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Seafloor structural observations, Costa Rica accretionary prism

Brian G. McAdoo[1], Daniel L. Orange[2], Eli A. Silver[1], Kirk McIntosh[3], Lon Abbott[1], Joe Galewsky[1], Leslie Kahn[1], and Marino Protti[4]

Abstract. By studying seafloor morphology we can make associations between near surface deformation, fluid flow and the overall structural framework of accretionary prisms. In February, 1994 a DS/RV ALVIN program to the Costa Rica accretionary prism investigated the relationship of fluid seepage and sediment deformation by using the distribution of chemosynthetic communities and heat flow anomalies as indicators of fluid flow. The active normal faults that cut the hemipelagic section on the Cocos plate may provide conduits for fluids that cause the regional heat flow to be extremely low. These normal faults intersect the toe of the prism at an oblique angle, creating localized regions of increased deformation. Positive heat flow anomalies observed at the deformation front indicate diffuse fluid flow, however, we discovered no seep communities indicative of focused flow. The seaward-most seep communities discovered are in a region of active out-of-sequence thrusts that cut a sediment apron which covers the complex to within 3 km of the prism toe. Vents occur consistently at the base of the fault scarps. Dives on a mud diapir show extensive seep communities, pock marks, and authigenic carbonates. Evidence of fluid release is on the crest which implies a low viscosity fluid migrating upward in the center of the structure. Normal faults on the upper slope can be seen in cross-section in the walls of a submarine canyon. The faults cut the slope apron and displace the seafloor, actively maintaining the critical taper of the prism.

Introduction

Accretion at convergent continental margins is accommodated by a combination of underplating and/or offscraping of fluid rich sediments deposited on the subducting plate. Tectonic and lithostatic compaction leads to dewatering throughout the accretionary prism. During February 1994 we carried out twenty DS/RV ALVIN dives and a SeaBeam survey in the vicinity of a 180 km^2 3D seismic grid in order to investigate the spatial relationship between sites of fluid venting and structural features such as faults and diapirs. Using chemosynthetic communities as evidence for focused fluid venting, we will examine the effect of elevated fluid pressures on deformation in the prism (Suess et al., 1985; Kulm et al., 1986; Brown et al., 1994). The dives examined five structurally distinct areas including normal faults on the Cocos plate seaward of the trench, the toe of the prism, a zone of out-of-sequence thrust faults, two mud diapirs, and a region of normal faulting on the upper slope (Fig. 1).

[1]University of California, Santa Cruz
[2]Monterey Bay Aquarium Research Institute, Pacific Grove, CA
[3]University of Texas, Austin
[4]Universidad Naçional, Costa Rica

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Geologic Setting

West of Costa Rica, late Oligocene-early Miocene crust of theCocos plate is subducting beneath the Caribbean plate at a rate of ~87 mm/y (Hey, 1977; McIntosh et al., 1993). Both offscraping and underplating adds material to the mud dominated prism from the top 40-80 m of the 300-450 m thick, normally faulted Cocos plate sediments (Shipley and Moore, 1986). The accretionary prism thickens via an out-of-sequence thrust fault zone which cuts a sediment apron that covers the lower slope to about 5 km from the toe (Shipley and Moore, 1986; Shipley et al., 1992). Normal faults on the upper slope cut the slope apron and the underlying prism, and maintain the critical taper of the prism by accommodating a total extension of 1.5 to 3 km (Fig. 2; McIntosh et al., 1993).

Shipley and Moore (1986) proposed that half of the fluids within the accreted sediments are expelled within 3-5 km of the toe. They interpreted the strong seismic reflector that marks the basal dècollement as a possible conduit for fluid expulsion. A 3D seismic data set in the same area images out-of-sequence faults as bold reflectors and possible fluid pathways along with five mud diapirs on the mid-slope, the result of advecting fluids entrained in overpressured sediments (Shipley et al., 1992; Brown, 1990). Heat flow is extremely low in the region (~20 mW/m^2); however transects show increased advection between the trench and the prism slope suggesting diffuse outflow of pore fluids and heat from depth (Langseth and Silver, this issue).

Observations

Sedimentary Units and Normal Faults of the Cocos Plate. Three of the five dives located near the toe of the accretionary prism crossed the trench and examined the sediments and structure of the Cocos plate (Fig. 1). Normal faults cutting the seafloor are continuous along strike throughout the region, have up to 100 m of relief and surface slopes approaching 30°. These features intersect the deformation front at an angle of ~10°. Bedding exposed along the top of the scarps exhibits a very shallow dip, <10° on average, but is rotated up to 40° in places. Bedding dips increase systematically to ~30° at the base of each scarp. The scarps are separated by ~5 km, with the seafloor in between being covered by a featureless hemipelagic sediment drape. We found no evidence (e.g. vent communities or elevated heat flow gradients) of outward fluid flow seaward of the toe.

Deformation Front. The deformation front is the seaward-most extent of compressional deformation, recognized here as the ~10° increase in slope from the flat- lying trench sediments to the faulted material of the wedge (Fig. 2). Two dives (2716 and 2717) traversed more than 3 km along the deformation front in search of active fluid venting, but found none. We observed regions where normal fault scarps intersect the deformation front, and other areas far from this intersection. Almost immediately inboard from the deformation front, there are a series of 10-15 m high scarps that coincide with thrust faults seen in the seismic reflection data. Other than scattered shells of unknown species noted on three dives, no evidence of fluid venting was seen in the trench.

Dive 2723 was located in the trench, 10 km from the closest normal fault intersection with the deformation front (Fig. 1). On

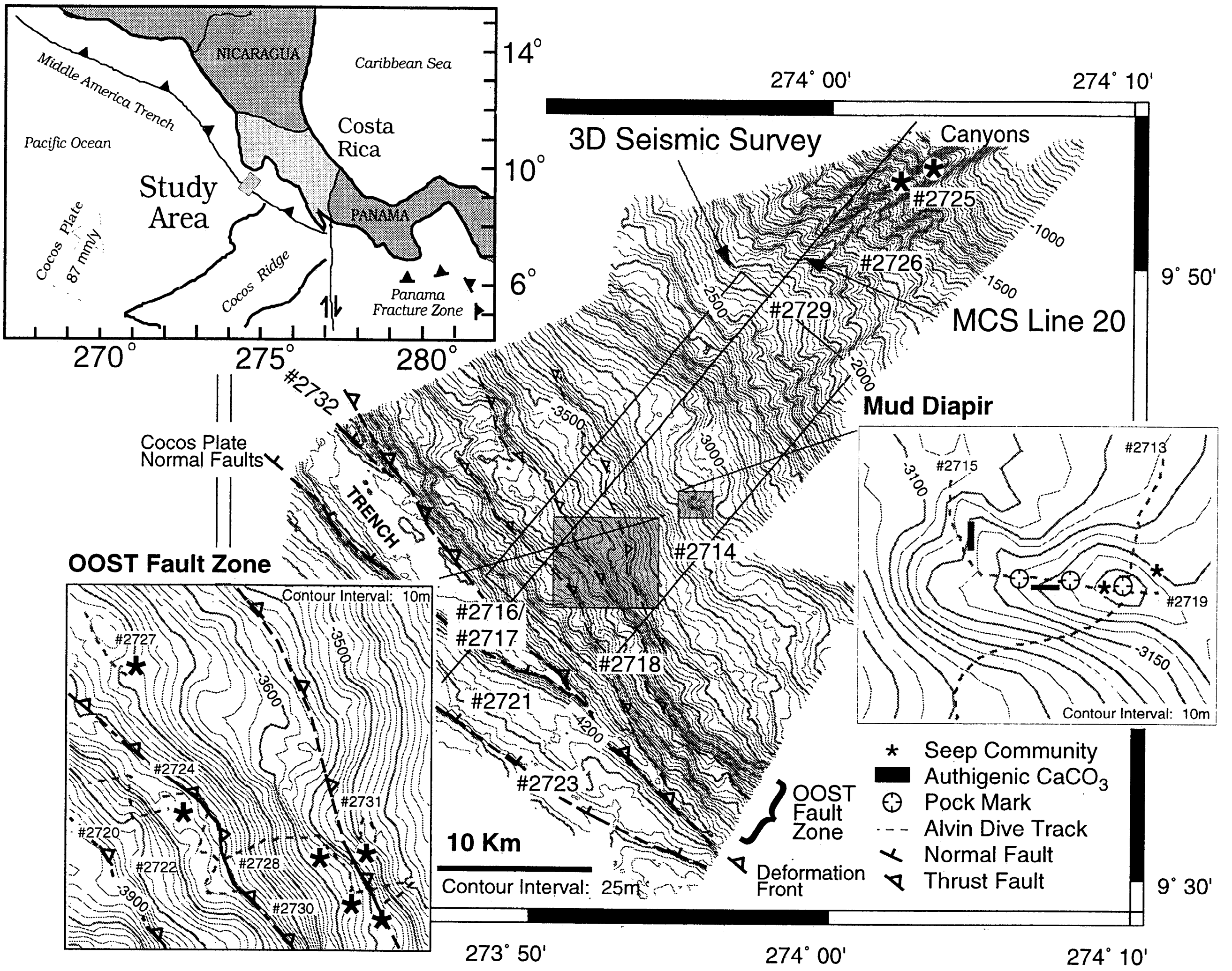

Figure 1. Location and bathymetric map of the Costa Rica accretionary prism study area with large scale structural features and chemical evidence of fluid venting shown. Enlarged in the insets are the seaward-most mud diapir and the lower slope out-of-sequence thrust (OOST) fault zone. Dive locations are numbered following pound (#) signs. Hachures show down thrown block on normal faults and teeth on the hanging wall of thrust faults. Bathymetry from a SeaBeam source.

the landward side of the trench, there is a 40 m high scarp with a slope of ~20°, significantly steeper than the area surveyed by Dives 2716 and 2717 (more than 10 km from the nearest normal fault intersection). Dive 2732 surveyed the trench to the north where another normal fault is impinging on the deformation front and observed very steep (50°-70°) slopes, composed of highly deformed material which contained light colored veins of uncertain composition.

Out-of-Sequence Thrust Zone. The out-of-sequence thrust fault zone is characterized by a series of anastomosing scarps and flats trending ~320°. The features are slightly oblique to the deformation front, which is oriented ~310°. Observations from the eight dives carried out in this area show biological evidence of fluid venting at seven locations including clams, bacterial mats and non-chemosynthetic, vent-associated fauna, associated with brecciated scarps (Kahn et al., this issue). The scarps, which can be over 200 m high, are remarkably continuous over 2-4 km (McIntosh et al., this issue), with slopes averaging ~25°-30°, and are near vertical in places. The steep scarps lack significant pelagic cover, and correlate with faults in the seismic reflection data.

Dive 2720 began in sandy sediments at the base of a 60 m high scarp sloping ~30° where one dead but articulated clam shell was discovered. The dive traversed the scarp, crossed smaller scarps each with ~1 m of relief continuous over 100's of meters, but without evidence of vent communities. At the top of the 60 m scarp, the seafloor rapidly drops 10 m into another sandy swale where a vent community was discovered at the base of another scarp. This scarp rises ~200 m then drops into another flat swale. Scarps expose sediments that are brecciated in places. Two sets of continuous (<3 m) fractures and lineations cut across the brecciated outcrops. One set has a rake <20° and the other 50°-70° with respect to the scarps which strike ~320°. Bedding is difficult to distinguish from the lineations, but appears to be dipping shallowly to 20°.

Mud Diapirs. Two of five mud diapirs imaged in the 3D data were investigated with the ALVIN. The diapir closest to the toe (15 km) is most actively seeping fluids. It is elliptical, approximately 2 km by 0.5 km, rises 100 m over the surrounding seafloor, and has a long axis that strikes 090°. Slopes on the flanks of the diapir average 15° while on the crest they are less than 5°. Evidence for active fluid venting is found entirely on the crest, including communities of chemosynthetic clams and tube worms, bacterial mats, pock marks (possibly the result of a rapid degassing event) and authigenic carbonates are present in astonishing abundance (Kahn et al., this issue). The second diapir lies 25 km from the toe. It is of similar size as the other diapir, but the long axis of the crest trends ~070°, and rises only 50 m above

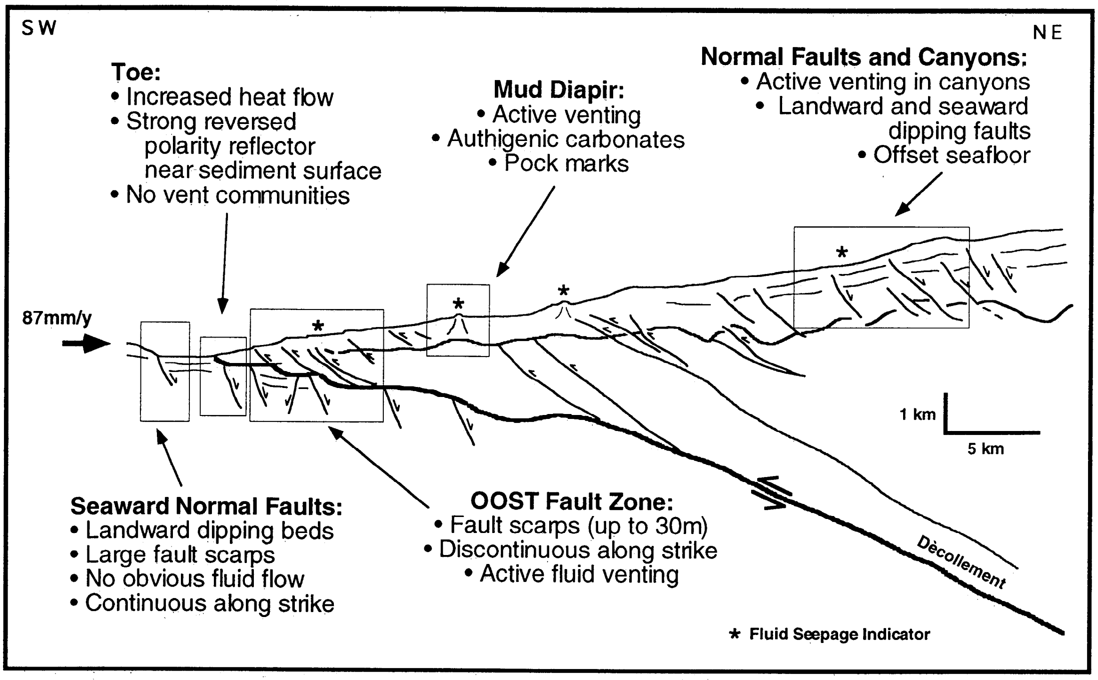

Figure 2. Diagrammatic cross-section of the study area from 2D seismic line 20 (from McIntosh et al., 1993). Asterisks (*) show locations where there is evidence of focused fluid flow. The mud diapir is projected onto this line from ~2 km to the southwest. Vertical exaggeration is about two times. OOST- Out-of-sequence thrust faults.

the seafloor with slopes averaging only 10° on the flanks. A single pock mark that is 2 m across and less than a meter deep is present on the crest which is otherwise smooth mud (Kahn et al., this issue).

Normal Faults and Canyons. The upper slope, approximately 30 km from the trench, is dominated by normal faults and two submarine canyons. Dives 2725 and 2726 investigated the walls of two canyons, as the canyon floor is covered by a blanket of sediment. The northwestern most canyon is incised over 300 m into the slope, with localized vertical to overhanging walls on an overall slope of 30°. This canyon provides a cross-sectional view of the slope apron sediments and the normal faults that cut them. In places, side canyons narrow to only 15 m across. The slope apron sediments are uniform, with beds dipping less than 5° seaward. Benches along the canyon wall, and sometimes the canyon base, are dip slopes. High angle fractures, which trend roughly normal to the canyon axis, dip primarily landward (60° to vertical), displace the seafloor several centimeters, and recur on wavelengths on the order of several meters. A second set of 5 m high, near vertical scarps occur on wavelengths to 100's of meters, with piles of angular boulders (2-3 m per side) at the base of each scarp. The top of the scarp is a bench with sand ripples that continue intermittently to a talus pile at the base of another scarp. Two vent sites were discovered on Dive 2725 near the axis of the canyon. We observed seep fauna including tube worms and clams, and bacterial mats, but no evidence of gas (e.g. carbonates or pock marks; Kahn et al., this issue). Both seep sites are present at the base of bedding scarps, >100 m away from the nearest 5 m high scarps.

Discussion

Detailed observations along traverses provide a basis for inferences on the relationship of active faults and vent sites. The normal faults on the Cocos plate appear to be currently active, as the hemipelagic sediment drape is faulted. This zone lacks evidence of fluid venting suggesting that fluids are not being forced out tectonically. Observed faults on the seafloor could provide conduits for water influx and a mechanism for reducing the regional heat flow as proposed by Langseth and Silver (this issue).

No seep communities were discovered where the frontal thrust approaches the seafloor in the trench. Shipley et al. (1990) found that the majority of fluids are expelled within 3-5 km landward of the frontal thrust where the seismic data shows a reversed polarity reflector close to the seafloor, and Langseth and Silver (this issue) report elevated heat flow. However, we observed no seep communities until 5 km inboard from the trench; consequently fluid venting must be occurring either diffusely (with an insufficient density of nutrients to support a seep community) or episodically. Scattered shell fragments noted on several dives in the trench could indicate gravity transport from upslope or undiscovered, perhaps transient, seep communities near the frontal thrust. Veins observed in a highly deformed section at the toe of the prism where a normal fault has impinged on the deformation front, suggest the possibility of past concentrated fluid flow in the region. If the deformation is more intense when the normal fault scarps intersect the toe of the prism, then regions (separated by ~30 km) and periods (~60 Ky, using the Hey (1977) convergence rate of 87 mm/y) of increased strain rates could lead to an episodic expulsion of fluids from the accreted sediments.

The out-of-sequence thrust zone is a region of active faulting as the tectonized scarps correlate with faults observed in the 3D seismic data (Shipley et al., 1992), lack hemipelagic cover, and contain organized fracture sets. The presence of these active faults is consistent with the interpretation of Shipley et al. (1992) that the prism is thickening and faulting in this zone to maintain critical taper. Seep communities in this region are all associated with fault scarps. Faults are often considered either fluid conduits or permeability barriers which concentrate fluids (e.g. Moore et al., 1990). The locations of the seep communities also coincide broadly with the seaward termination of the slope apron, 5 km from the toe of the prism.

Evidence for concentrated fluid flow affecting seafloor morphology is also observed on the mud diapirs. Studies elsewhere by Brown (1990) and Orange (1990) show that fluid venting concentrated on the crest of the diapir, as is the case with both diapirs studied in this area, suggest a low viscosity material highly enriched in possibly two phase fluids (water and methane gas as evidenced by the seep communities and pock marks and authigenic carbonates), whereas diapirs made of more viscous material (lower fluid content) develop margins that channel fluids from depth, and seeps are found on the perimeter of the diapir.

McIntosh et al. (1993) investigated forearc extension in the upper slope where normal faults accommodate a total extension of 1.5 to 3 km (Fig. 2). We interpret the two parallel sets of near vertical fractures as antithetic and synthetic faults, one with several centimeters of displacement and wavelengths of meters and the other with throws of meters on wavelengths of hundreds of meters. There does not appear to be any relationship between the normal faults on the upper slope and the occurrence of seep communities on the seafloor. Instead, seeps were observed in canyons which act to focus fluid flow by changing the localized head gradients (Orange and Breen, 1992).

Conclusions

Observations made in the Costa Rica accretionary prism show a remarkable amount of structural diversity and associated fluid dynamics. Active normal faults on the subducting Cocos plate may provide conduits for the influx of seawater providing a possible explanation for the extremely low regional heat flow. The intersection of the normal faults with the deformation front results in steepening of scarps at the toe of the prism. Active out-of-sequence thrust faults maintain the critical taper of the prism, and provide permeability variations which focus the fluids that support seep communities. Mud diapirs are locations of fluid rich material advecting through the prism. Normal faults on the upper slope also act to maintain the critical taper of the prism, but show little evidence of fluid seepage. Instead, fluids that support the seep communities on the upper slope migrate through stratigraphic conduits in the slope apron sediments and are drawn to the canyons due to local perturbations in the head gradients.

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B. G. McAdoo, E. A. Silver, L. Abbott, J. Galewsky, and L Kahn, Earth Sciences Department and Institute of Tectonics, University of California, Santa Cruz, CA 95064. (e-mail: bmcadoo@earthsci.ucsc.edu).

D. L. Orange, Monterey Bay Aquarium Research Institute, 160 Central Avenue, Pacific Grove, CA 93950.

K. McIntosh, University of Texas Institute of Geophysics, Austin, TX 78759

M. Protti, OVSICORI, Universidad Naçional, Costa Rica.

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