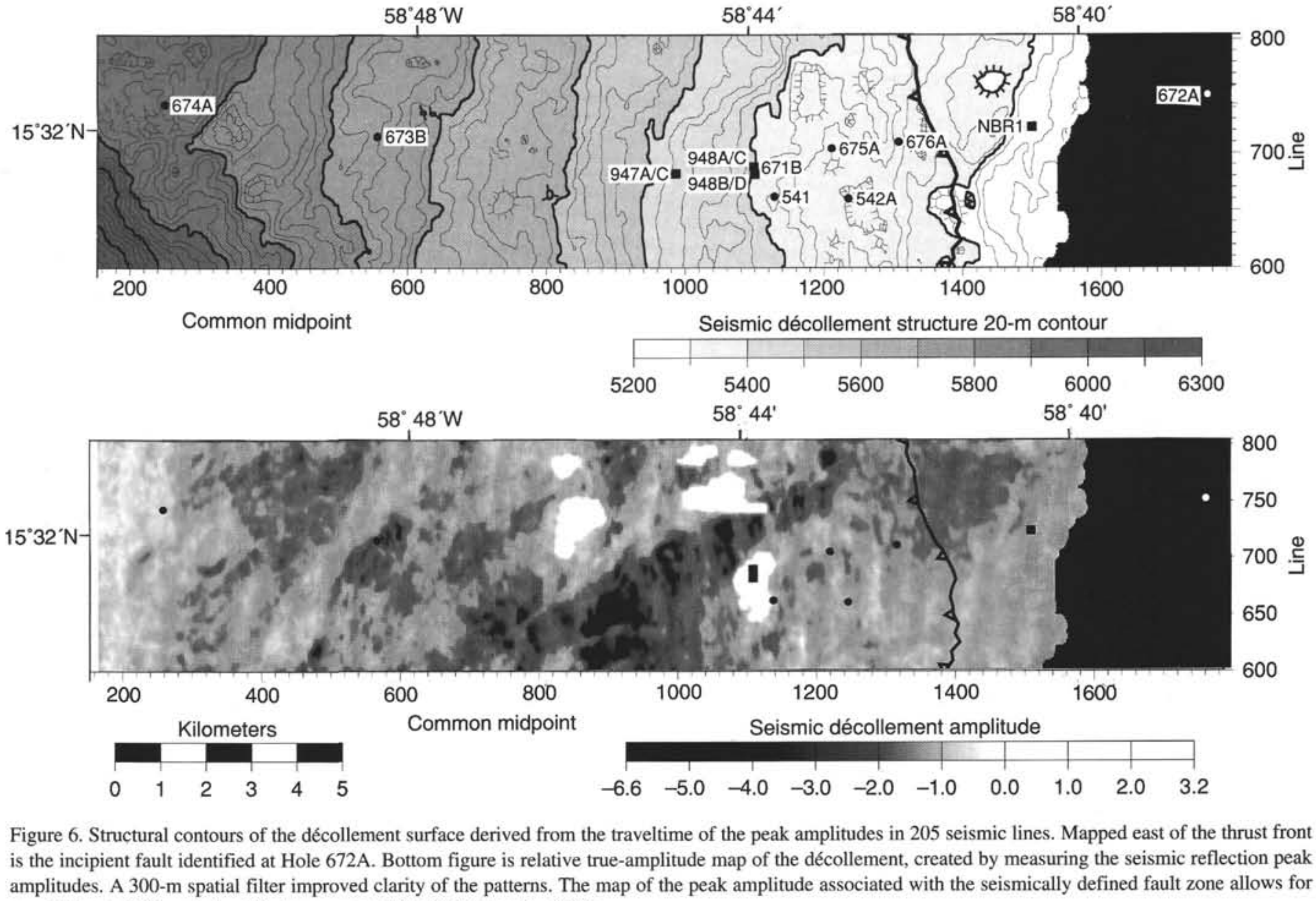

Figure 6. Structural contours of the décollement surface derived from the traveltime of the peak amplitudes in 205 seismic lines. Mapped east of the thrust front is the incipient fault identified at Hole 672A. Bottom figure is relative true-amplitude map of the décollement, created by measuring the seismic reflection peak amplitudes. A 300-m spatial filter improved clarity of the patterns. The map of the peak amplitude associated with the seismically defined fault zone allows for correlation to drilling-derived fault zone properties (Shipley et al., 1994).

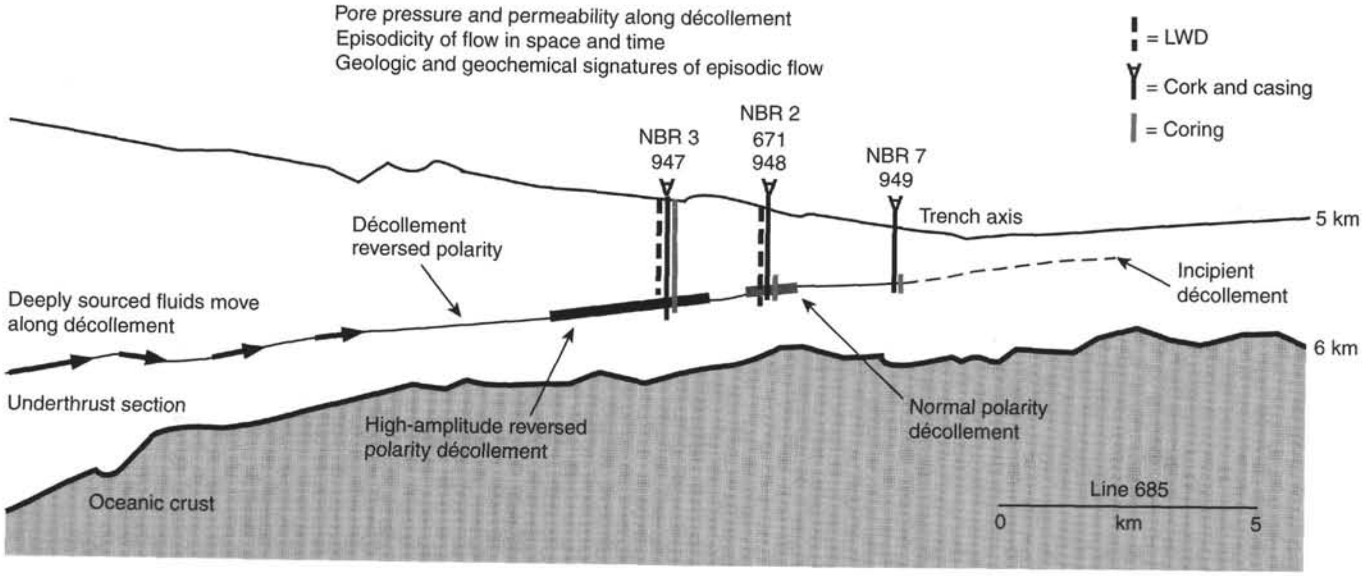

Figure 7. Schematic layout of the Leg 156 drilling program.