Vol. 1, No. 12 December 1991

GSA TODAY

A Publication of the Geological Society of America

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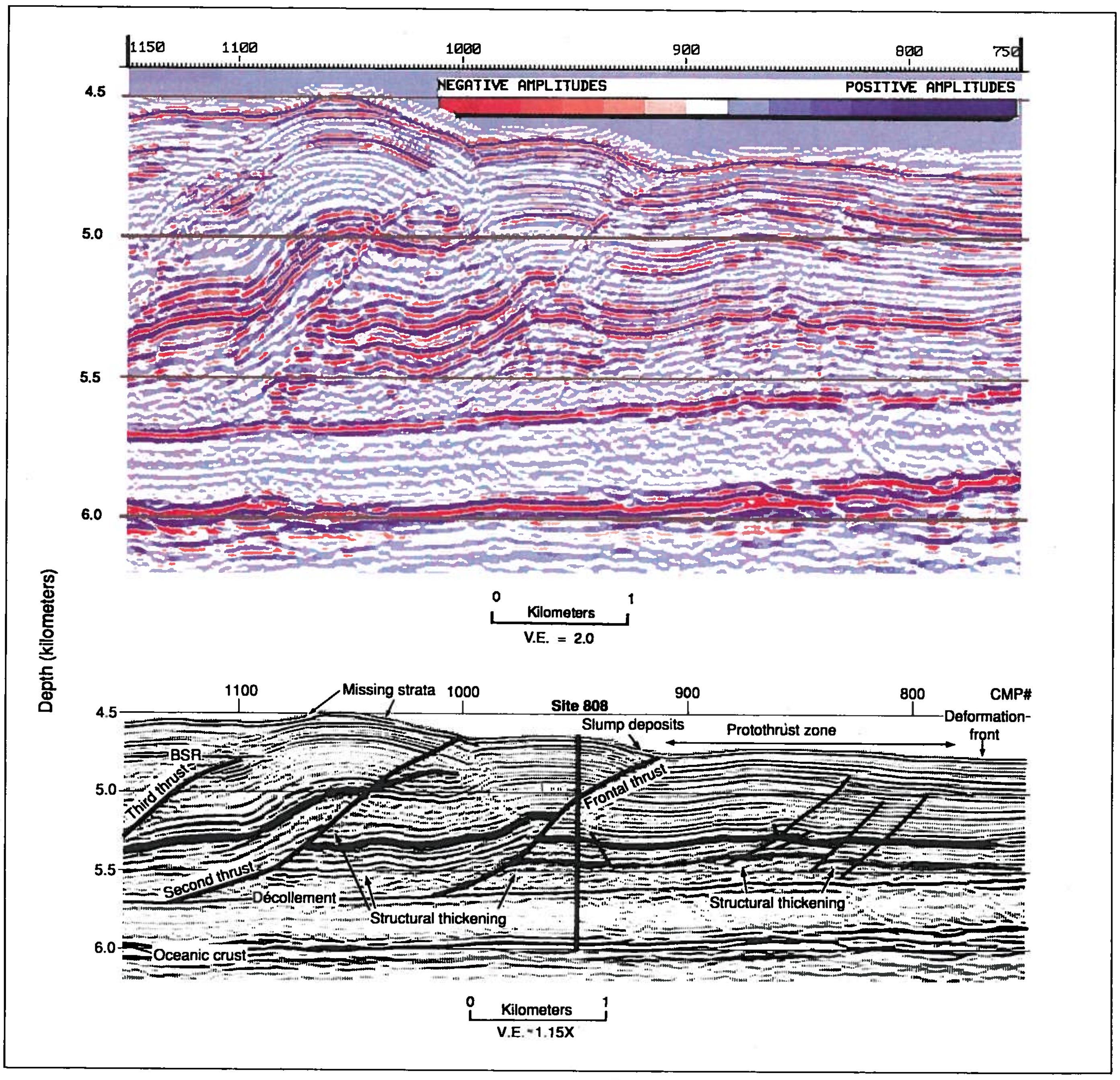

Figure 1. Seismic line along transect of recent Nankai Trough drilling. Upper section is a migrated, uninterpreted depth section with color scale to show seismic polarity. Lower profile shows structural interpretation (after Moore et al., 1991). BSR reflector probably represents a gas hydrate phase boundary.

Ocean Drilling and Accretionary Processes

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ABSTRACT

Recent ocean drilling of accretionary prisms has penetrated completely through the incoming sedimentary section, crossing the plate boundary. Intriguing features observed on high-quality seismic reflection profiles have been confirmed and elucidated by drilling. Many structural fabrics that characterize shallowly buried on-land accretionary prisms have been sampled in drill cores, providing constraints on their conditions of formation; the validity of inferring plate-tectonic vectors from the orientation of structural fabrics has been confirmed by observations from the Nankai prism. Drilling into serpentine diapirs of the Mariana forearc reveals a mechanism for transport of blueschists and chemically exotic volcanic rocks from 10 to 20 km depth to the surface. Drilling has documented the ongoing emplacement of a tectonostratigraphic terrane in the Vanuatu fore arc. Subduction erosion of several drilled fore arcs is indicated by a small accretionary prism and substantial subsidence. Anomalies in pore-water geochemistry of drill cores demonstrate that fluids flow both laterally and vertically over tens of kilometres, primarily along faults. In the accretionary prism environment, fluids control structural evolution, cause a significant redistribution of heat, solutes, and solids, and feed surficial biological communities.

Drilling in the immediate future will focus on the processes of ridge-trench interaction off southern Chile, the role of fluid flow in gas hydrate genesis off Vancouver Island, and the dynamics of the faults that feed fluid to surface vents off Oregon. An ultimate goal of ocean drilling in fore arcs includes complete documentation of in situ conditions to understand the processes responsible for the geologic features of the cores. Additionally, the community hopes to drill deeply in accretionary prisms with long-term monitoring designed to record phenomena associated with the earthquake cycle. A broad range of earth scientists, including geologists, geophysicists, geochemists, hydrogeologists, petroleum geologists, and metamorphic petrologists, are needed to achieve these goals and build on the scientific synergism of this program.

INTRODUCTION

Fore arcs are the most dynamic tectonic environment on Earth, being characterized by the largest earthquakes and the highest strain rates. Accordingly, this plate-boundary regime has long been the target of ocean drilling investigations, with studies principally focused on tectonics. The Deep Sea Drilling Project (DSDP) documented the plate-tectonic concept of subduction accretion and discovered subduction erosion. The successor to DSDP, the Ocean Drilling Program (ODP), has focused on more specific process-oriented issues of structural evolution in accretionary prisms, including the calibration of the ever-improving seismic reflection images, and of material transfer during both accretion and subduction erosion. Recently the major scientific driving force for ocean drilling in fore arcs has been the interaction of fluids and rocks in this saturated, structurally complex regime.

ACCRETION

DSDP investigations demonstrated that deposits of the oceanic plate were being progressively accreted at the deformation front of accretionary prisms, verifying simple plate-tectonic models of accretion (Moore, Watkins, et al., 1979). Drilling results also showed that underthrust sediments were underplated at depth (Watkins et al., 1981), that frontally accreted material can constitute only a rind a few kilometres thick, and therefore that the great bulk of subaerially exposed and eroded prisms must have been emplaced by underplating. Recent drilling investigations have fostered better interpretations of subaerially exposed equivalents by further elaborating large-scale processes.

Accretionary Processes: Calibration of Seismic Reflection Images

Over the past decade the quality of seismic reflection images of accretionary prisms has improved dramatically and has provided tantalizing targets for drilling. For example, the seismic reflection profile crossing the deformation front of the Nankai accretionary prism in southwestern Japan outlines a series of imbricate thrusts and a subjacent decollement in unparalleled detail (Fig. 1; Moore et al., 1991). Drilling near the deformation front of this accretionary prism penetrated completely through the incoming sedimentary sequence, transecting the frontal thrust, the decollement zone, and underthrust deposits to the ocean crust (Taira, Hill, Firth, et al., 1991). The drill core characterized the

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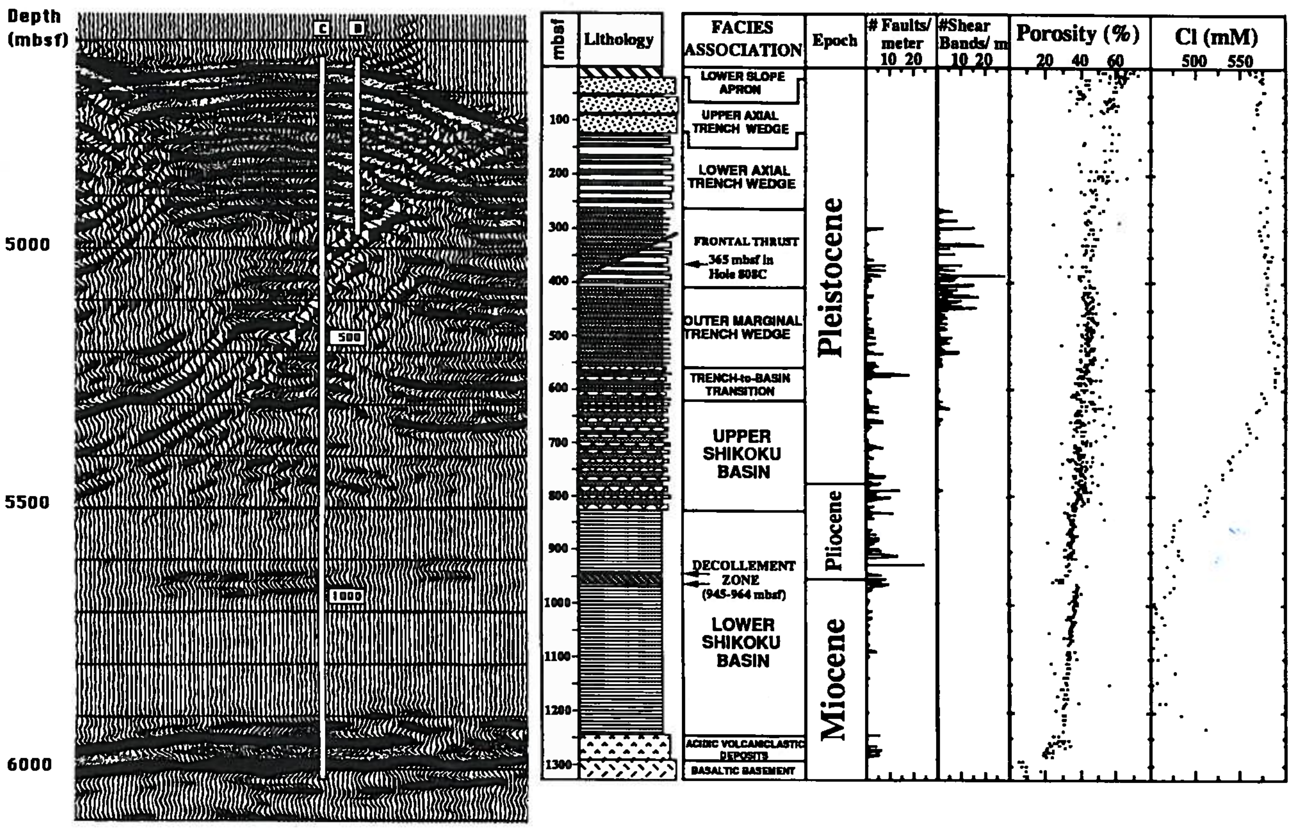

Figure 2. Detail of seismic reflection data showing lithology, structural geology, physical properties, and fluid chemistry from Site 808. Chloride values are millimoles per litre. Note sharp decrease in porosity across decollement zone, apparently due to rapid underthrusting of sediments beneath the accretionary prism (from Taira, Hill, Firth, et al., 1991).

small-scale structural features developing during this initial deformation and allowed measurement of displacement on the frontal thrust and definition of the thickness of the decollement zone. In addition to clarifying the geology of this zone of initial deformation, the core shows a sharp decrease in acoustic velocity and density, leading to a lower acoustic impedance across the decollement and providing an explanation for the reversed reflection polarity of this surface (Fig. 2; G. F. Moore et al., 1990).

Accretionary Processes: Small-scale Structures, Convergence Directions, Fabric Evolution, and Stratal Disruption

The extraordinary core from the toe of the Nankai accretionary prism was largely coherent but contained many small-scale structures reflecting the deformation of the incoming sedimentary section. Most spectacularly, small faults and conjugate shear bands faithfully recorded the geophysically determined direction of plate convergence (Fig. 3). Such verification of the connection between small-scale structural development and plate motions lends a whole new level of credibility to studies that claim this correlation in ancient rocks (e.g., Byrne, 1984).

Where sampled by drilling, the initial deformation of the incoming sediments is largely coherent; however, transects across several accretionary prisms show development of stratal disruption or melange-style deformation at shallow depths. For example, stratal disruption occurs within 14 km of the deformation front of the Barbados Ridge in sediments of 40% to 50% porosity near an out-of-sequence thrust (Figs. 4, 5; Brown and Behrmann, 1990). In aggregate, DSDP and ODP drill cores from accretionary prisms have identified the initial stages of many small-scale structures known from subaerially exposed melanges (stratal disruption, scaly fabric, cataclastic shear zones, disrupted veins) and limited the conditions under which they develop (Lundberg and Moore, 1986).

NONACCRETION AND SUBDUCTION EROSION

In some fore arcs, accretionary prisms are conspicuous by their absence and may have been removed by subduction erosion or strike-slip faulting (von Huene and Scholl, 1991). Drilling results supporting subduction erosion include the small volume and limited age of prisms in spite of prolonged subduction; additionally, drilling has documented the subsidence of fore arc regions, suggesting removal of material (Fig. 6; von Huene et al., 1980; von Huene, Suess et al., 1988). Nonaccretion is difficult to distinguish from subduction erosion, but it may be occurring off Guatemala (Aubouin and von Huene, 1985). Nonaccretion and subduction erosion, like stratigraphic unconformities, leave gaps in the rock record, which if unrecognized radically diminish our understanding of geologic history.

Basal abrasion of the upper plate by horsts and grabens or other irregularities on the downgoing plate, known as the buzz-saw model (Hilde, 1983), has been a popular mechanism for subduction erosion. However, high-quality seismic data show that the decollement rides smoothly over the horsts without obvious basal erosion (Shipley and Moore, 1986). Alternatively, the underthrusting of seamounts may cause local oversteepening and slope failure, and therefore erosion of the toe of the prism (von Huene and Lallemand, 1990; Taira and Pickering, 1991).

BLUESCHISTS, EXOTIC BLOCKS, SERPENTINE DIAPIRS, AND TERRANES

How high-grade exotic blocks are mixed with materials of lower metamorphic grade is a perennial problem of accretionary tectonics. Recent penetrations of serpentine diapirs and serpentine volcanoes in the Mariana fore arc (Fryer, Pearce, Stokking, et al., 1990) document intermixed blocks of mid-ocean ridge basalt (MORB) (Johnson et al., 1991) and blueschist (Maekawa et al., 1992). The metamorphic grade indicates transport of the blueschists from sources 13–18 km below the serpentine volcano (Fig. 7). The serpentine diapirs penetrate island-arc volcanic rocks at the surface about 50 km arcward of the modern trench; oceanic rocks have been recovered in drill cores and dredges from the lower trench slope (Johnson et al., 1991). Apparently, the source of the MORBs and blueschists in the serpentine diapir is some of these accreted rocks that extend beneath the fore arc.

Exotic tectonostratigraphic terranes are interpreted as rafted fragments of oceanic plateaus or island

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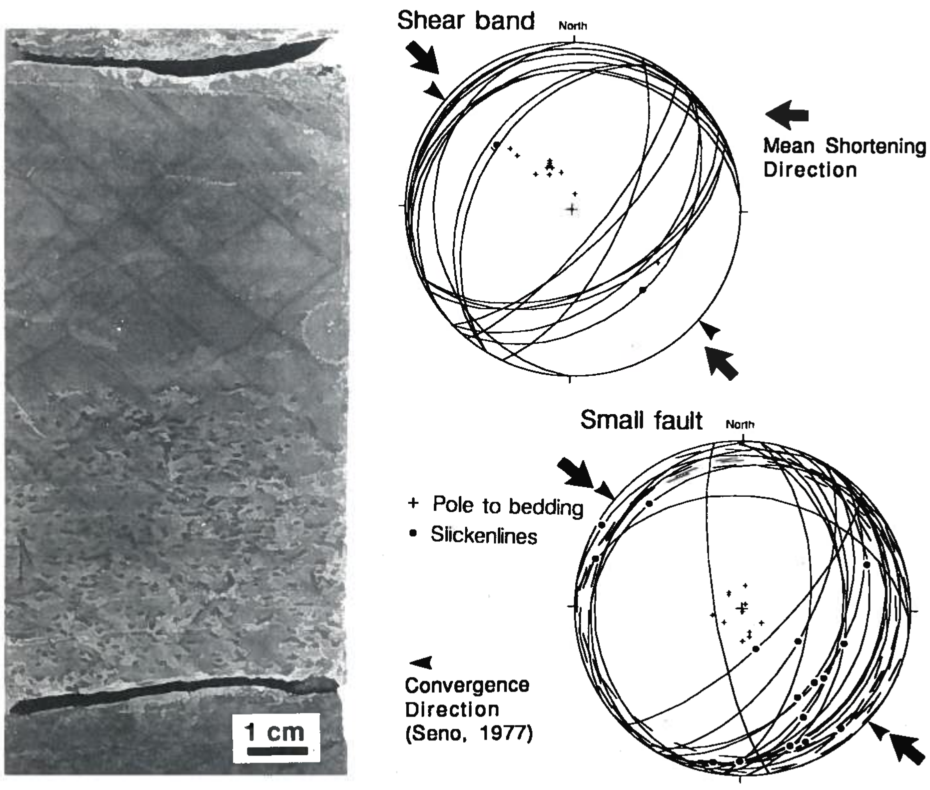

Figure 3. Conjugate shear bands and lower-hemisphere stereonets of paleomagnetically reoriented conjugate shear bands and faults (after Taira, Hill, Firth, et al., 1991). Shortening direction from these structures (northwest-southeast) coincides with the local plate-tectonic convergence direction (Seno, 1977).

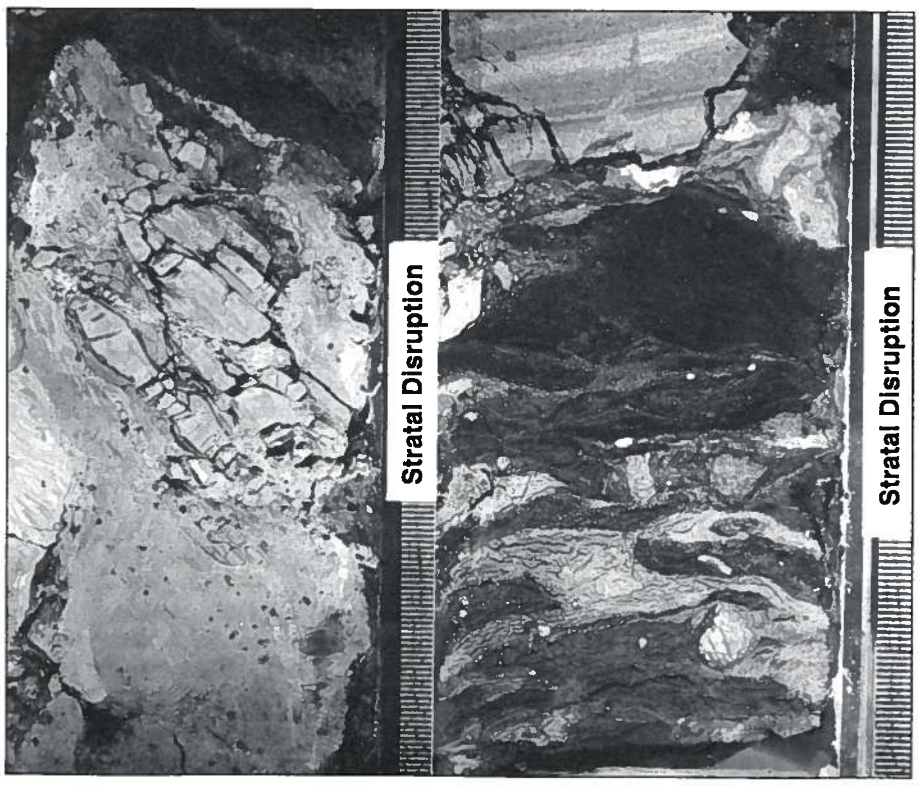

Figure 4. Stratal disruption developed cores sampled from 260 m subbottom from Site 674 of the northern Barbados Ridge (Brown and Behrmann, 1990). Stratal disruption developed adjacent to an out-of-sequence thrust (Fig. 5). Some of the horizontal banding in the core section to the right is due to drilling deformation, but geologic processes caused the dispersion of sandstone fragments. Scale to right of the core is in millimetres.

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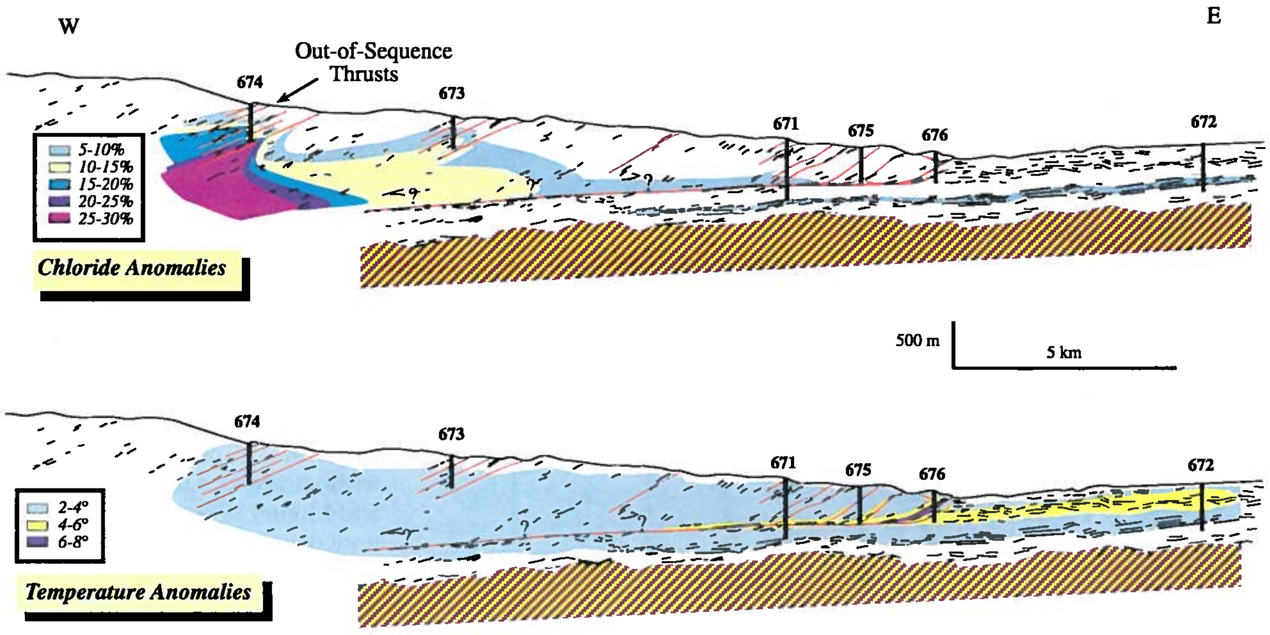

Figure 5. Barbados cross section showing anomalies in chloride content of pore waters and temperature, suggesting fluid flow, especially along faults (after Vrolijk et al., 1991).

arcs. Recent drilling in the Vanuatu fore arc of the southwest Pacific has unequivocally demonstrated the accretion of sediments and MORB volcanic rocks from an incoming oceanic high as discrete thrust sheets, in a sense, forming a tectonostratigraphic terrane (Collot, Green, Stokking, et al., 1992).

FLUIDS IN ACCRETIONARY PRISMS

Although it has long been recognized that high fluid pressures facilitate thrust faulting and therefore are important in accretionary prisms (e.g., von Huene and Lee, 1982), only recently did earth scientists fully appreciate the important role of fluids in water-rock interactions, compositional changes, and solute and heat transfer. In retrospect the importance of fluids is obvious because accretionary prisms consist of partially consolidated sediments being rapidly deformed and buried in a water-saturated environment. However, documentation of fluid-flow paths, sources, rates, and effects has just begun.

Detecting Fluid Flow: Defining Conduits

The conduits of fluid flow have been best detected through mapping anomalies in pore-water chemistry and temperature (Fig. 5; Gieskes et al., 1990; Kastner et al., 1991; Fisher and Hounslow, 1990). In each case the fluid geochemistry or in situ temperature deviated from background values; such deviations would be lost to either chemical or thermal diffusion within hundreds to hundreds of thousands of years unless continually resupplied. Generally, drilling results indicate that the fluid is flowing along faults, probably via fracture permeability (Moore, Mascle, et al., 1988; Suess, von Huene, et al., 1988; Taira, Hill, Firth, et al., 1991). Other investigations of modern accretionary prisms have argued for diffuse fluid flow through intergranular permeability (Davis et al., 1990; Han and Suess, 1989) or focused flow along sand layers (J. C. Moore et al., 1990). Studies of modern accretionary prisms are focused on understanding of their overall plumbing over a range of lithologic variations and structural styles. Although geochemical and temperature data have revealed much about the geometry of fluid flow, little is known about pore pressures, fracture permeability, and flow rates.

Long-Distance Migration of Fluids

Drilling results indicate long-distance migration of fluids over tens of kilometres. The pore waters along the decollement near the deformation front of the northern Barbados Ridge (Fig. 5) contain thermogenic methane, requiring formation temperatures of more than 100 °C and deep sources many tens of kilometres arcward from the deformation front (Vrolijk et al., 1990). Similarly, deep sources are required if the ubiquitous chloride-poor waters (Fig. 5) are derived from dehydration of smectite, which also must occur above at least 100 °C (Pytte and Reynolds, 1989). These chemically exotic fluids are but a small proportion of the water produced by the total volume of fluid expelled during burial of a sediment package (Kastner et al., 1991); they must be produced after substantial porosity reduction due to consolidation, and they must be efficiently transported to the surface to avoid dilution. Thus, any faults along which the fluids flow must root deeply and be of relatively high permeability (Fig. 8). The serpentine volcanoes of the Mariana fore arc (Fig. 7) expel fluids containing thermogenic hydrocarbons probably derived from sedimentary organic matter (Haggerty, 1991). Because the rocks surrounding the serpentine volcanoes are volcanic basement, the logical source of the organic matter is underthrust or underplated material, implying many kilometres of vertical fluid migration (Haggerty, 1991).

Bottom-Simulating Reflectors, Methane Hydrate, Energy Resources, and Global Change

Bottom-simulating reflectors that cut across stratigraphic layering and faults are widespread along outer continental slopes (BSR reflector in Fig. 1). Both DSDP and ODP drilling principally in fore arcs has shown that these reflections arise from the phase boundary between methane hydrate (a methane-water ice) above and liquid water and methane below (Shipley and Didyk, 1982; Kvenvolden and McDonald, 1985; Kvenvolden and Kastner, 1990). The solid methane hydrate contains up to 160 times its volume in free gas, and its widespread distribution may comprise a large reservoir of methane and carbon, with implications for energy resources and climate change (Kvenvolden, 1988). A current debate concerns whether methane hydrate forms from a local reservoir of methane (Kvenvolden and Kastner, 1990) or from the continual flux of fluid being expelled from a consolidating sedimentary sequence (Hyndman et al., 1991).

FUTURE PLANS

1992 Drilling: Chile Triple Junction and Cascadia

The Chile drilling program will for the first time penetrate an accretionary prism where an active spreading center is being underthrust. The expected interaction of both the basaltic magma and high-temperature fluids in this structurally complex environment of the accretionary prism should provide critical uniformitarian models for evaluation of inferred ridge-trench interactions in the geologic record. The accretionary prism of the Chile trench is also of limited volume, despite a history of subduction from the Mesozoic; drilling should provide a better understanding of the processes of subduction erosion or nonaccretion along this margin.

Drilling off Vancouver Island will test whether methane hydrate forms by flow of fluids from depth, with the progressive scavenging of methane from fluid and its concentration in the solid hydrate layer. Off Oregon, faults that supply fluid to prism vent communities will be penetrated; these faults show anomalous seismic reflections, suggesting overpressuring, dilation, and active fluid flow. Here drilling may calibrate the seismic reflection data to allow remote mapping of hydrological properties of faults. Long-term monitoring of pressure and temperature is planned in boreholes in the Cascadia prism.

Down-hole Measurements and Long-term Monitoring

Ocean drilling has been very successful in obtaining cores to depths greater than 1300 m in the fore-arc environment. Thus, the basic geologic features of this environment are becoming well defined. True understanding of the processes active during the development of these features requires down-hole measurements of temperature, stress, fluid pressure, permeability, and in situ pore-water chemistry. These measurements are difficult to achieve but are essential to interpret completely both the drill cores and the rocks preserved in subaerially exposed accretionary prisms.

Ocean drilling through the decollement zone transects convergent

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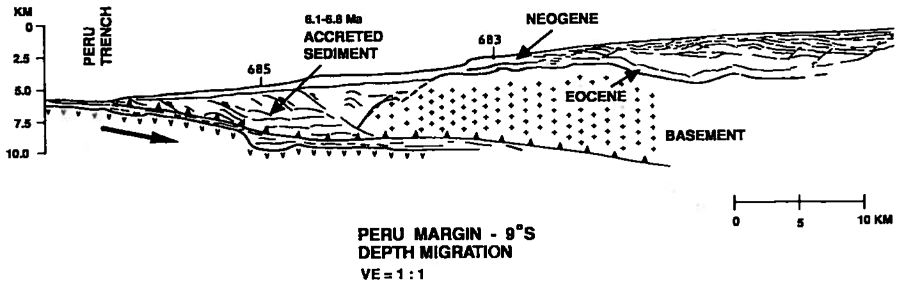

Figure 6. Peru margin cross section based on results of ODP Leg 112 (von Huene, Suess, et al., 1988). Note the limited development of the extent of the accretionary complex. A mid-slope sedimentary sequence has undergone considerable subsidence during the Tertiary, presumably due to subduction erosion.

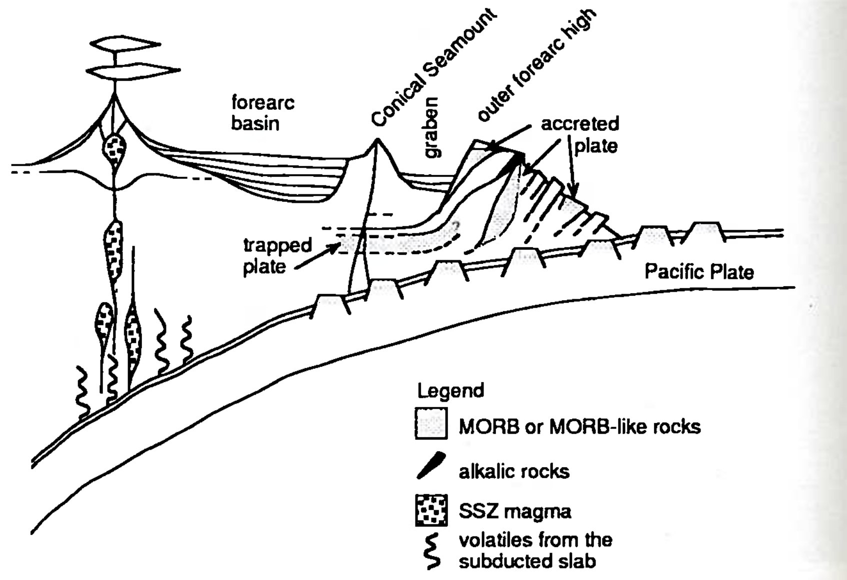

Figure 7. Schematic cross section through the Mariana fore arc showing serpentine volcanoes (conical seamount) and possible source depths for MORBs and blueschists included in serpentine of drill cores (Johnson et al., 1991).

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plate boundaries, which at depth produce Earth's largest earthquakes. The presence of fluids from deep sources at shallow depths demonstrates a hydrologic connection to the seismogenic interval of the plate boundary. By emplacement of appropriate sensors in faults accessible by drilling, we can monitor fluid pressure variations and perhaps correlate these variations to the earthquake cycle.

Deeper Drilling

Although high-quality down-hole measurements are a must for understanding processes in accretionary prisms, deeper drilling is necessary to link these insights more effectively with exposures of subaerially exposed equivalents. The current maximum depth of more than 1300 m can probably be extended to 1500 to 2000 m. Drilling beyond these depths will probably require some system to equalize lateral stresses, probably a heavy mud system.

Broadening of the Constituency of Accretionary Prism Drilling

Currently the principal constituency of drilling in accretionary prisms consists of geophysicists, structural geologists, geochemists, and geotechnical specialists. With the developing emphasis on fluids, down-hole measurements, and deeper drilling, participation is needed from hydrogeologists interested in geologic problems, from petroleum geologists interested in fluid migration, and from metamorphic petrologists interested in water-rock interactions. Drilling in accretionary prisms provides the unparalleled opportunity to evaluate processes while they are occurring. The problems of accretionary prism evolution are multidisciplinary, require the involvement of a broad group of earth scientists, and offer some of the most synergistic and exciting research opportunities anywhere.

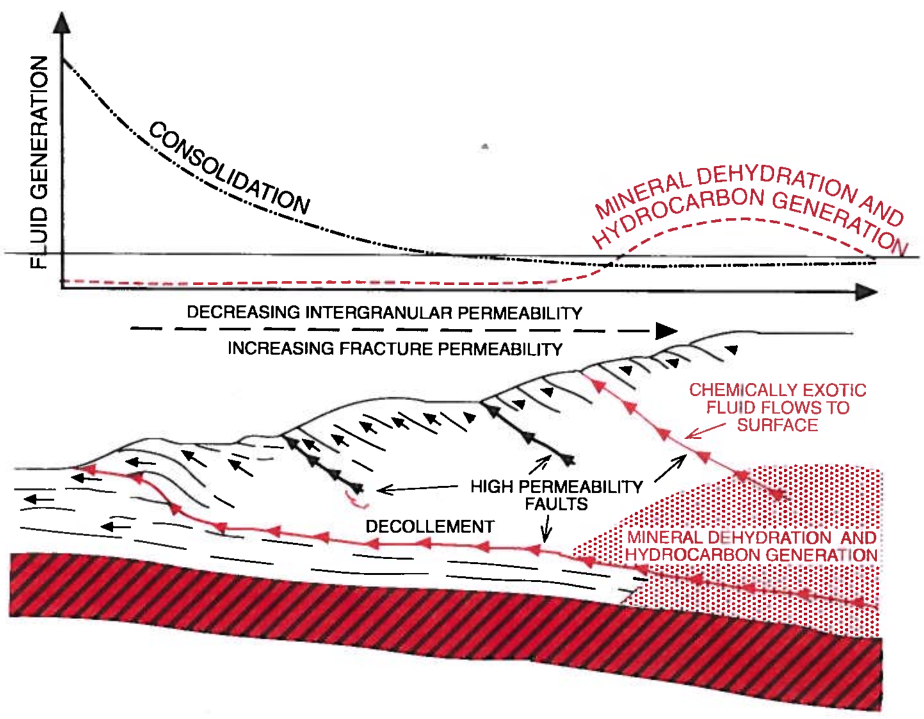

Figure 8. Diagram showing how faults tap deep sources, even in a sandy accretionary prism. Faults and stratigraphic layers have approximately equivalent permeabilities near a deformation front; active faults maintain high permeabilities landward through the accretionary prism. Conversely, stratigraphically controlled conduits decrease substantially in permeability landward because of cementation, consolidation, and deformation. Fluid generation due to consolidation decreases sharply landward and is relatively small at the onset of fluid production due to mineral dehydration and generation of thermogenic hydrocarbons. Active faults cutting into regions of fluid generation by mineral dehydration and hydrocarbon generation can transport chemically exotic fluids to the surface. Arrow length is approximately proportional to the log of permeability.

ACKNOWLEDGMENTS

The U.S. National Science Foundation and equivalent agencies in foreign countries have supported DSDP and ODP for more than two decades. Not only has this partnership vastly increased our scientific knowledge but it has also provided a prime venue for scientific exchange, a stimulating, multidisciplinary "international university." Preparation of this paper was supported in part by National Science Foundation Grants OCE-8813907 and OCE-8917705 (Moore.) We thank Rob Twiss and Peter Vrolijk for helpful reviews of this manuscript.

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During the commotion, the Coast Guard apprehended the remaining Greenpeace inflatable boats and a fishing boat that strayed within the safety perimeter, and the demonstration was curtailed. When the bound intruder was taken into custody by the Coast Guard, he repeatedly spat on the arresting officer, possibly to provoke retaliation. Taken onshore with the other activist (who was cut free with little ado), he demanded, according to the Coast Guard, to be examined in the Gold Beach hospital for injuries sustained from being "beaten and kicked by the ship's crew." A total of 15 persons were arrested, and the apprehended vessels confiscated. All protesters were released shortly after being jailed in Gold Beach, and all vessels were returned within a few days.

In the hours following the direct confrontation, I elected not to run planned geophysical surveys that would potentially take the *Aloha* into the course of the protesting vessels, thereby provoking further reaction. We focused instead on surficial sampling of the sea floor. At the end of the day, the fishing vessels went home, and two days later, without further confrontation, the *Rainbow Warrior* departed for San Francisco, the site of its next protest. We finished the two-week cruise without further incident, perhaps partly because the Coast Guard kept a vessel in our general vicinity. Onshore, however, threatening phone calls to the owner of a trailer park caused him to ask our navigational support team to seek other facilities.

The protests had little impact on the ultimate scientific success of the cruise. We collected a superb set of high-resolution seismic and magnetic data that constrain the models for placer-mineral accumulation on this and other shelves. The biologists were pleased with their results, which provided fresh information on the living resources of the area. The integration of biological data and geological substrate results was particularly gratifying. Coring in the secondary work area resolved its placer resource potential as minimal. Our major disappointment was that a combination of sea conditions and operational problems prevented coring in the primary work area. Ironically, after we reported the general success of the study in a post-cruise press conference, a Greenpeace spokesperson notified the press that, irrespective of our assessment, we had gotten little information and the cruise was "an immense waste of the taxpayers' money."

The encounters on the Oregon shelf make for some good story-telling, but they also raise philosophical and procedural questions that warrant consideration by the geoscience community. Such circumstances demand a continuing succession of field decisions. The options are numerous: withdrawal, proceeding but avoiding confrontation, engaging in a battle of wits with the protesters, physical confrontation. Considerations include the physical safety of ourselves, our colleagues, and the protesters; the security of scientific equipment; the cost and importance of the mission; the probability of completing work in the face of protest. Discussion of these possibilities with colleagues yields no consensus. I employed all of the options save withdrawal, and in retrospect, I would do nothing differently. Yet, I suspect that the decisions would have differed as the cruise progressed and the circumstances changed. Some choices, which were probably right at the time, were troubling. I didn't like to admit that a few people in inflatable boats could keep us from proceeding with our research. Because the incidents occurred early in the cruise, I correctly felt that we could afford to be patient. If the situation had prevailed until late in the cruise, I might have been willing to take greater risks. Every new situation will demand its own set of decisions; I think the scientist's most important assets in any case are a cool head

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