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# Using 3D Seismic reflection data to find fluid seeps from the Costa Rica accretionary prism

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***Abstract.*** Submersible dives planned using 2D and 3D seismic reflection data off Costa Rica successfully found numerous sites of fluid expulsion predominantly along surface fault scarps. These data were used because more typical data, such as deep-towed side-scan sonar, bottom photography, and heat flow, were unavailable. Because fluids and fluid pressure distribution profoundly affect the way an accretionary prism deforms, detecting fluid pathways and recovering fluids is a key to its deformation processes. Detailed seismic interpretation of the shallow subsurface identified apparently active faults which are most likely to act as fluid pathways. Due to a quasi inverse relationship between surface dip and reflection amplitude, the amplitude of the seafloor reflection, displayed in map-view, shows the orientation and extent of surface scarps, many of which appear related to subsurface faults. Because the seafloor amplitude response depends on seafloor morphology as well as near-surface physical properties, removing the effect of the surface dip, calculated directly from picked surface structure, leaves a residual that may be related to variation in physical properties. Although the search for fluid seeps by submersible dives over the Costa Rica prism was sparse and irregular, the seeps that have been discovered are all on structural highs of the apron/prism boundary.

## Introduction

It is generally recognized that fluids within and at the base of accretionary prisms can profoundly influence their overall shape, their structural development, and, in part, the location of the seismogenic zone. Significant effort has been focused on identifying fluid flow paths to understand whether fluids migrate primarily by diffuse flow through the rock formations or by focused flow through fault zones [Moore et al., 1991], especially the basal decollement. Because rock strength is strongly influenced by the fluid pressure related effective stress, the flow paths and fluid pressure distributions are the key to understanding deformation of accretionary prisms [Brown et al., 1994].

To identify fluid flow, investigations commonly examine the seafloor for diagnostic biological communities or authigenic carbonate deposits [Kulm and Suess, 1990]. Evidence for fluid flow is also found in anomalous heat flow measurements [Langseth et al., 1990], and elevated fluid pressures may be inferred from seismic reflection observations [Shipley et al., 1994] and drilling (DSDP and ODP). Typical tools for examining the seafloor are high resolution, deep-towed side scan sonar, bottom photography, remotely operated submersibles vehicles (ROV), and manned submersibles.

The accretionary prism off the Nicoya Peninsula, Costa Rica has been surveyed using 3D seismic reflection techniques [Stoffa et al., 1991]. The structural configuration of the prism interpreted from these data shows a network of potentially active faults that may represent important fluid pathways. To build on this interpretation and to obtain quantitative data about fluid flow and fluid chemistry of the prism, a program of submersible dives, coring, and heat flow measurements was executed in February 1994. During this program we found that a map-view display of the seafloor reflection amplitude derived from the 3D seismic survey was a remarkably effective guide for identifying surface trends of active faults likely to act as fluid expulsion pathways. In addition, we observed that seeps discovered during the submersible dives correspond to subsurface structural highs of the apron/prism boundary.

Here we present initial interpretations of the Costa Rica 3D data set focused on fluid pathways. The primary emphasis is on use of the seafloor reflection amplitude and morphology and their relationship. We also examine the relationship between seep locations and the underlying prism structure.

## Seismic Reflection Data and Interpretations

The 3D seismic data volume used for this work resulted from acquisition of 88 parallel dip lines spaced at 100 m, each ~22 km long. After binning, the data were processed as 170 lines spaced at 50 m, covering a ~8.5 X 22 km area of the lower slope off Costa Rica (Fig. 1). The final stage of processing was a post-stack, 3D depth migration [Stoffa et al., 1991].

The initial interpretation of this data volume focused on the interior structure of the accretionary prism. One of the principal observations was that deformational structures change rapidly along strike reflecting variable sediment accretion, variable degree of deformation, and probable influence of the irregular subducting basement structure [Shipley et al., 1992; McIntosh, 1992]. Paradoxically, another key observation is that several prominent reflection events, interpreted as major fault zones within and near the base of the prism, are mappable across the entire width of the data set and may thus be regionally significant fluid pathways [Shipley et al., 1992]. Other evidence suggesting specific pathways for fluid flow in this data set include five diapiric structures and a well developed reversed polarity decollement reflection near the prism toe.



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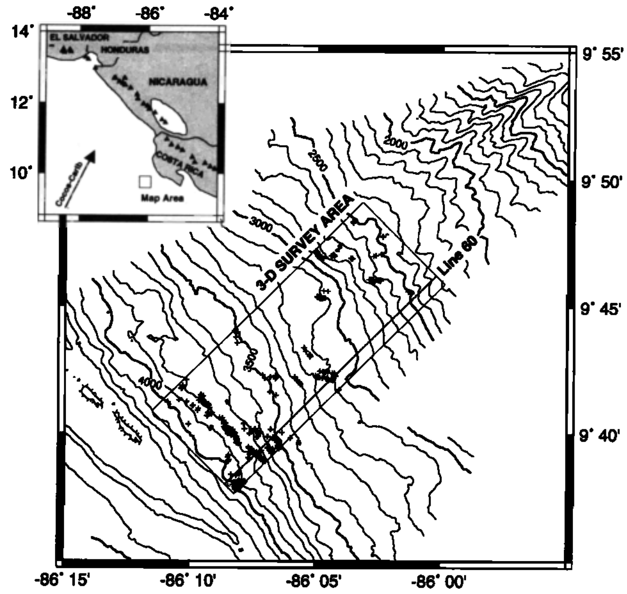


**Figure 1.** Map of trench slope off the Nicoya Peninsula, Costa Rica. Contours are from SeaBeam data set acquired in 1994, the box encloses the 3D seismic reflection area, and the cross symbols mark apparently active faults picked in the subsurface that extend to the surface. Inset shows geographical position of the map area. The Cocos-Caribbean relative plate motion is ~87 mm/yr off the central Nicoya Peninsula (calculated from DeMets et al. [1990]).

In preparation for the submersible dive program, and in conjunction with the ongoing seismic study of fluid pathways, we made a detailed analysis of the surface structures and the relatively shallow subsurface section. The idea was to identify apparently active faults in the subsurface, to substantiate their recent movement by identifying associated scarps on the seafloor, and thus establish diving targets. As noted by Shipley et al. [1992] and shown in Fig. 2, the sedimentary slope apron across the lower slope is poorly reflective and little, if any, stratigraphic layering is resolvable in the underlying accreted sediment due to accretion in small, thin blocks and subsequent intense deformation. Consequently, most reflection events in the prism and many in the overlying apron are interpreted to indicate faults rather than stratigraphic layering. The faults we identified are considered "active" and significant if they can be traced 100s of meters to kilometers, consistently offset other intersecting reflection events, and are not apparently offset by other, younger faults.

While we were able to identify apparently active faults and locate their scarps at the seafloor (Fig. 1), we also were interested in knowing the orientation and lateral extent of the scarps on the seafloor. Shipley et al. [1992] previously pointed out that the seafloor reflection amplitude appeared to correlate with surface dip and, specifically, that bands of low reflection amplitude correspond to scarps identified on the vertical seismic sections (Figs. 2 and 3). In a set of detailed displays we plotted the seafloor reflection amplitude and overlaid bathymetry (from the 3D seismic) and the picked fault locations. These plots, the seismic sections, and SeaBeam bathymetry acquired during the cruise, provided the basis for selecting our dive locations and establishing our dive plans. The specific diving targets included sampling the diapiric structures and, in particular, a zone of thrust faults in the lower slope. Other diving targets, the outcrop of the frontal thrust and normal faults in the upper slope, were identified from regional 2D seismic profiles.

## Relation of Dive Results to Seismic Data

Fluid seeps were found in eight locations across the lower trench slope during dives with the DS/V *Alvin* (Fig. 3). The first seep found was at the crest of the largest diapir (~9° 42' N, Fig. 3). The steep flanks of the diapir are clearly defined on the seafloor amplitude map and the diapiric nature of the edifice is indicated on the seismic sections (Fig. 2). Despite traverses from numerous directions up the flanks, the only active seeps were found at the crest [Kahn et al., 1995]. The other lower-slope seeps were detected in a structurally complicated zone 6-9 km upslope from the trench axis. The amplitude map (Fig. 3) shows this to be an area of interconnected low amplitude zones, suggesting numerous scarps. Seismic sections show that the corresponding scarps have relief of a few to several tens of meters. Although not true in all cases, the seeps found in this area typically occurred near the base of the scarps. One dive also investigated parts of a three-km-long low amplitude zone ~1.5 km downslope from the previously mentioned diapir (Fig. 3). The dive confirmed this feature to be a structural scarp, but no fluid seeps were found.

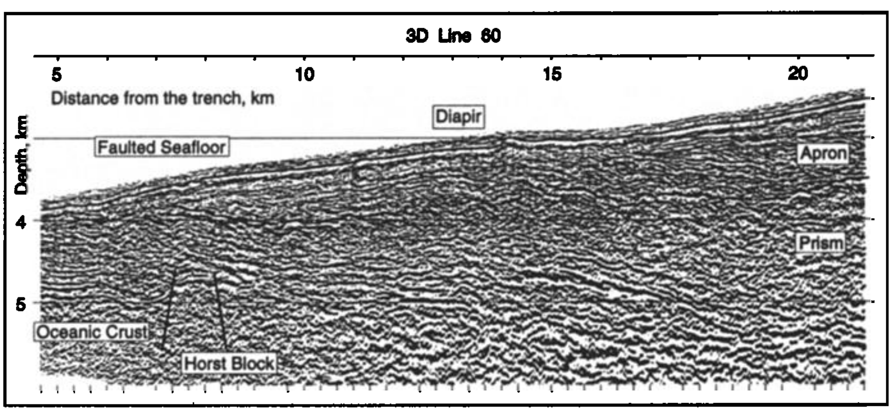


**Figure 2.** 3D Seismic line 60. This section crosses a diapir (14 km), shows an example of the of the apron/prism boundary structure, and shows the location of the underthrust horst block (8 km). Note the thrust ramp in the vicinity of the horst block (inclined reflections) and the faulted, rough seafloor from 6-9 km. Seafloor dip and reflection amplitude used for Figure 4 were taken along this line from a gridded data set.

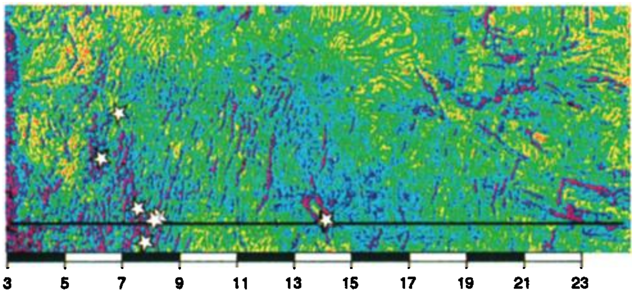


**Figure 3.** Amplitude of the seafloor reflection over the 3D survey area (box in Fig. 1; line 60 is marked) displayed in map-view. The amplitude values are arbitrarily scaled with light purple to dark blue representing low amplitudes and yellow to orange indicating high amplitude seafloor reflections. Trends of low amplitude correlate with zones of high surface dip and provide a useful guide to the surface morphology. White stars mark fluid seeps.

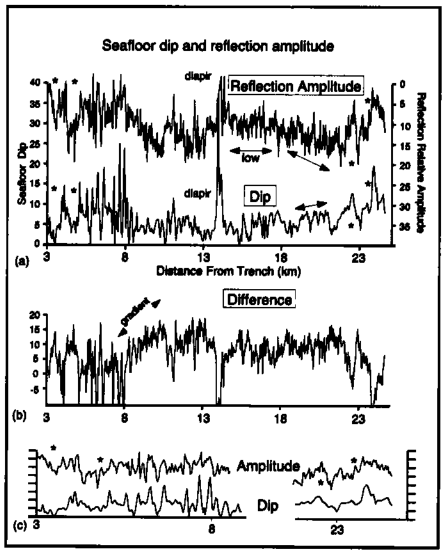


**Figure 4.** Reflection amplitude along line 60 linearly scaled to approximately match the seafloor dip (a). Reflection amplitude plotted increasing downward and dip increases upward due to their inverse relationship. Matching patterns on the two curves confirm a general relationship. Slopes in the difference curve (b) indicate areas of poor correlation that may have geologic significance (see text for further discussion). Selected expanded displays (c) show surprising detailed correspondence between amplitude and surface dip. Asterisks used to indicate matching or diverging patterns. Compare to line 60 (Fig. 3).

## Seafloor Reflection Amplitude Versus Surface Dip

The validity of a quasi inverse relationship between seafloor amplitude and the surface dip or roughness [Shipley et al., 1992] was supported by overlaying the seafloor amplitude map and the seismically-derived bathymetry and was further reinforced by the results of dives traversing the diapir flanks and nearby fault scarp described above, all of which were indicated by low amplitude zones on the seafloor reflection map. To help assess this relationship further we compared seafloor dip, calculated from seismic bathymetry, to reflection amplitude along 3D line 60 by linearly scaling the amplitude to be similar to the range of dips (Fig. 4). The strong inverse correlation between surface dip and reflection amplitude is evident; in particular, the generally higher dips between 5 km and 8 km correspond to low amplitudes, and the high dips on the flanks of the diapir match very low amplitude. However, significant variation is unrelated to the seismically resolvable dip. Specifically, zones where the response is similarly shaped on both curves frequently show differences in response amplitude. Some of this difference can be attributed to the difficulty in calibrating reflection amplitude values with dip, but it also requires the relationship between dip and reflection amplitude to be non-linear. In other areas, where the shapes of the curves is dissimilar, observed variation may be due to seafloor curvature, differences in incident angle, or changing properties of the near surface sediments [Sheriff, 1975]. Changing near surface properties may occur between 8 km and 10.5 km where the gradient in the difference curve indicates that reflection amplitudes increase without a corresponding decrease in dip. This lack of correlation may suggest somewhat denser near surface sediment at 10.5 km or, alternatively, a reduction in small scale faulting leading to decreased scattering and higher reflection amplitude. Between 15 km and 17 km low dips occur where the reflection amplitude is also relatively low. This area is quite flat (Fig. 2) and sits between the diapir and a significantly steeper slope. Thus the relatively low amplitude may indicate active sediment deposition in this zone leading to a less dense near surface layer. In contrast, the generally increasing difference between 18 km and 21 km suggests that reduced sedimentation rate or

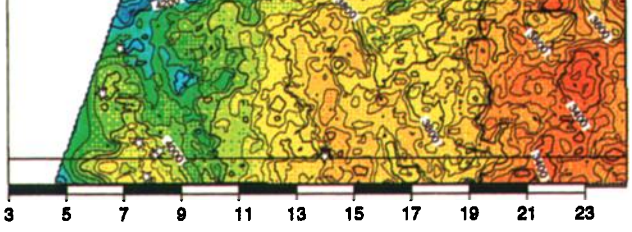


**Figure 5.** Structure contour map on the apron/prism boundary reflection over the 3D area (box in Fig. 1; interval 50 m). Line 60 is marked. Fluid seeps found during cruise 131-10 are indicated by white stars. Note that all the seeps are located on structural highs of this surface.

even erosion on the steeper slope may lead to a denser, more reflective near surface.

## Discussion

A goal of the seismic reflection interpretation project and the dive campaign was to identify the fluid pathways in the Costa Rica accretionary prism. Although the dive program covered only a fraction of this limited portion of the margin, the results suggest that the criteria used for picking active faults are appropriate indicators for fluid pathways and thus helpful for locating fluid seeps. However, as noted above, fluid expulsion was not observed along all of the apparently active fault zones associated with surface scarps. As pointed out from heat flow data [Fisher and Hounslow, 1990] and a few direct fluid rate measurements [Carson et al., 1990], fluid expulsion in accretionary prisms is likely to be a transient process. The factors that control the distribution of flow in space and time, however, are not well understood.

Some factors controlling intraprism fluid flow may be suggested by the fact that all the seeps found in the lower slope area occur above relative highs of the apron/prism boundary (Fig. 5). Although the submersible dive program provides too sparse a data set to allow strong inferences to be drawn about this possible relationship, two possibilities are worth noting. In one case, the apron/prism boundary retards upward fluid flow and acts to focus flow into the structural highs where existing faults or fractures may allow limited flow to the surface. Shipley et al. [1992] showed a seismic "bright spot" at this boundary which points to its trapping ability and provides general support for this interpretation. Judging from the incoming sedimentary section and assuming similar lithology of the accreted material, however, the prism material is likely to be low porosity, low permeability, and highly consolidated; fluid flow should be dominated by fracture permeability. Thus, fluid trapping and focusing is questionable, and, because most observed faults are landward dipping, good lateral permeability is unlikely and fluid migration for significant distances along the boundary is doubtful. Another way to view the role of the structural highs is that they occur where concentrations of thrust faults (out-of-sequence) deform the prism. One structural high, at about 5 km from the deformation front, coincides with an underthrust horst block on the subducting Cocos plate (Fig. 2). The horst block increases the basal detachment slope on its landward side and is the locus of much more intense faulting in the overlying prism. Thus the fluid seeps may occur preferentially in this position due to the migration paths established by the active faulting, which, along with the underthrust horst, forms the structural high. In the vicinity of the largest diapir, the structural high may be due to structural thickening of the prism by duplex emplacement. Numerous out-of-sequence thrusts are also evident with offsets in the apron/prism boundary and landward dipping events in the apron section, so this diapir marks another zone of active deformation.

## Conclusions

1. 3-D seismic reflection data are extremely useful in the search for fluid seeps and vents because they provide surface information, much as multibeam bathymetry or sidescan sonar do, but also provide a densely sampled subsurface view to evaluate the surface features.
2. The seafloor reflection amplitude displays a generally inverse relationship with surface dip and can be a useful tool in identifying shallow structural trends.
3. Appropriately scaled subtraction of seafloor dip and reflection amplitude may yield, as a residual, information about surface lithology changes, depositional variability, or small-scale surface roughness.
4. Because the fluid seeps discovered on the lower trench slope were all on structural highs of the apron/prism boundary, there may be a causal relationship. One possibility is that fluids migrate along and collect at the base of the boundary. A more likely possibility is that the structural highs form in locations of greatest active deformation, in which case the active faults provide the fluid pathways necessary for the observed fluid expulsion.

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