OCEAN DRILLING PROGRAM

LEG 170 SCIENTIFIC PROSPECTUS

COSTA RICA ACCRETIONARY WEDGE

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ABSTRACT

To gain a better understanding of the mechanical and chemical behavior of accretion and underplating and tectonic erosion and to determine how deformation and dewatering are distributed throughout an accretionary prism, it is essential to establish the flow pattern of materials through subduction systems.

Leg 170 consists of a program of drilling at four primary sites (proposed Sites CR-1 through CR-4) on the Costa Rica convergent margin to investigate mass- and fluid-flow patterns through the accretionary prism and will integrate structural analysis and sediment, fluid, and chemical mass-balance calculations. The objectives are to determine (1) the relative importance of frontal accretion, underplating, out-of-sequence thrusting, sediment subduction, and subduction erosion; (2) the timing, rate, and modes of the accretionary prism development; (3) the importance of fluids in both strengthening and weakening the prism, particularly in the presence of underthrust carbonates; and (4) the fate of subcrustally subducted sediments and the associated fluxes.

Drilling on the Costa Rica margin could provide us with the first good estimates of the total material and chemical fluxes through a subduction system, because of the ideal conditions (the capping sediment apron and the lack of trench turbidites), extensive seismic imaging of the accretionary complex, and the opportunity to constrain the deeper parts of the sediment cycle, which are reflected in the forearc fluids and arc volcanic rocks. Because of the global importance of understanding material and fluid fluxes through subduction zones, it is critical that these systems become well understood.

The specific objectives of the drilling program are to determine the age and nature of the accretionary wedge beneath the slope apron; the rate of accretion of the wedge; the nature of the lower part of the apron and time sequence of formation; the physical properties of the material above, within, and below the top-prism reflector; the relative importance of underplating vs. out-of-sequence faulting; the evidence of fluid stratigraphy and flow distribution within the

wedge materials; and the nature of apron material relative to deep-sea hemipelagic sediment.

INTRODUCTION

Essential observations for establishing the mechanisms of accretion and underplating, tectonic erosion, and deformation and dewatering must include (1) the rate (positive and negative) of prism growth as a function of incoming sediment volume and type; (2) the partitioning of frontal offscraping, underplating, internal prism deformation, and subduction erosion; and (3) the effects of fluids. Excellent control is required of material mass-balance and residence time in the prism, in addition to detailed structural geometry of the complex interior regions of forearcs. Such control and imaging is not well established in any convergent margin, despite expending a great amount of effort to understand these margins.

The scarcity of accurate mass-balance estimates is due to the complexity of both sedimentary and structural processes at convergent margins, the poor structural imaging of the deeper parts of forearc regions, and the need for reliable age estimates that generally require drilling. The presence of trench turbidites, varying dramatically in thickness both spatially and temporally, is a major obstacle in estimating material influx. Erosion and redeposition of accreted material are additional complications that can not be taken easily into account. A first step in addressing these problems is to locate an experiment along a convergent margin that lacks trench turbidites, has a slope cover preventing erosion of the accreted material, and has clearly imaged deep and shallow structural control.

If the convergence rate is known, the incoming sediment flux can be estimated closely and prism size will reveal the relative importance of sediment accretion or bypassing. The case of subduction erosion may also be documented with additional structural, stratigraphic, or biostratigraphic data to show subsidence or arcward retreat. The final requirement is availability of accurate emplacement dates for the accreted material.

The convergent margin off Costa Rica (Figs. 1 and 2) satisfies all the requirements necessary to determine accurate mass-balance and flow estimates, except for knowledge of the age and residence time of the prism material. The trench is devoid of turbidites here and the convergence rate is known. Recently acquired 2D and 3D seismic reflection data across the margin provide excellent control of the internal structure of the forearc, and they define boundaries between the accretionary prism and the overlying slope cover, as well as between the prism and the subducting plate (Fig. 2). These data show that the slope cover extends to within 3-5 km of the trench, so it protects the accreted mass from erosion and conserves its volume. Consequently, the growth rate of this prism can be calculated accurately when the emplacement age of the accreted material is determined by drilling through the basal slope cover and top of the prism.

This relatively closed system is also a superior environment in which to investigate the fluid and chemical fluxes in a subduction system. Comparison of physical (i.e., velocity and porosity) and chemical properties of sediments seaward of the trench with sediments that have been subducted or accreted can provide important information on the nature and rate of diagenetic processes in subduction zones. Aided by relatively rapid plate convergence and a stratigraphically consistent subducting sedimentary section, the sediment and pore-water chemistry can also be compared with the constituents of arc volcanic rocks using geochemical tracers. By their presence or absence in the volcanic rocks, tracers such as ^{10}Be and Ba may be used to indicate the amounts of sediment accretion, amounts of sediment recycling to the volcanic arc, and subduction into the mantle (Tera et al., 1986; Plank and Langmuir, 1993).

Prominent lithologic or structural boundaries that produce high-amplitude seismic reflectors in the interior of this moderately accreting prism are within reach through drilling. The existing 3D seismic grid will allow exceptionally good correlation between seismic and borehole data as a result of accurate 3D imaging. Certain coherent intraprism reflectors identified in the seismic data appear to be unrelated to offscraping but are interpreted as faults (Shipley et al., 1992), which formed during out-of-sequence thrusting and underplating. These and other faults are likely pathways along which fluids escape from the prism. Identifying the physical properties, lithologies, and geologic processes that produce these impedance contrasts will provide essential information for the structural interpretation of this margin and fundamental data about the nature of seismic reflections in accretionary prisms.

BACKGROUND

Material Mass Balance in the Accretionary Complex

Mass-balance studies at convergent margins are useful for quantifying processes such as sediment underplating, sediment subduction, and subduction erosion that are not documented easily by seismic imaging. Platt et al. (1985) used a combination of field relations, seismic reflection data, and mass-balance calculations to interpret large-scale underplating in the Makran accretionary complex of Pakistan. Their mass-balance calculations showed that with only frontal accretion of sediments since the middle Miocene, 70% postaccretion shortening would be required to account for the present prism width of 180 km. However, because field relations allow for only 30% shortening during this period, the mass-balance calculations strongly support an underplating mechanism to reconcile the sediment supply and the 7-27 km thickness of the Makran prism.

Recent interpretations of the Cascadia accretionary prism off Vancouver Island suggest that growth is occurring entirely by frontal accretion and that nearly all of the incoming sediments are accreted (Davis and Hyndman, 1989). For the period since 1.8 Ma, the accreted mass is approximately equal to the estimated sediment supply, suggesting that the current processes may have persisted through the Pleistocene.

A different type of mass-balance analysis applies to the Peru-northern Chile convergent margin. This part of the South American margin lacks a significant accretionary complex (Schweller et al., 1981); instead, margin subsidence and a shortened gap between the trench and the Mesozoic magmatic arc indicate active subduction erosion. The type of mass-balance study applicable here is to determine the mass of material that has been tectonically eroded.

Von Huene and Lallemand (1990) estimated subsidence and landward migration of the trench along the Lima Basin since 20 Ma and calculated an erosion rate of 31-55 km^3/m.y. per km of trench. Along the Chile margin (latitude 24°-35°S), Stern (1991) estimated rates of subduction erosion of 50-500 km^3/m.y. per km of trench.

Material Mass Balance of the Costa Rica Accretionary Complex

Preliminary mass-balance calculations were made for the study area off the Nicoya Peninsula, Costa Rica (McIntosh et al., 1990; McIntosh, 1992). The emplacement age of material accreted beneath the lower slope is loosely constrained by Deep Sea Drilling Project (DSDP) Site 565. Site 565 penetrated 328 m of terrigenous mud in the slope apron section, bottoming in lowermost Pliocene sediments. This age indicates a mean sedimentation rate of 60 m/m.y. and suggests that the age of the prism below Site 565 could range from about 6 to more than 10 Ma (Shipley et al., 1992). By graphing sediment accretion vs. time (Fig. 3), we have estimated that if all the incoming sediments were accreted the observed volume could be accumulated in about 1 m.y. However, if the amount accreted were 20%-40% of the incoming sediments, then the time required to accrete the observed volume is 6-10 m.y. (Fig. 3), which is consistent with Site 565 age estimates.

The incoming section is roughly 40% hemipelagic and 60% pelagic, so 40% accretion beneath Site 565 implies accretion of the upper hemipelagic layer and underthrusting of the lower pelagic layer. This can be an important constraint for interpretation of the lower slope structure (Shipley et al., 1992) and rate of accretion through time. However, Site 565 does not adequately restrict the underlying prism emplacement age; if the accreted material is >10 Ma, it could imply episodic accretion or subduction erosion. Proposed Site CR-3, located near Site 565, will sample the base of the slope apron and supply an emplacement age capable of tightly delimiting the lower slope rate of accretion.

Mass-balance calculations based on prism emplacement ages at proposed Site CR-4 are also planned. This will allow study of accretion rates over a longer term. Combined with the results from proposed Site CR-3, these calculations will quantify sediment bypassing or erosion, as suggested by the abrupt change in slope apron thickness at 20-25 km from the trench.

Mass Balance at Costa Rica vs. Other Convergent Margins

Two essential values must be determined or known to reconcile the sediment budget at a convergent margin. First, the incoming sediment flux must be determined, and, second, the amount of material accreted over a designated time span must be measured. Estimating the incoming sediment flux can be a difficult problem, especially with the presence of trench turbidites for which the thickness can vary in both time and space along a margin. Another problem in estimating sediment influx is to determine the convergence rate; although plate convergence rates are generally known satisfactorily across most convergent boundaries, the rate of seaward advancement of the growing wedge must be taken into account in rapidly accreting margins such as Nankai, Cascadia, and parts of Barbados. For example, seaward advancement of the Cascadia accretionary complex just during the Pleistocene is estimated at 25 km (Davis and Hyndman, 1989). This calculates to a rate of advancement of about 14 mm/yr, or 31% of the 45 mm/yr convergence rate. To avoid serious inaccuracy in the effective convergence rate, the age of the accreted material must be controlled, and shortening or extension in the older part of the wedge must be well known or negligible. Seaward advancement of the deformation front in Costa Rica, however, is negligible compared to the convergence rate. Estimates of the advancement rate are 1.4-2.3 mm/yr, or less than 3% of the 87-mm/yr plate convergence.

The Costa Rica prism is also better suited than most for accurately identifying and measuring the accreted volume. The top prism reflector gives Costa Rica a demonstrably closed and bounded system, free from the effects of surface erosion. This unusual feature differs from many margins, where erosion of accreted material is common. Furthermore, the moderate rate of accretion off Costa Rica has resulted in a relatively thin prism beneath the middle and lower slope. This geometry, combined with the 2D and 3D seismic reflection data, allows good interpretations of the internal structure of the prism and consequently good estimates of the geometry of the accreted mass. Other mass-balance estimates, such as off southern Mexico (Watkins et al., 1982), are subject to considerable uncertainty because of difficulty in measuring the geometry of the accreted mass.

Fluid Effects

It is estimated that a volume of fluid roughly equal to the mass volume of the accretionary prism passes through the prism during accretion (Carson, 1977). Numerous studies have indicated that the décollement, intraprism faults, highly permeable (sandy) layers, and mud volcanoes provide conduits for water flow to escape. Detailed studies of the Barbados (Foucher et al., 1990; Fisher and Hounslow, 1990), Oregon-Washington (Moore et al., 1990), and Japan (Henry et al., 1989) accretionary wedges document that rates of fluid expulsion from vents and mud volcanoes can be as great as, or significantly greater than, the total rate of fluids entering the subduction zone, implying that fluid vents and mud volcanoes are transient features. The Costa Rica margin probably has few sandy layers, so any elevated permeability is most likely fracture permeability. We have discovered four mud volcanoes in the 3D grid. These and numerous through-prism faults, many of them out-of-sequence thrusts, may play a significant role in dewatering the prism.

An additional process of great importance in fluid and mass transport within accretionary wedges is dissolution and precipitation of carbonates. Kulm and Suess (1990) have mapped a large area of probable carbonate outcrop off Oregon-Washington. Sample (1990) conducted experiments on the stability of carbonate cementation in subduction zones and discussed the importance of such cementation to the physical properties, and, therefore, the structural development, of the prism. His results suggest that carbonate cementation within underthrust sediments may lead to accretion of coherent duplexes rather than diffuse underplating of sedimentary melange.

We are interested in carbonate sedimentation with respect to the Costa Rica margin, because the lower pelagic sediments on the subducting Cocos plate are carbonate rich. Cementation of the accreted material by carbonate released from the dewatering underthrust section is a possible explanation for the major change in seismic velocity marking the top of the prism. If so, it may result in significant differences in rock strength between the top of the prism and the base of the apron. Cementation in the underthrust section itself may allow deeper sediment underthrusting, and, if eventually accreted, these sediments may remain in coherent underplated blocks (e.g., Sample, 1990). Early cementation will also increase the importance of fracture permeability in dewatering, possibly concentrating fluid flow along fault zones. These speculations must be tested by drilling. The total volume of internal fluids available in the Costa Rica subduction zone could be estimated by assuming steady-state sediment mass conservation, by thoroughly characterizing the amount and nature of the incoming sediments, and by establishing the degree and nature of alteration of the uppermost oceanic basement (plus extrapolation to greater depths).

Fluid expulsion at the seafloor is an important consequence of porosity reduction, subduction-induced sediment diagenesis, and metamorphic deformation. It is well established that fluids affect virtually all aspects of the geologic evolution of subduction zones and that fluids play a central role in the deformational, thermal, and geochemical evaluation of this environment (von Huene, 1984; Bray and Karig, 1985; Moore et al., 1990, and references therein). Here, extensive fluid-solid diagenetic and metamorphic reactions take place (Ritger et al., 1987; Peacock, 1990; Gieskes et al., 1990; Kastner et al., 1990, 1991) and significant fluid volumes are expelled (Kulm et al., 1986; Carson et al., 1990; von Huene and Scholl, 1991; Le Pichon et al., 1990, 1991). These fluids contain key information on the relative mobility of important elements for mass-balance calculations and on the degree to which these fluid-flow regimes influence global geochemical and heat budgets. It is clear from the data presently available from Barbados, Nankai, Peru, and Cascadia that the fluid compositions are chemically and isotopically very different from those of present-day seawater. Therefore, the chemical and isotopic fluxes are potentially significant. It is imperative to document and compare the incoming sediment and pore-fluid chemistry and isotopic compositions at a reference site with those that have been modified by diagenesis and metamorphism throughout the subduction zone.

Typically, sediments entering subduction zones have porosities of approximately 50% ± 10% (e.g., Hamilton, 1976), whereas subaerially exposed accretionary complex sediments have porosities of less than 5% to 10%. Expulsion of fluids through porosity reduction and by devolatilization reactions (e.g., dehydration and thermal decomposition of hydrous minerals and organic matter and decarbonation of calcareous minerals) occurs through the décollement and other major and minor faults and by flow dispersed through the sediments. Determining the relative importance of channelized vs. dispersed (diffuse) fluid flow is critical for understanding the hydrogeology of subduction zones. Thus, capturing and analyzing the fluids in the décollement, across faults, and within the sediment pore space is a primary objective.

Studies of the pore-fluid and sediment geochemical and isotopic compositions would also permit evaluation of the types and extent of fluid-rock reactions that have occurred and possibly even detect mixing with external fluids (principally with meteoric water?). Modeling the pore-fluid chemical and isotopic depth profiles together with the temperature profiles would give solute fluxes into seawater. In order to determine the origin of the pore fluids, to establish the contributions from each of the possible internal devolatilization processes, and to assess the possibility of external fluid sources, these fluids must be analyzed not only for their major components (conducted onboard) but also for a number of diagnostic minor and trace components that would provide insights into the abovementioned key recycling processes (e.g., oxygen, hydrogen, and carbon isotopic ratios; Ba, Li, Be, B, Cl, Sr, and rare earth element [REE] concentrations). The need for multi-isotopic analyses arises because some isotopes record important but nonunique environmental physical-chemical conditions, whereas the others are controlled by the sources and sinks involved.

Mass-Balance Constraints From Arc Volcanic Rocks

Volumes of sediments underplated at depth, eroded, or subcrustally subducted are necessarily estimated by difference in the physical mass-balance calculations described above. Chemical mass-balance calculations, in contrast, measure the percentage of subducted sediment-hosted elements that are recycled in arc volcanism and so permit minimum estimates of the amount of sediment bypassing the accretionary margin altogether. Volcanic recycling, thus, provides important limits on processes in the deep accretionary prism not attainable by other imaging techniques. Incorporating these estimates of subduction recycling highlights the inherent difficulties of studying the accretionary prism as an integrated whole; material in the different parts of the prism has been in the system for different lengths of time and comparison implicitly requires an assumption of steady state. The sediments presently beneath the volcanoes generally were supplied to the trench some 2-4 m.y. ago and, to be rigorous, steady state must apply over this interval.

Assuming a steady-state supply, cosmogenic ^{10}Be is particularly useful in partitioning the incoming sediments into those sediment volumes accreted, underplated, diluted by erosion, or deeply subducted. Cosmic rays in the atmosphere create ^{10}Be. It is strongly adsorptive on settling sediment particles in the oceans, and has a half-life of 1.5 m.y.; therefore, ^{10}Be tags only the uppermost part of the sediment column (Lal and Peters, 1967; Anderson et al., 1990; Yiou and Raisbeck, 1972). This is shown by measurements for DSDP Site 495, off the coast of Guatemala (Fig. 4A). Efficient subduction of these sediments is indicated by the ^{10}Be recycled in the volcanic arc of Guatemala. It is also important to note that erosion of old material from the deep prism will dilute the ^{10}Be in the oceanic column, so the presence of ^{10}Be in the volcanoes may also place limits on the amount of permissible subduction erosion.

The situation is different in Costa Rica; the arc volcanoes do not have measurable quantities of ^{10}Be. Measurement of ^{10}Be at proposed Site CR-1 will provide a detailed picture of the ^{10}Be distribution in the sediment column, which can be combined with physical mass-balance models and the absence of recycled ^{10}Be to further quantify estimates of accretion and underplating. This situation is shown in Figure 4B, where the expected age-depth-lithology relations are shown. If only 44 m (~10%-15% of the sediment column) is accreted frontally, then much of the remaining hemipelagic sediments must be underplated or diluted by subduction erosion; these masses can be determined when the distribution of ^{10}Be at proposed Site CR-1 is known.

Proposed Sites CR-2 and CR-3 provide opportunities to assess the amount of ^{10}Be stored in the forearc, a quantity that is important for mass-balance calculations. In addition, a model of episodic accretion or erosion is indicated if sediments too old to contain ^{10}Be (>12-15 Ma) are recovered at these sites. If the sediments are young enough, the ^{10}Be distribution may help to distinguish between the different origins proposed for the coherent intraprism reflectors seen near this site. The column labeled “hypothetical ^{10}Be conc. for Site CR-2” (Fig. 4B) shows the pattern of ^{10}Be distribution with depth that is expected if the reflectors are old, gently folded décollements; out-of-sequence thrusting would not be expected to preserve simple age-depth ^{10}Be patterns. For any of these approaches to work, ^{10}Be in the sediment column cannot be significantly redistributed by diagenesis or fluid flow. Experimental studies in simple water-sediment systems suggest that ^{10}Be (with partitioning coefficient, *Kd* sediment/water ~104-105) is relatively immobile (Nyffeler et al., 1984; You et al., 1989). However, recent results (You et al., 1989) indicate that this question should be investigated carefully in natural systems. This can be done in the context of fluid-flow and chemical studies at the proposed drill sites.

The geochemical stratigraphy of the incoming sediment column may be an important aid in constraining the accretionary processes. Like ^{10}Be, other elements can also be traced through the subduction zone (Plank and Langmuir, 1993), and because these elements do not decay like ^{10}Be, they can potentially tell us about processes affecting the entire sedimentary column. For example, although northern Costa Rica volcanic rocks have no ^{10}Be, they have roughly the same enrichment in Ba as Guatemalan volcanic rocks. Because Ba in Central American volcanic rocks appears to originate in subducted sediment, similarity in the volcanic materials suggests similar mass fluxes of subducted Ba. This is perhaps surprising given the different accretionary styles along the margin. Almost no net accretion has occurred at the Guatemala margin throughout the Neogene, and so the entire sedimentary package is apparently subducted (von Huene and Aubouin, 1982). On the other hand, frontal accretion at the Costa Rica margin should reduce the flux of subducted Ba available to the arc. Figure 5 shows the effect of accretion on the flux of subducted Ba for a 450 m incoming sediment section with the same density and Ba concentration as Site 495 sediments (off Guatemala). For these parameters, 50 m of offscraping would bring Costa Rica into line with the global trend. Although there is uncertainty in the global trend, this type of calculation demonstrates, at least conceptually, how the chemical fluxes can help to constrain physical processes. This example also underscores the importance of integrating trace element and isotope studies. This is especially true for Costa Rica because the trace element and isotopic composition of the volcanic rocks seem to require a delicate balance between sediment accretion and subduction. Enough of the uppermost sediment must be accreted or underplated to remove the ^{10}Be, but not so much as to deplete the Ba flux to the arc. This balance can be determined once actual ^{10}Be and Ba measurements are made (at the reference proposed Site CR-1 and within the prism).

Global Sediment Budgets

Von Huene and Scholl (1991) have examined convergent margins around the world in an attempt to study the global sediment budget and to make corollary estimates of the volume of terrestrial crust through time. They characterized convergent margins by either the presence (Type-1) or the absence (Type-2) of an accretionary prism. They further subdivided Type-1 margins into those with small- to medium-sized (5-40 km wide) accretionary prisms and those with large (>40 km wide) prisms. Based on mass-balance estimates and direct observations at several “best-controlled” margins, they estimated that for Type-1 small-prism margins, more than one-half of the incoming sediment bypasses the accretionary complex, whereas for Type-1 large-prism margins, only about 10% of the incoming sediment bypasses the accretionary complex. At Type-2 margins, von Huene and Scholl (1991) assumed that virtually all of the incoming sediment is subcrustally subducted.

By extrapolating these sediment-bypassing estimates worldwide (incorporating convergence rates and observed sediment thicknesses) and adding products of subduction erosion, von Huene and Scholl (1991) calculated that approximately 1.6 km^3/yr of terrestrial material is subcrustally subducted. This rate compares closely with the estimated 1.65 km^3/yr addition of new igneous continental and island arc crust (Reymer and Schubert, 1984). This apparent balance of crust/mantle mass exchange suggested to von Huene and Scholl (1991) that the volume of terrestrial crust may have remained fairly constant over the last 100-200 m.y.

Continuous injection of crustal material into the mantle at subduction zones may have a profound effect on the chemical and physical evolution of the continents and mantle over the history of the earth. This topic was appreciated long ago by Armstrong (1968), but few precise estimates of subducted fluxes have been made since then. The recent calculations by von Huene and Scholl (1991) show that the flux of sedimentary material into the mantle is potentially large—similar to modern crustal growth rates. Although their calculations provide a good estimate for the global flux of subcrustally subducted sediment, this flux is an upper limit because some material is recycled to the arc crust. It is a common misconception that the sediment contribution to the arc is trivial (~1%), based on isotopic mixing arguments that constrain only the proportion of sediment to the mantle and not the proportion of the total subducting budget that contributes to the arc. In order to calculate the latter, estimates of input fluxes (sediment) and output fluxes (volcanic material) are required. Earlier flux balances by Karig and Kay (1981) for the Marianas suggested that 10% of the sedimentary section contributes elements to the arc. More recent calculations by Plank and Langmuir (1993) suggest that the value might be closer to 20% globally, and uncertainties in mobile components could increase this figure even more. These studies, however, do not consider underplating or erosion at the forearc. Thus, in order to determine the return flux of crustal material into the deep mantle at subduction zones, we need to consider the sediment cycle through the entire subduction zone—from trench to volcanic arc.

Determining this total chemical mass balance for a subduction zone has not been possible previously, because it requires good control of many factors: bulk sediment dynamics within the accretionary complex, fluid flow through the shallow subduction zone, and recycling fluxes to the volcanic arc. Drilling on the Costa Rica margin could provide us with the first good estimates of the total chemical fluxes, partly because of the ideal conditions (the capping sediment apron and the lack of trench turbidites) and extensive seismic imaging of the accretionary complex and partly because of the opportunity to constrain the deeper parts of the sediment cycle, which are reflected in the forearc fluids and arc volcanic rocks.

The Costa Rica subduction zone is ideally amenable for chemical and isotopic mass-balance calculations mainly for the following reasons.

1. It is feasible to drill a reference site there through the sediment into the oceanic basement (>50 m) to provide the chemical and isotopic stratigraphy and the amount of volatiles entering the subduction zone.

2. The sediment dynamics, including the approximate percentage of sediment accreted per unit time, can be well determined through drilling, and the convergence rate is well known. In addition, there are no mass-balance complications from trench turbidites.

3. The subduction rate is significantly higher than at the Barbados, Nankai, and Cascadia subduction systems, thus providing significant volumes of fluids and solute fluxes.

4. The active volcanic arc is one of the most thoroughly studied in the world (Carr and Rose, 1987; Carr et al., 1990), and, thus, a vast and comprehensive chemical data set exists for the volcanic output with which to compare to sediment inputs.

5. The sediment signal in the arc is demonstrably high; sediment input affects arc output for many elements, and the fluxes into the Middle America Trench are extreme for some of these elements (Plank and Langmuir, 1993). For example, the anomalously high Ba and Sr in Central American volcanic rocks (from Guatemala to Costa Rica) are well explained by the Ba and Sr sediment fluxes into the Middle America Trench, which are among the highest in the world (based on DSDP Site 495; see Fig. 5).

6. The incoming sediments have a distinctive composition. The high proportion of biogenic to detrital phases leads to the high Ba and Sr (which are associated with biogenic opal and carbonate, respectively), but low K and Th. This signal is easy to detect at the arc because these four elements are not easily fractionated by igneous processes.

All of these factors combine to make Central America an ideal place to calculate mass balance for the sediment fluxes through the entire subduction zone.

Geology and Seismic Data

Costa Rica is situated on the western edge of the Caribbean plate (Fig. 1). The Middle America Trench (MAT) is the surface trace of the convergent boundary between the Caribbean plate and the subducting Cocos plate. The convergence rate along this part of the MAT is estimated at 87 km/m.y. (computed using NUVEL-1, DeMets et al., 1990) with oceanic crust of late Oligocene-early Miocene age currently being subducted (Hey, 1977).

The trench slope west of the Nicoya Peninsula of Costa Rica is relatively smooth. It is underlain by a sedimentary apron that reaches 2 km in thickness and generally decreases in thickness downslope. The apron is underlain by an accretionary complex that is separated from the apron by a set of irregular, high-amplitude reflectors. About 400 m of very uniform sediments enter the trench. They are divided into an upper hemipelagic unit and a lower pelagic unit (Shipley and Moore, 1986). No turbidites occur along this section of the trench. This is probably a result of a subsiding, sediment-trapping, inner forearc region and a strong axial gradient along the trench, which was produced and maintained over the last several million years by underthrusting of the Cocos Ridge beneath Central America, 300 km to the southeast.

The accretionary wedge has been constructed and deformed by frontal offscraping, underplating, and out-of-sequence faulting. A décollement marks the base of the accretionary wedge (Fig. 2). The apron is also faulted, by thrusts in the lower slope region and by normal faults in the upper slope. In addition, diapirs (which may have a source either in the lower part of the apron or in the prism) intrude the apron in the mid-slope and locally erupt onto the surface. DSDP Site 565 penetrated part way through the apron and bottomed in lowermost Pliocene mud.

Seismic reflection data acquired in the area off the Nicoya Peninsula include a high-resolution water gun survey (Shipley and Moore, 1986), conventional multichannel data (Shipley et al., 1982; Crowe and Buffler, 1983), and a combination 2D and 3D survey (Stoffa et al., 1991; Shipley et al., 1992). The conventionally acquired 2D seismic data show reflections that delineate the top of the subducting Cocos plate from the trench to the shelf edge but do not clearly image the interior structure of the accretionary prism (Crowe and Buffler, 1983; Shipley and Moore, 1986; Moore and Shipley, 1988). Coltrin et al. (1989) found that much of the difficulty in producing accurate seismic images of prisms with conventional seismic techniques lies in the rapidly changing velocity fields and three-dimensional structural variation present in this environment.

3D Seismic Data

To improve the structural resolution within the Costa Rica accretionary prism, a 3D seismic survey was acquired and processed (Stoffa et al., 1991). These data reveal unprecedented details of the interior of this prism, both because of the dense sampling of the 3D grid and because the 3D processing techniques (sorting and migration) correctly position the seismic reflectors. These data confirm that certain features of the margin are regional in extent, whereas others are much more localized (Shipley et al., 1992). In particular, the high-amplitude reflection at the base of the slope apron and prominent, internal prism reflectors are mappable over much of the 3D grid. Conversely, structures near the prism toe and in the slope apron tend to vary rapidly and many are identifiable for only hundreds of meters along strike (Shipley et al., 1992).

Incoming Sediment and Offscraping

Active accretion has built up a mud-dominated prism along the Costa Rica convergent margin. Shipley and Moore (1986) observed that the trench axis lacks a turbidite wedge and that approximately 88 m of the incoming, 300-450-m-thick section is scraped off and accreted to the upper plate. In the study area, covered by more recent 2D and 3D seismic data, the amount of offscraping appears to be closer to 45 m (Shipley et al., 1990). Arcward of the frontal thrust ramp, Shipley and Moore (1986) imaged the décollement to study the effects of subducted basement structures. They demonstrated that, despite normal faults with relief of 300 m on the Cocos plate, subduction erosion does not appear to be occurring beneath the lower slope.

Another important result of this earlier work is that the underthrust section apparently dewaters rapidly in the first 3-5 km landward of the trench. Based on seismic velocities and thinning between prominent seismic reflections, Shipley et al. (1990) estimated that one-half the fluid initially contained in the incoming section may be expelled in this zone. This result is particularly interesting in consideration of the fine grain size and low permeability expected for sediment in this area.

The incoming section was not sampled directly in this area, but oceanic sections of the Cocos plate drilled in DSDP Legs 9, 66, and 67 and ODP Leg 138 suggest a two-layer interpretation. Legs 66 and 67, off the continental margins of Mexico and Guatemala, both found an upper hemipelagic layer and a lower carbonate-rich pelagic section in holes seaward of the Middle America Trench (Watkins et al., 1982; von Huene et al., 1982). Leg 9 Sites 83 and 84, away from the continental margin, penetrated carbonate-rich pelagic sediments before hitting basaltic basement (Hays, Cook, et al., 1972). Leg 138 recently drilled 175 m of silicic hemipelagic ooze overlying 115 m of carbonate ooze. Based on these drilling results, the top of the pelagic section off Costa Rica is expected to be middle to late Miocene in age.

Underplating

The 3D seismic reflection data extend the observations of Shipley and Moore (1986) and Shipley et al. (1990), who concluded that the upper hemipelagic sedimentary layer on the subducting Cocos Plate is accreted in part by offscraping and in part by underplating. In contrast to the upper layer, distinct seismic images show the basement and pelagic section apparently thrust intact beneath the lower slope. Analysis of the 3D data illustrates a variety of structural geometries inferred for the underplating process (McIntosh, 1992). Both duplexes and out-of-sequence thrusts prefer to nucleate at sites of lower plate-normal faulting.

Underplating begins 3-10 km arcward of the trench, coinciding with the first appearance of the high-amplitude reflector at the base of the slope apron and high-amplitude internal reflectors. The prism thickens significantly at a distance of 10-20 km from the trench, coinciding with an increased number of high-amplitude internal reflectors (Fig. 2).

A major enigma is the nature of the reflector at the top of the prism (Fig. 2). Our initial interpretation of the 3D data (Shipley et al., 1992) suggests that this faulted surface probably marks the base of the depositional slope apron section and the top of the tectonically accreted prism material. One alternative explanation that cannot yet be eliminated is that this surface marks the boundary between offscraped sediments (above) and underplated sediments (below).

Another important consideration is that a portion of the top-prism surface may represent a contact between the sedimentary apron and underlying ophiolitic rocks of the Nicoya complex. Despite the good quality of both the 2D and 3D seismic data, the seaward limit of the Nicoya complex basement, which crops out onshore near the coast, is not clearly defined. Shipley et al. (1992) interpreted that the material beneath the apron section is composed of accreted sediments, based on observed sediment accretion at the toe, observed structure within the apron and prism (on seismic reflection data), migration velocities, refraction velocities (Crowe and Buffler, 1983), gravity data and interpretation (Ponce and Case, 1987), and lack of anomalies in magnetic data diagnostic of crystalline rock (T.H. Shipley, unpubl. data). In contrast, other workers in the Costa Rica area interpret that the forearc is composed dominantly of ophiolite, on the basis originally of comparisons to the Guatemala forearc (Azema et al., 1985; Corrigan et al., 1990; R. von Huene, pers. comm., 1993) and more recently on the results of wide-angle refraction experiments (Ye et al., unpublished data), showing significantly higher velocities beneath the apron than were previously determined. Identifying the nature of the apron/prism boundary and its age distribution is fundamental to understanding the tectonic history of the Costa Rica margin and that of southern Central America, but drilling is required to do so.

Out-of-sequence Faulting

A first-order discovery of the 3D seismic data set is the prominence of long, shallow reflectors within the wedge (Fig. 2). Their length and smooth character far exceed that expected from duplexes, which are themselves well-imaged on many lines about 3-10 km from the toe of the wedge. These long, smooth interior reflectors are interpreted as possible out-of-sequence thrusts (Shipley et al., 1992). The seismic data cannot fully resolve whether these faults are truly out of sequence or are old décollements that were uplifted and gently folded by underplating. Drilling can distinguish these alternatives (Moore, Mascle, et al., 1990) and can therefore allow us to calibrate the seismic data and understand the strain partitioning within the wedge.

Subduction Erosion

Although the currently observed processes of the Costa Rica convergent margin suggest accretion accompanied by some unknown amount of sediment bypassing, the slope apron also records a possible period of erosion or nonaccretion. At approximately 20-25 km seaward of the trench, there is a zone of severe disruption in the slope apron and upper prism (Fig. 2). A thick apron section (1-2 km thick), displaying well-layered, coherent reflections across the middle and upper slope, is segregated by this zone from the apron of the lower slope, which is abruptly thinner (generally <800 m thick) and characterized by discontinuous and typically landward-dipping reflections. The discrepancy in apron thickness across the disturbed zone may be explained by an extended period of nonaccretion during which slope deposition continued and was followed by renewed accretion to accumulate the present lower slope mass. Alternatively, truncation of the margin by transcurrent faulting or subduction erosion, followed by renewed accretion, may also explain the apron variations.

Diapirism

At least four separate mud diapirs have erupted as mud volcanoes onto the surface of the apron within the 3D data volume. They occur generally in the mid-slope region of the wedge. The diapirs are elongate east-west, oblique to the slope contours (Shipley et al., 1992). Seismic data indicate that the diapirs root at, or near, the base of the apron. In some profiles, the high-amplitude surface of the accretionary wedge is displaced by faulting just beneath the diapirs, suggesting a relation between structure and diapirism.

Extension on the Upper Slope

The long 2D seismic lines crossing the Costa Rica margin have each imaged a wide zone of normal faulting cutting the upper slope segment of the sedimentary apron (Fig. 2). This deformation contrasts with that observed in the middle and lower slope regions of all seismic lines where the apron and prism are pervasively cut by thrust faults. The transition from convergence to extension in the apron occurs above a significant change in the dip of the décollement and is associated with thickening of the wedge. The normal faults may represent extension of a wedge that has become overcritically tapered (McIntosh et al., 1993). We have measured approximately 1.5 km of extension in the zone of normal faulting (McIntosh et al., 1993).

Results of Submersible Observations off Costa Rica Using the *Alvin*

Dive Results

During February 1994, 20 dives were made with the *Alvin* to investigate the surficial evidence for fluid flow and fault structure of the Costa Rica accretionary wedge. The nature and distribution of chemosynthetic communities and authigenic carbonates indicate present, and paleo-fluid, venting at three localities: in the lower slope out-of-sequence-thrust (OOST) zone, in one mid-slope mud diapir, and in one upper slope canyon (Kahn et al., 1996). No surficial evidence for venting is apparent at the deformation front (McAdoo et al., 1996).

Heat-Flow Results

During the February 1994 cruise, we made 98 individual heat-flow measurements along 10 lines (Langseth and Silver, 1996). The lower slope region proved difficult to penetrate with the heat-flow probe, indicating (in conjunction with the seismic data) that the lower slope is severely dewatered. Of the 19 measurements made west of the deformation front, none exceeded 20 mW/m^2 and the mean of these measurements was about 14 mW/m^2. As the approximate age of the incoming crust is about 20 Ma, we expect heat-flow values to be in the range of 80 to 100 mW/m^2. The extraordinarily low values indicate nonequilibrium conditions and suggest widespread refrigeration of the crust by vigorous fluid flow at depth. The deformation front forms a sharp geothermal boundary between the lower plate zone of very low heat flow (14 mW/m^2) and the toe of the slope, where heat-flow values range between 20 and 30 mW/m^2. The average value of heat flow on the slope is about 30 mW/m^2. The increase in heat flow at the toe of the wedge could be a result of a pervasive flow of somewhat warmer fluids from depth in the wedge. However, no signs of fluid venting were seen on the lower slope, which does not rule out diffuse fluid flow. Slightly elevated heat flow values (~50 mW/m^2) were measured near sites of fluid venting.

SCIENTIFIC OBJECTIVES

The main focus of Leg 170 is to determine mass- and fluid-flow paths through a remarkably well-constrained accretionary complex to calculate mass and fluid balances. Drilling data will facilitate an integrated effort to understand these processes using structural data and the physical and chemical properties of both the sediments and their pore fluids.

The general objectives of the leg are:

- Determine the sediment, chemical, and fluid mass balances within the accretionary prism and the larger subduction system (including the volcanic arc).
- Test whether or not the prism is developing in equilibrium with the incoming sedimentary material and, if so, to quantify the partitioning of material into offscraped, underplated, internally shortened, and subducted volumes.
- Determine the effects of fluids on prism deformation.

The specific objectives of the drilling program are to determine:

- Age and nature of the accretionary wedge beneath the slope apron.
- Rate of accretion of the wedge.
- Nature of the lower part of the apron and time sequence of formation.
- Physical properties of the material above, within, and below the top-prism reflector.

- Relative importance of underplating vs. out-of-sequence faulting.
- Evidence of fluid stratigraphy and flow distribution within the wedge materials.
- Nature of apron material relative to deep-sea hemipelagic sediment.

PROPOSED SITES

Leg 170 will consist of three drill sites (proposed Sites CR-1 through CR-3) and two alternate drill sites (proposed sites CR-4 and CR-5) to achieve the drilling objectives for the Costa Rica convergent margin (Table 1, Fig. 1). The depth requirements for some of the sites may require multiple holes for adequate sampling.

Site CR-1 (Middle America Trench Axis)

Proposed Site CR-1 is located on Swath Line 20, seaward of the Middle America Trench, and acts as a reference for the age, thickness, lithology, physical properties, and fluid composition of the incoming sedimentary section. The planned depth of penetration is 500 m (sub-bottom), including 50 to 100 m into oceanic basement. This site has taken on greater significance as a result of the discovery of regional, extremely low heat flow on the lower plate during the February 1994 cruise of the *Alvin*. Deeper drilling would certainly be helpful but would seriously impact other major objectives. We plan to take heat-flow measurements with the Adara temperature tool on every other core recovered with the advanced hydraulic piston core (APC) technique, as well as five heat-flow measurements with the downhole water sampler, temperature, and pressure probe (WSTP). The downhole logging program consists of wireline logging (triple-combo and Formation MicroScanner [FMS] and sonic), as well as logging-while-drilling (LWD). Porosity data from the LWD Compensated Density Neutron (CDN) tool and velocity data from the standard logging suite (C1 and C2, see Table 1) will be used to empirically correlate velocity to seismic data at the other holes.

Site CR-2

Proposed Site CR-2 is located on Swath Line 20, 1.5 km from the toe of the accretionary wedge, near the base of the slope. Drilling targets include drilling through the accretionary wedge, the décollement, and an additional 150 m beneath the décollement to a total depth of 750 mbsf. The objectives for this site include understanding the rate of dewatering of wedge sediments, the hydrogeology of the décollement, and constraining the amount of dewatering occurring in the underthrust strata. We plan to take heat-flow measurements with the Adara tool on every other APC core, as well as five heat-flow measurements with the WSTP tool. The logging program consists of LWD; however, if time permits, standard wireline logging tools may be utilized. Deployment of the Lamont shear sonic tool is subject to availability of the tool onboard, as well as time available.

Site CR-3 (Lower Trench Slope)

Proposed Site CR-3 is located on Line CR3D-177, 14 km landward of the trench, where the hole can penetrate the slope apron, the high-amplitude reflector at the base of the apron, and one or more of the interpreted fault zone reflectors. This key site will constrain the age, lithology (hemipelagic or carbonate), structure, and physical properties of the slope apron, the prism, and important boundaries. It will allow us to utilize geochemical markers to determine the significance of fluid flow along the décollement, as well as through other fault zones within the wedge. This site also has potential for providing some input on the concept of a flow channel, proposed by Cloos and Shreve (1988a, 1988b), although the drilling depths will be too shallow to fully test the idea. Target depths are 500 m of sedimentary apron material and a total depth of 1400 m to sample out-of-sequence thrusts within the prism. We plan to take heat-flow measurements with the Adara tool on every other APC core, as well as five heat-flow measurements with the WSTP tool . The logging program consists of LWD; however, if time permits, standard wireline logging tools may be utilized. Deployment of the Lamont shear sonic tool is subject to availability of the tool onboard, as well as time available.

Site CR-4 (Middle Trench Slope)

Proposed Site CR-4 is located on 3D line 132, 23 km landward of the trench. This site will sample a portion of the slope apron that is thicker and less deformed than the portion at proposed Sites CR-2 or CR-3 and also will penetrate the high-amplitude reflector, to a total depth of 950 mbsf. The purpose of sampling the slope apron is to date regionally correlatable seismic sequences and thereby constrain a large portion of the upper slope. Additional penetration of the apron-prism boundary is important to confirm the nature of this seismic impedance boundary and to calculate the growth rate of a larger portion of the accretionary complex. This site is upslope from a major structural disturbance and change in thickness of the slope apron. Proposed Site CR-4 will allow us to calibrate the seismic stratigraphy, which is well developed in the middle and upper slope regions of the margin, but more poorly developed on the lower slope. Penetration of the apron-prism boundary will provide the second datum for determining an age gradient for the rate of underplating (if that process is documented) and information on variation in material properties of the subapron prism. It will allow us to determine whether the underlying rocks are recently underplated or if they are older basement rocks such as those found off Guatemala. Standard wireline logging is planned at this site.

Site CR-5 (Lower Trench Slope)

Proposed Site CR-5 is located on 3D seismic line 172, 5.5 km landward of the base of the trench slope, and is designed to intersect a major out-of-sequence thrust that has abundant fluid vents where it crops out at the surface. Because of time constraints, proposed Site CR-5 is considered an alternate site to be drilled if one of the other sites (CR-1 or CR-2) cannot be drilled. We plan to drill to a depth of 1150 m, which would cross the OOST and penetrate into the décollement. If this site is drilled in place of either Site CR-2 or CR-3, then we plan to carry out LWD, as well as Adara and 5 WSTP heat-flow measurements at this site.

Additional Operational Notes

Contingencies
Should additional time become available as a result of more favorable drilling conditions than anticipated at this time, we would add the following, unranked list of operations. The ranking will depend on the amount of additional time and the results of the program at the time of the decision.

- Add 2 days to proposed Site CR-2 to carry out shear sonic logging, which will allow measurement of both *P*-waves and shear waves.
- Drill deeper into basement at proposed Site CR-1.
- Drill proposed Site CR-4.

Whole-round Sampling
Because of the focus on structural fabrics, mechanical properties, and fluid flow within the wedge, sampling of whole rounds for structural and geotechnical analyses and interstitial pore fluid is needed. We anticipate needing whole-round sampling in excess of the specimen number and specimen length outlined in the general ODP curation policy.

In Situ Fluid Sampling

It is planned to attempt sampling of formation fluids with the WSTP and if feasible with the developmental "Fissler Water Sampling Tool." Alternatively, the Pressure Core Sampler (PCS) could be deployed for pore-water sampling. If gas hydrate is encountered, hydrate sampling may be attempted with the PCS as well. The anticipated total number of fluid and gas hydrate sampling runs will be limited by the operational time available.

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TABLE 1. SITE TIME ESTIMATES

Site	Latitude Longitude	Water Depth (m)	Penetration (mbsf)	Drilling Operations (days)	Logging *Tools	Logging (days)	Transit Time (days)
Primary							
Transit San Diego to CR-1							8.3
CR-1	9°38.4'N 86°12'W	4350	550	6.3	LWD, C1, C2, T	3.2	
Transit from CR-1 to CR-2							0.1
CR-2	9°39.7'N 86°12'W	4160	750	9.4	LWD, C1**, C2**, T	3.0	
Transit from CR-2 to CR-3							0.1
CR-3	9°43.8'N 86°7.2'W	3320	1400	17.9	LWD, C1**, C2**, T	6.1	
Transit to Panama							1.6
Total				33.6		12.3	10.1
Total Days at Sea = 56.0		(Available Time = 56.0)					
Alternate							
CR-4	9°46.8'N 86°2.4'W	2200	1000	9.0	C1**, T**	1.3	
CR-5	9°42.0'N 86°8.4'W	3580	1150	13.6	LWD**, T**	6.3	
Total				22.6		7.6	0.0
Total Days at Sea = 79.1		(Available Time = 56.0)					

* LWD=Logging while drilling, C1= Triple-combo (resistivity, lithodensity, neutron porosity), C2=FMS & sonic combo, T=APC (aka Adara) or WSTP temperature measurements

**If time permits

T measurement times have been incorporated into drilling operations

FIGURE CAPTIONS

Figure 1. Location of 2D and 3D seismic profiles from 1987 cruise of *Fred Moore*. Inset shows map of Central America, Cocos plate, and Caribbean plate. Nicoya Peninsula is located just below the “C” in Costa Rica on the inset drawing. The stippled rectangle shows the location of the 3D seismic grid. The longer, labeled lines are 2D profiles.

Figure 2. Simplified interpretation of a section through the lower and middle slope region of the Costa Rica continental margin.

Figure 3. Summary of solid rock volume balance calculations by plotting sediment accumulation vs. time. The diagonal lines represent different rates of accretion as a volume percent of the total incoming sedimentary section assuming zero porosity. Estimates of the accreted volume for the Costa Rica accretionary prism are between the two horizontal dashed lines labeled “observed accretion” This graph represents results pertaining only to the lower slope (from McIntosh, 1992).

Figure 4A. ^{10}Be (half-life = 1.5 m.y.) concentrations and lithology vs. depth (data from Zheng and Morris, unpubl. data) at DSDP Site 495, offshore of Guatemala. The solid ^{10}Be profile emphasizes the high concentrations of ^{10}Be measured in near-surface sediments and the exponential decay to unmeasurable values at about 200 m (approximately 12 Ma). For the volcanoes to contain ^{10}Be, more than 90% of these uppermost sediments must subduct to the arc source region. The total amount (or inventory) of ^{10}Be in a 1-cm-by-1-cm sediment column = 13.2 x 10^{12} a/cm^2. The ^{10}Be inventory is calculated by integrating beneath the solid ^{10}Be-depth curve shown in the graph. The dashed curve on the graph indicates the distribution of ^{10}Be in the sediments after correcting for radioactive decay ($^{10}B_{corr}$ = 5.7 x 10^{12} a/cm^2) during the roughly 2 m.y. required to subduct the sediments from the trench axis to a point beneath the present volcanic front. The bulk atom ^{10}Be/^{9}Be ratio = 460 x 10^{-11} . This ratio is averaged for the sediment column and uses the decay-corrected $^{10}Be_{corr}$ concentration above and the total ^{9}Be abundance. (See Brown et al., 1992; Tera et al., 1986; Monaghan et al., 1988; Morris and Tera, 1989; Morris et al., 1990; and Morris et al., in prep.; for discussion of the ^{10}Be systematics and results from volcanic arcs and oceanic sediments). **B**. The equivalent diagram for Costa Rica, showing the approximate age-depth-lithology relations in the incoming sediment column. The absence of ^{10}Be in the volcanoes indicates that the uppermost part of the incoming sediment is accreted and/or underplated. The column labeled “hypothetical ^{10}Be conc. for Site CR-2” shows the distribution of ^{10}Be concentrations (curved lines) expected with depth if the intraprism reflectors (horizontal lines) are gently folded décollements ("D"). The age of the packets decreases with depth, but the sediments within a packet are youngest at the top. The ^{10}Be concentrations at proposed Site CR-2 will be at measurable levels if the sediments are younger than about 12 Ma. An absence of ^{10}Be at proposed Site CR-2 implies older ages, which is consistent with episodic erosion or subduction erosion as discussed. The base of the underplated hemipelagic sediments is ~6-11 Ma, and the base of the carbonate is ~24 Ma. Stratigraphy for Costa Rica is inferred from seismic stratigraphy (Shipley and Moore, 1986) and by analogy with DSDP Site 495.

Figure 5. Correlation between Ba flux in subducted sediment and Ba enrichment of arc basalts, for the Northern Antilles (Ant), Marianas (Mar), Tonga (T), Mexico (Mex), Java, Aleutians (Al), and Guatemala (Guat) arcs (after Plank and Langmuir, 1993). These types of correlations, which are present for other elements as well, suggest that volcanic output is linked to sediment input in subduction zones. Line is best fit of solid points; vertical error bars are one standard deviation of the mean of volcanoes within each arc; horizontal error bars represent uncertainties in the thickness of sediment being subducted resulting from variable supply, underplating, and erosion (generally +100 m). Input fluxes do not include accreted material, however (see Plank and Langmuir, 1993). Open circles are for the Costa Rica subduction zone. Ba/Na ratios are for Arenal and Rincon volcanoes (data from Carr and Rose, 1987), which are the Costa Rican volcanoes closest to the proposed drilling transect (these northern Costa Rican volcanoes are also chemically distinct from the alkalic southern Costa Rica volcanoes, as noted by Carr et al., 1990). The Ba fluxes for Costa Rica are calculated from the composition and density of the sedimentary column at Site 495, off Guatemala. The arrow at the open circles shows the effect of frontal accretion on the subducted flux, where increasing amounts of the upper hemipelagic mud unit are removed (total meters of sediment subducted as indicated). Fifty meters of offscraping would bring the Ba flux for Costa Rica in line with the global trend. This is an illustrative example of how chemical fluxes might help to constrain accretionary processes. Accurate estimates require better control of the global trend (from improved constraints on the accretionary dynamics at other subduction zones) and Ba data on the incoming sedimentary column off Costa Rica (e.g., proposed Site CR-1).

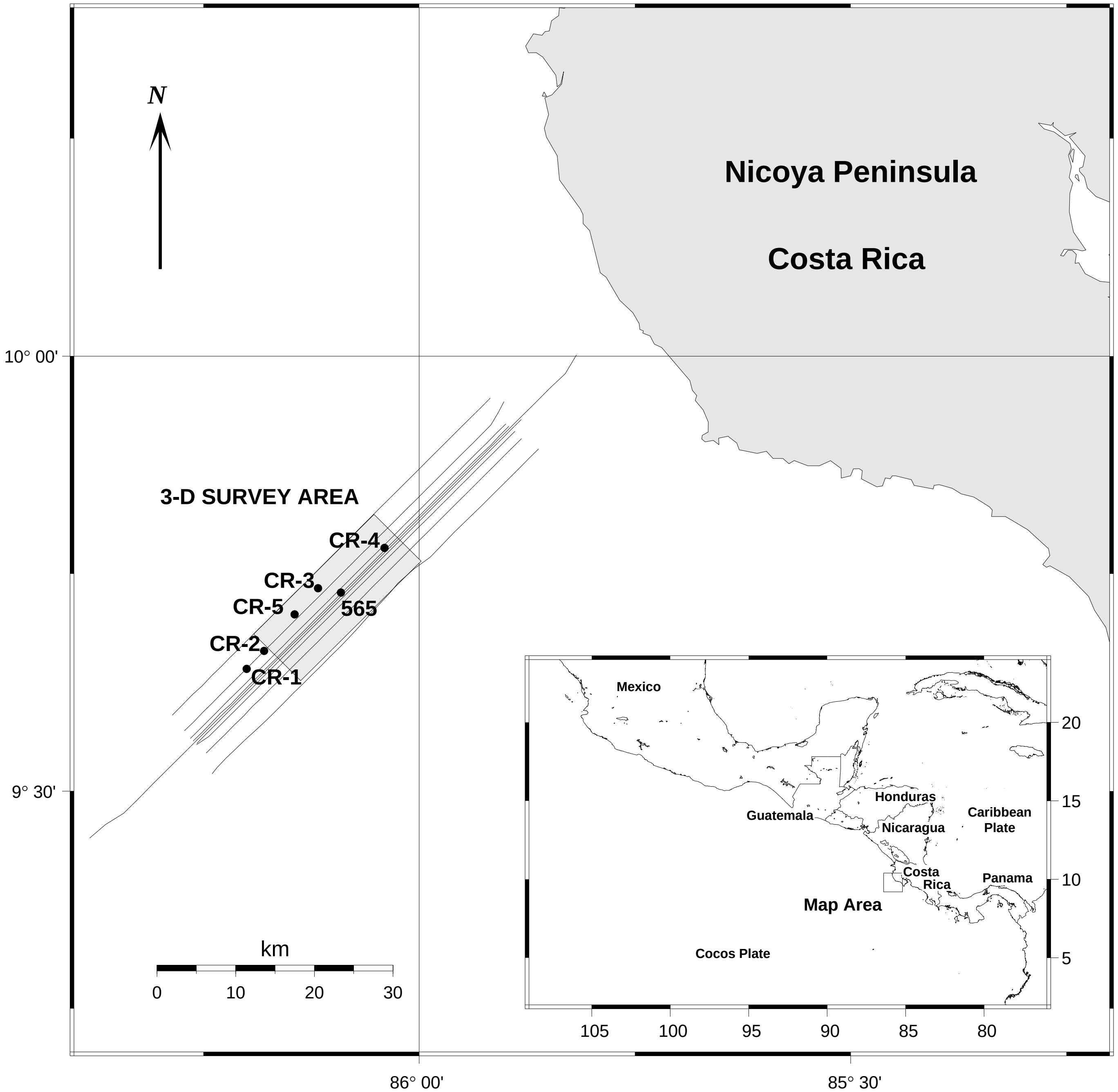

Nicoya Peninsula
Costa Rica
N
10° 00'
9° 30'
86° 00'
85° 30'
3-D SURVEY AREA
CR-4
CR-3
CR-5
565
CR-2
CR-1
km
0
10
20
30
Mexico
Honduras
Guatemala
Nicaragua
Caribbean
Plate
Costa
Rica
Panama
Map Area
Cocos Plate
20
15
10
5
105
100
95
90
85
80

Figure 1

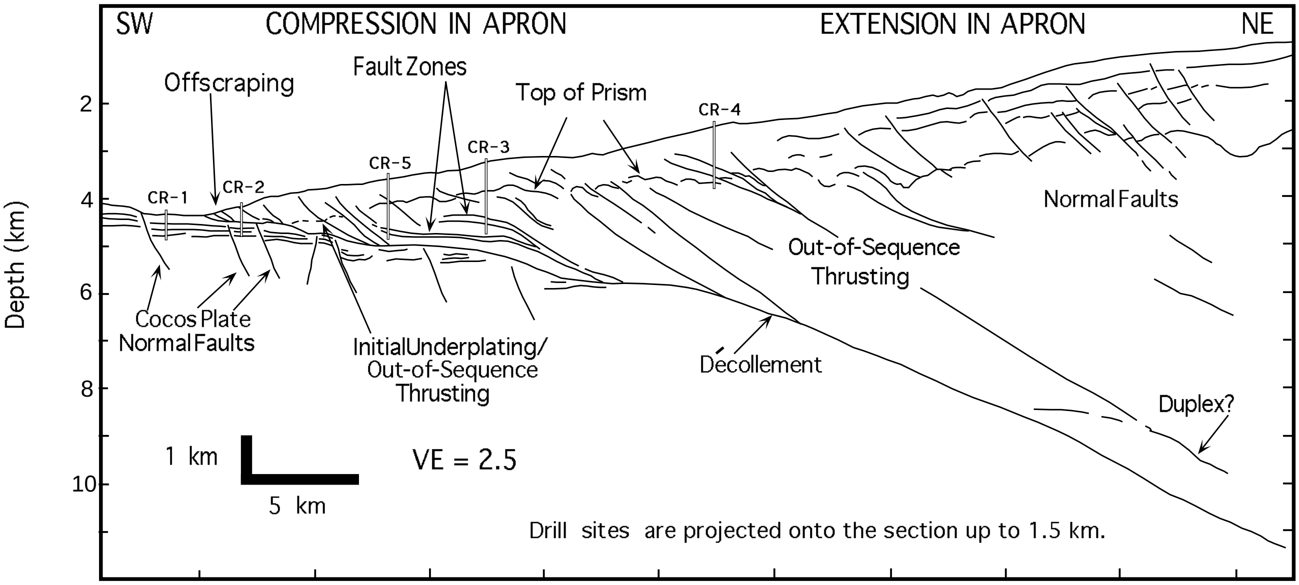

SW
COMPRESSION IN APRON
EXTENSION IN APRON
NE
Offscraping
Fault Zones
Top of Prism
CR-1
CR-2
CR-5
CR-3
CR-4
Normal Faults
Out-of-Sequence Thrusting
Cocos Plate Normal Faults
Initial Underplating/ Out-of-Sequence Thrusting
Decollement
Duplex?
Depth (km)
2
4
6
8
10
1 km
5 km
VE = 2.5
Drill sites are projected onto the section up to 1.5 km.

Figure 2

ACCRETION VS TIME

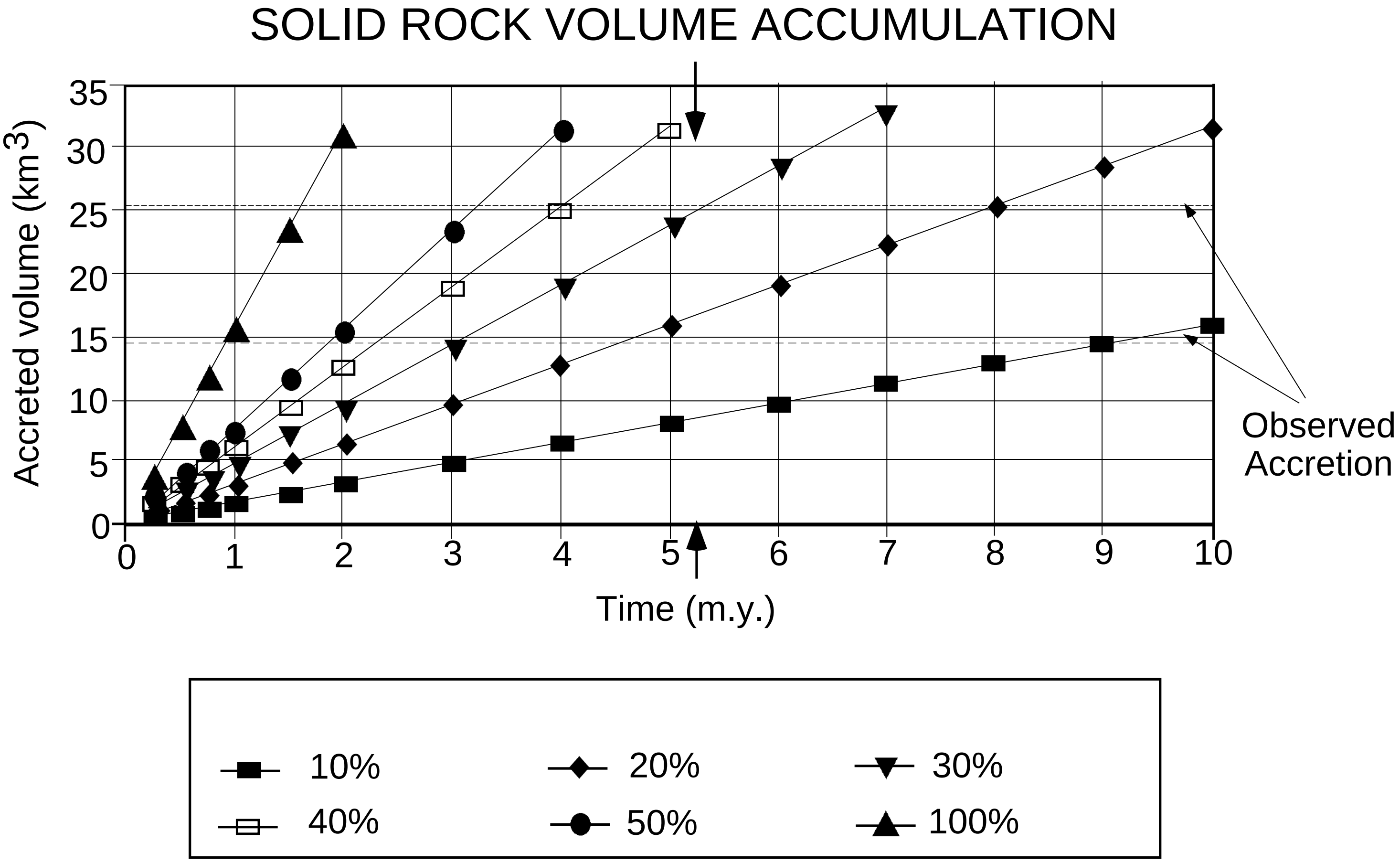


Figure 3

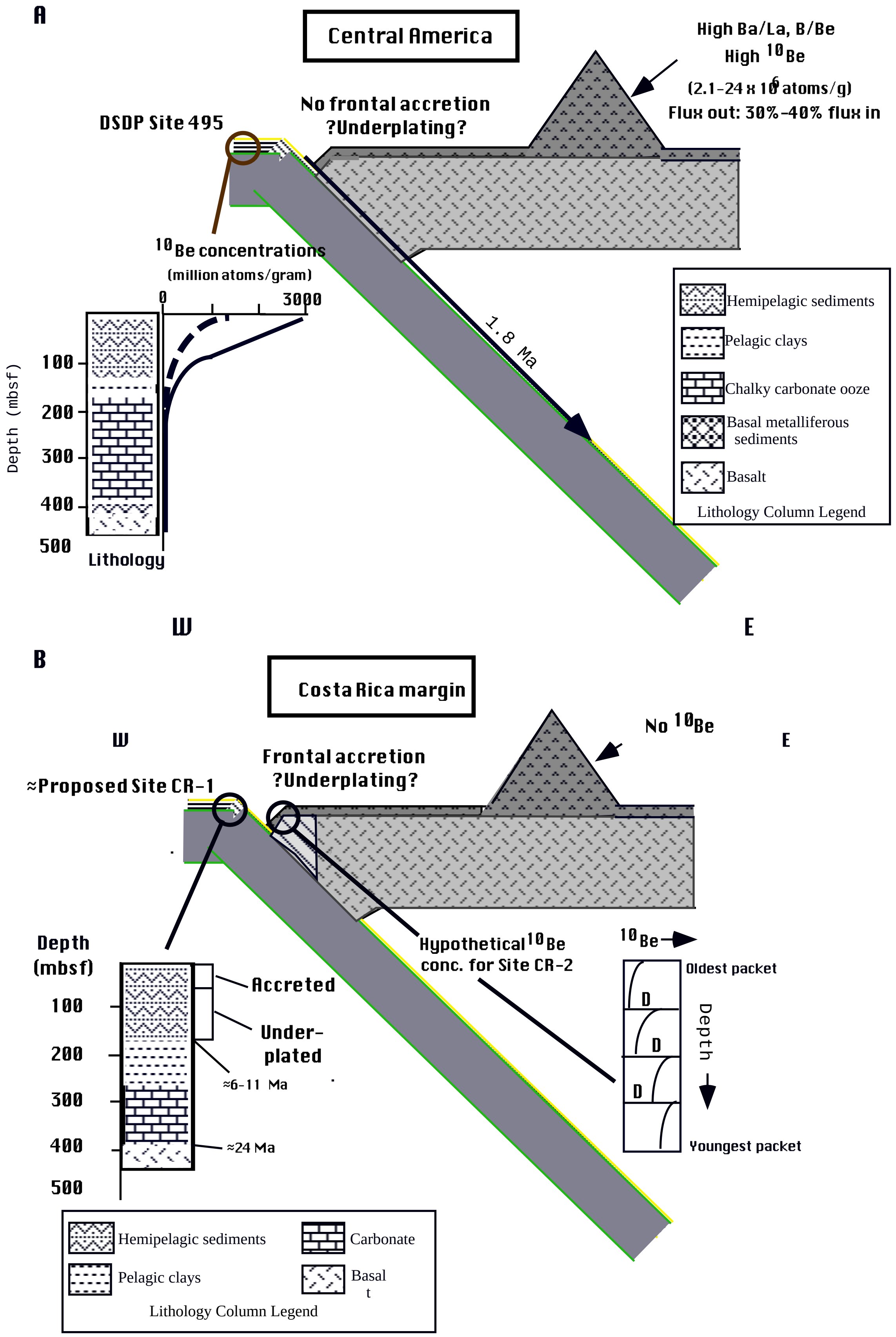
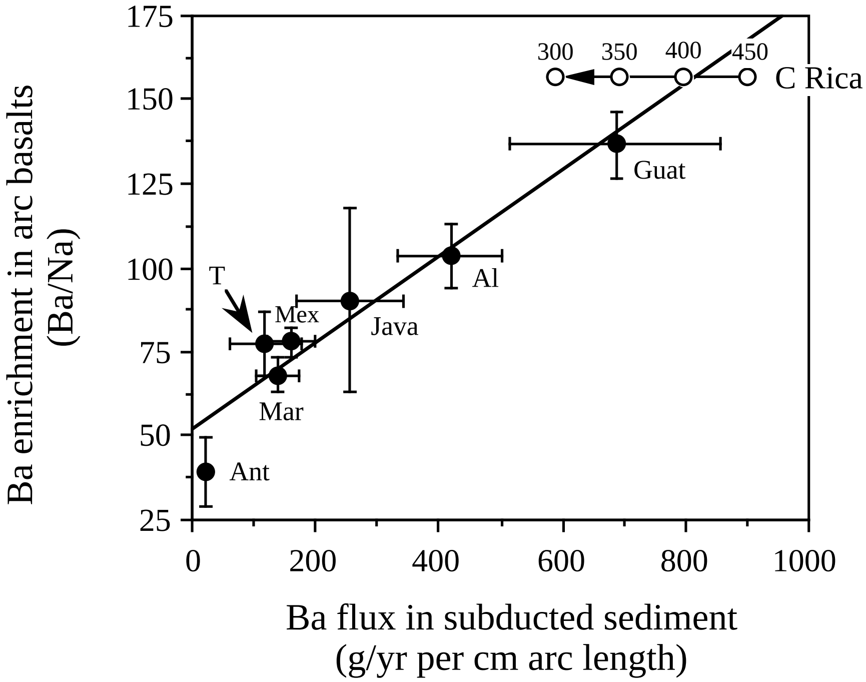
A
Central America
High Ba/La, B/Be
High ^{10}Be
(2.1-24 x 10^6 atoms/g)
Flux out: 30%-40% flux in
No frontal accretion
?Underplating?
DSDP Site 495
^{10}Be concentrations
(million atoms/gram)
0
3000
1.8 Ma
Depth (mbsf)
100
200
300
400
500
Lithology
Hemipelagic sediments
Pelagic clays
Chalky carbonate ooze
Basal metalliferous sediments
Basalt
Lithology Column Legend
W
E
B
Costa Rica margin
No ^{10}Be
W
E
Frontal accretion
?Underplating?
≈Proposed Site CR-1
Depth (mbsf)
100
200
300
400
500
Accreted
Under-plated
≈6-11 Ma
≈24 Ma
Hypothetical ^{10}Be conc. for Site CR-2
^{10}Be
Oldest packet
D
D
D
Depth
Youngest packet
Hemipelagic sediments
Pelagic clays
Carbonate
Basalt
Lithology Column Legend

Figure 4



Ba enrichment in arc basalts (Ba/Na)
Ba flux in subducted sediment (g/yr per cm arc length)
175
150
125
100
75
50
25
0
200
400
600
800
1000
300
350
400
450
C Rica
Guat
Al
Java
T
Mex
Mar
Ant

Figure 5

Site: CR-1

Priority: 1
Position: 9°38.4'N, 86°12'W
Water depth: 4350 m
Sediment thickness: 450 m
Total penetration: 550 mbsf (approved to a depth of 750 mbsf)
Seismic coverage: 2D seismic reflection lines (2D Line 20)

Objectives: The objectives of CR-1 are to determine the:

1. Stratigraphy of the incoming sedimentary section on the Cocos plate, to serve as a reference site for the wedge sites.

2. Physical properties of the incoming sedimentary section, to serve as a reference site.

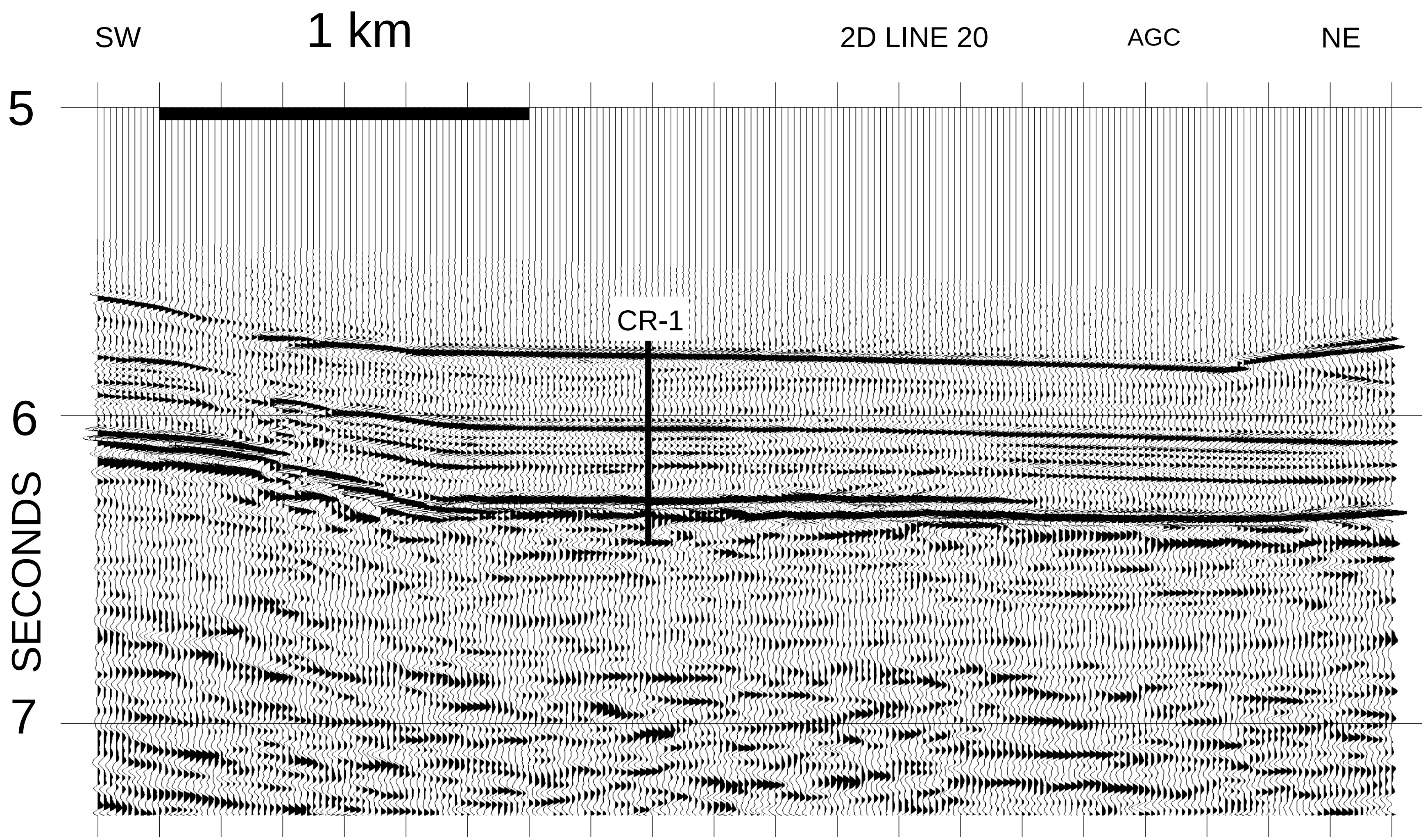
3. Physical properties of the basement to gain an understanding of the role of fluids in refrigerating the plate in this region.

Drilling program:

Hole A:	APC/XCB with Adara tool to 460 mbsf plus 5 WSTP measurements, MDCB core from 460 to 500 mbsf
Hole B:	Drill with LWD tools to 500 mbsf

Logging and downhole: Logging while drilling, triple-combo, FMS-sonic

Nature of rock anticipated: Hemipelagic siliceous mud and carbonate-rich pelagic mudstone. Basaltic basement.


SW
1 km
2D LINE 20
AGC
NE
5
6
SECONDS
7
CR-1

Site: CR-2

Priority: 1
Position: 9°39.7'N, 86°12'W
Water depth: 4160 m
Sediment thickness: 750 m
Total penetration: 750 mbsf (approved to a depth of 750 mbsf)
Seismic coverage: 2D and 3D seismic reflection data (2D Line 20), OBH refraction

Objectives: The objectives of CR-2 are to:

1. Establish the sequence and structure of deformed sedimentary section in the lower slope accretionary wedge.

2. Penetrate the décollement and establish the age and stratigraphy of the underthrust sediment.

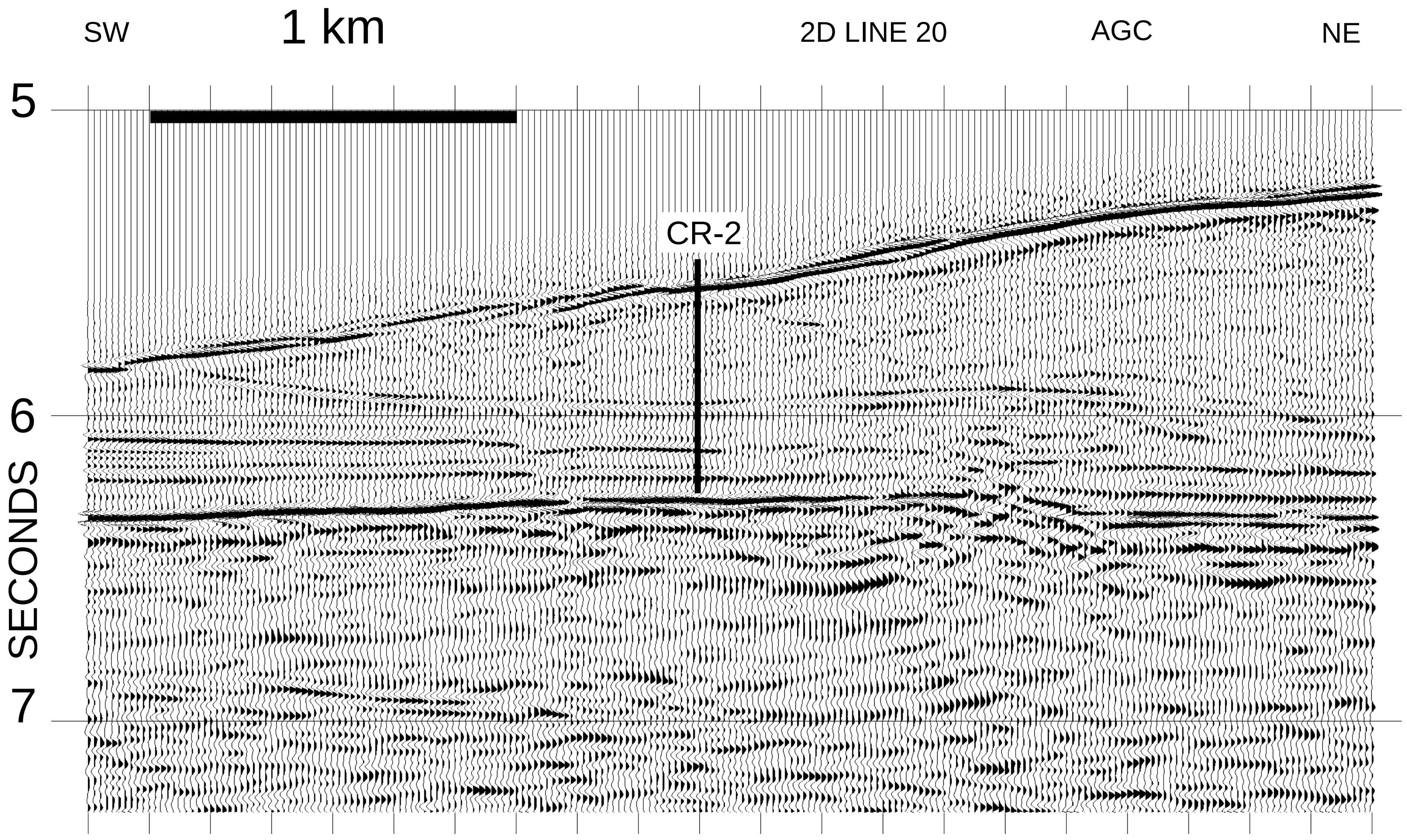
3. Determine the physical properties of the accreted and underthust sections and establish the mass flow through the lowermost part of the wedge.

Drilling program:

Hole A: APC/XCB with Adara tool to 450 mbsf plus 5 WSTP measurements
Hole B: Drill to 450 mbsf, RCB to 750 mbsf
Hole C: Drill with LWD tools to 500 mbsf

Logging and downhole: Logging while drilling (shear sonic if time permits)

Nature of rock anticipated: Deformed hemipelagic mudstone and carbonate-rich pelagic mudstone.


SW
1 km
2D LINE 20
AGC
NE
CR-2
5
6
SECONDS
7

Site: CR-3

Priority: 1
Position: 9°43.8'N, 86°7.2'W
Water depth: 3320 m
Sediment thickness: 1400 m
Total penetration: 1400 mbsf (approved to a depth of 1400 mbsf)
Seismic coverage: 3D seismic reflection data (3D Line 177; 3D cross Line 450)

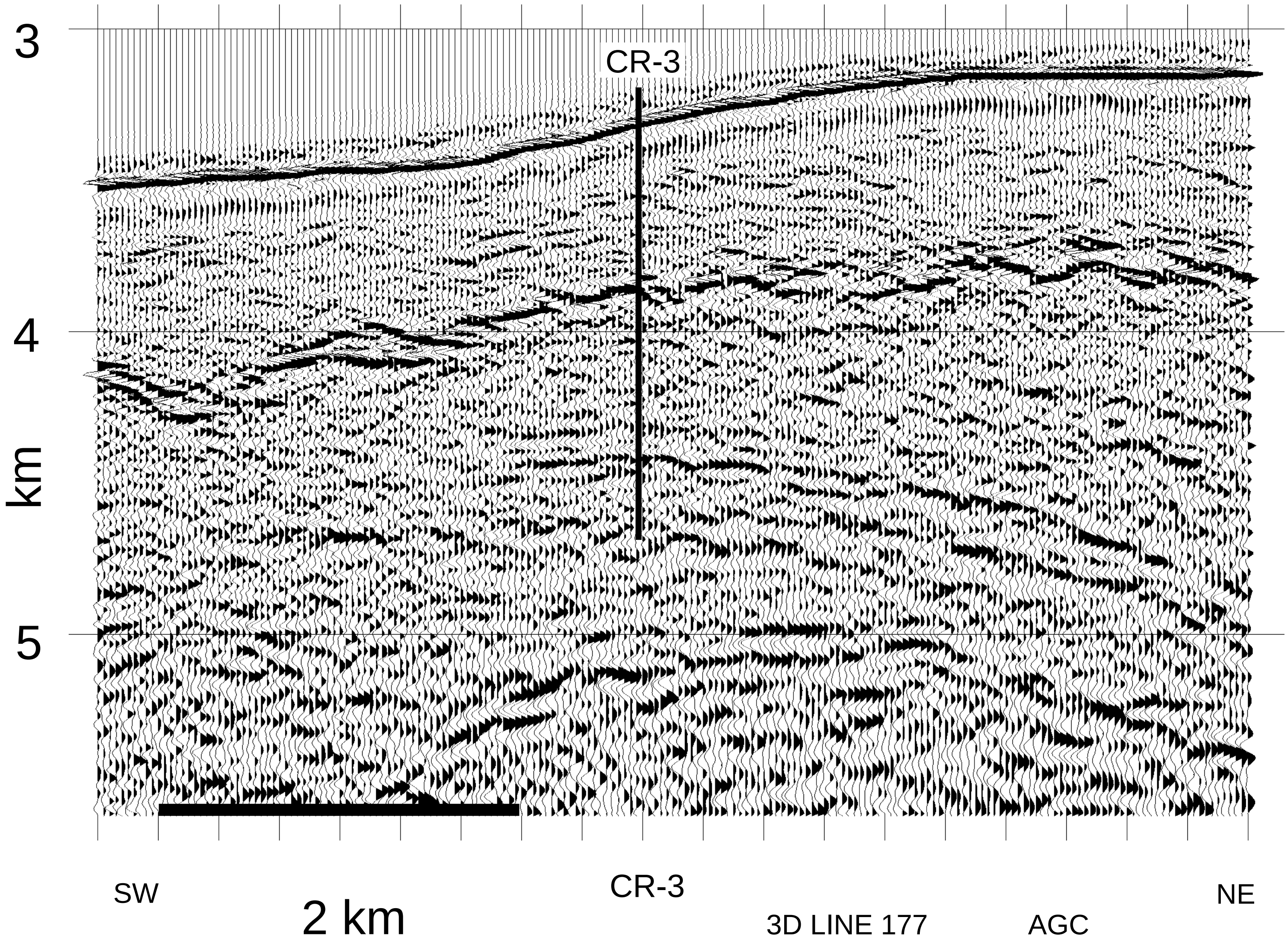
Objectives: The objectives of CR-3 are to:

1. Determine the age and physical properties of the sedimentary apron.
2. Penetrate beneath the high amplitude reflector and determine the nature of the material beneath this layer.
3. Penetrate to the zone of out-of-sequence thrusting and determine the nature of material above and below this layer.
4. Use the results of the drilling to compute a mass balance between incoming and accreted strata.

Drilling program:
Hole A: APC/XCB with Adara tool to 500 mbsf plus 5 WSTP measurements
Hole B: Reentry cone, set 10-3/4" casing to 500 mbsf, RCB to 1400 mbsf
Hole C: Drill with LWD tools to 1400 mbsf

Logging and downhole: Logging while drilling

Nature of rock anticipated: Hemipelagic mudstone and carbonate-rich pelagic mudstone. Possibly serpentine and/or mafic rocks at depth.


3
4
km
5
CR-3
SW
2 km
CR-3
3D LINE 177
AGC
NE

Site: CR-4

Priority: 1
Position: 9°46.8'N, 86°2.4'W
Water depth: 2200 m
Sediment thickness: 5000 m
Total penetration: 1000 mbsf (approved to a depth of 750 mbsf)
Seismic coverage: 3D seismic reflection (3D line 132; 3D cross line 735)

Objectives: The objectives of CR-4 are to:

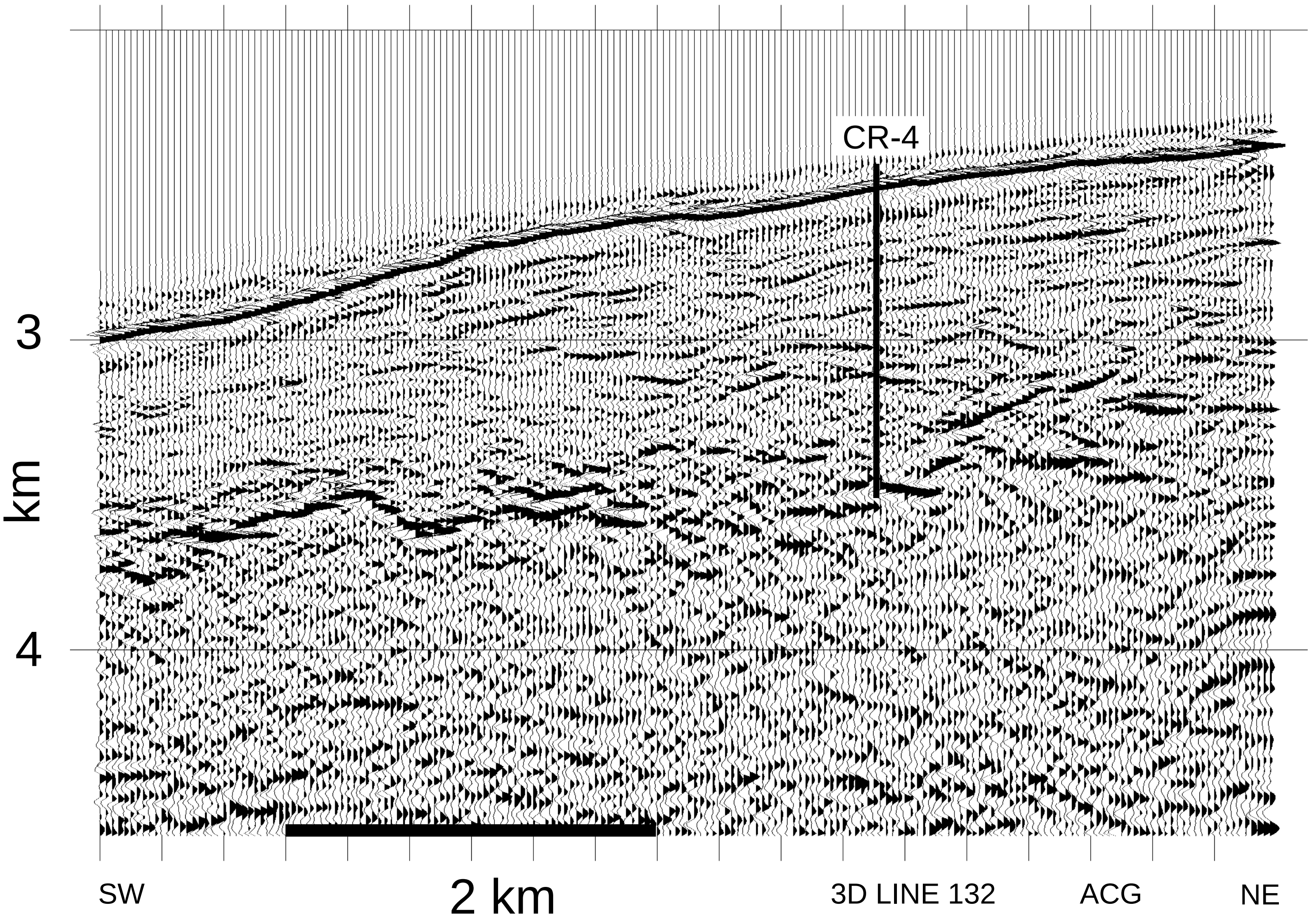
1. Determine the stratigraphy of the slope sediments in this area where reflectors can be trace widely.

2. Penetrate the high-amplitude reflector to determine the lithology and age of the material beneath it.

Drilling program:
Hole A: APC/XCB with Adara tool to 500 mbsf plus 5 WSTP measurements
Hole B: Drill to 500 mbsf, RCB to 950 mbsf

Logging and downhole: Standard wireline logging only

Nature of rock anticipated: Hemipelagic mudstone/sandstone in apron. Either deformed accreted sediment or mafic rock beneath the high-amplitude reflector.


CR-4
3
km
4
SW
2 km
3D LINE 132
ACG
NE

Site: CR-5 (alternate to CR-1 or CR-2)

Priority: 2
Position: 9°42'N, 86°8.4'W
Water depth: 3580 m
Sediment thickness: 1150 m
Total penetration: 1150 mbsf (approved to a depth of 1150 mbsf)
Seismic coverage: 3D Line 172

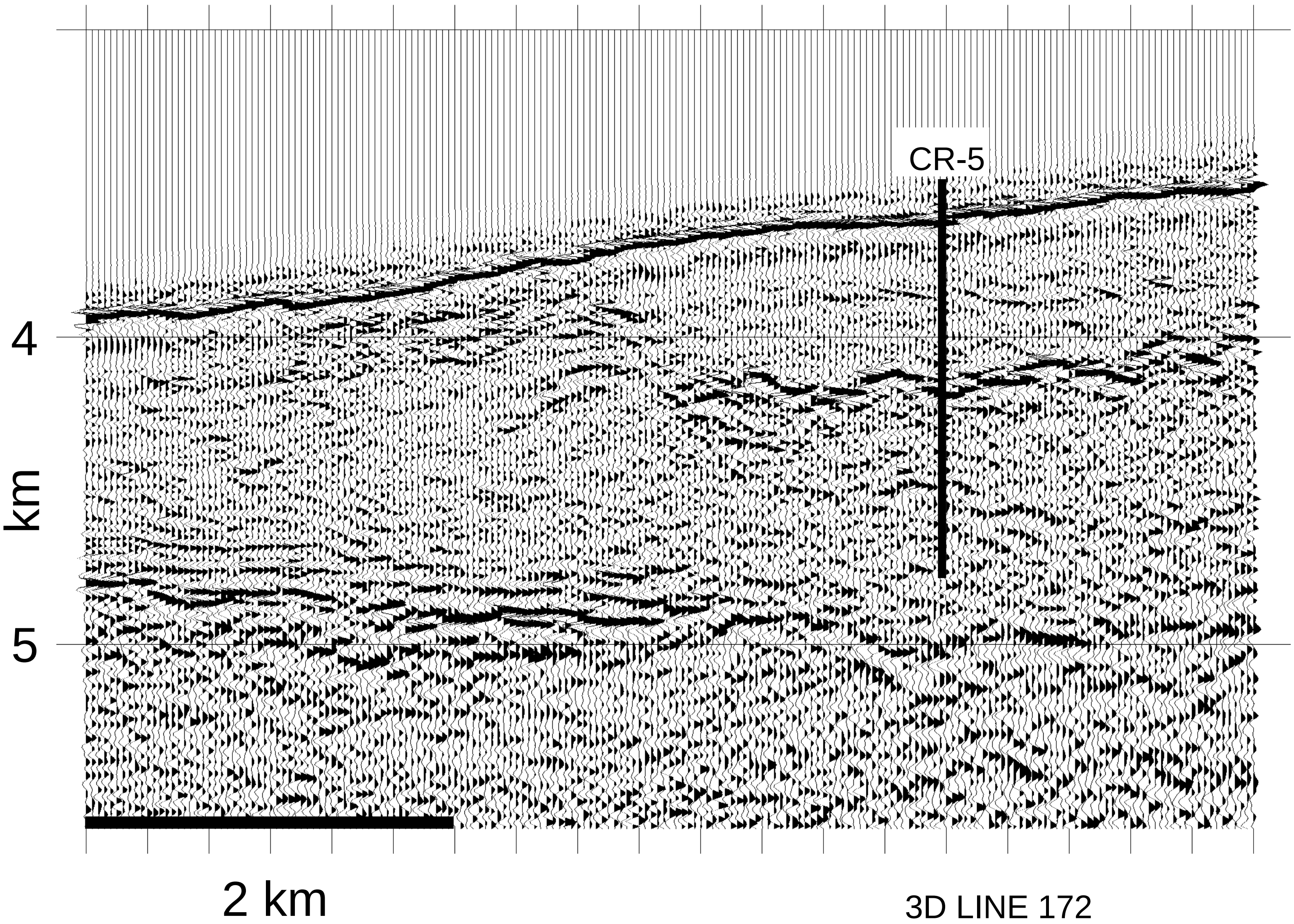
Objectives: The objectives of CR-5 are to:

1. Determine the age and physical properties of the sedimentary apron.
2. Penetrate beneath the high-amplitude reflector and determine the nature of the material beneath this layer.
3. Penetrate to the zone of out-of-sequence thrusting and determine the nature of material above and below this layer.
4. Use the results of the drilling to compute a mass balance between incoming and accreted strata.

Drilling program:
Hole A: APC/XCB with Adara tool to 500 mbsf plus WSTP measurements
Hole B: Drill to 500 mbsf, RCB to 1150 mbsf
Hole C: Drill with LWD tools to 1150 mbsf

Logging and downhole: Logging while drilling

Nature of rock anticipated: Hemipelagic mudstone and carbonate-rich pelagic mudstone. Possible serpentine slivers beneath high-amplitude reflector.


CR-5
4
km
5
2 km
3D LINE 172