An 8–10 Ma tectonic event on the Cocos Plate offshore Costa Rica: Result of Cocos Ridge collision?

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[1] Upper oceanic crust within the Cocos Plate offshore northwestern Costa Rica is dominated by sill intrusions of various ages, recognized regionally as smooth, high amplitude seismic reflections at the base of the sedimentary sequence and locally by dolerites and microgabbros recovered by drilling. Earlier interpretation of seafloor magnetic anomalies documented a set of spreading ridge jumps at 19.5 and 14.5 Ma, continuing to the present. In addition to these events, we present evidence for a widespread tectonic event in the period 8–10 Ma displayed in reflection seismic data recorded during the Ticoflux 1 and 2 experiments and dated by seismic correlation to ODP Site 1039. The 8–10 Ma events may have been triggered by collision of the Cocos Ridge at this time and facilitated by widespread sill intrusion associated with the Galapagos Hot Spot. *INDEX TERMS:* 3015 Marine Geology and Geophysics: Heat flow (benthic) and hydrothermal processes; 3025 Marine Geology and Geophysics: Marine seismics (0935); 3035 Marine Geology and Geophysics: Midocean ridge processes; 3045 Marine Geology and Geophysics: Seafloor morphology and bottom photography; 8150 Tectonophysics: Plate boundary—general (3040). **Citation:** Silver, E., P. Costa Pisani, M. Hutnak, A. Fisher, H. DeShon, and B. Taylor (2004), An 8–10 Ma tectonic event on the Cocos Plate offshore Costa Rica: Result of Cocos Ridge collision?, *Geophys. Res. Lett.*, *31*, L18601, doi:10.1029/2004GL020272.

1. Introduction

[2] The Pacific sea floor offshore Costa Rica has had a complex history; its origins and evolution are fundamental to understanding the fluid flow system that has created highly anomalous thermal signatures in this region [*Vacquier et al.*, 1967; *Langseth and Silver*, 1996; *Silver et al.*, 2000; *Fisher et al.*, 2003]. Interpretations of Cocos Plate magnetic patterns indicated seafloor evolution through several ridge jumps, continuing ridge propagation, and a complex interaction of the Cocos and Nazca Plates with the Galapagos Hot Spot [*Hey*, 1977]. *Barckausen et al.* [2001] and *Werner et al.* [2003] recently refined the Cocos Plate development into three stages. The first stage incorporated the initial spreading geometry prior to 22.5 Ma. The second stage, separating crust derived from the Cocos-Nazca Spreading Center (CNS) into regions of different magnetic orientation, was marked by ridge jumps at 19.5 and 14.5 Ma. The final stage of development includes minor ridge jumps and ridge propagations, which continue to the present with plate formation ongoing along the East-Pacific Rise (EPR). We present evidence for a widespread, previously unreported event at 8–10 Ma, which we relate to Cocos Ridge collision with Costa Rica.

[3] We acquired approximately 3000 km of seismic reflection data on the Cocos Plate in 2001 and 2002 using the R/V Ewing (Ticoflux 1: 1800 km) and R/V Melville (Ticoflux 2: 1200 km) expeditions. The Ticoflux 1 data set, the focus of this paper (Figure 2), utilized a 50 liter, 10 air gun seismic array and recorded on the Ewing's 6000 m, 480 channel streamer. Shot interval was 37.5 m and receiver spacing 12.5 m, giving 6.25 m common depth point spacing at 80 fold.

2. Structure of the Sea Floor Offshore Costa Rica

[4] The sea floor on the Pacific basin offshore Costa Rica can be separated to a first order into crust formed from the CNS and that formed at the EPR. Much of the CNS crust is marked by the Cocos Ridge and by a flanking seamount province, which is subducting and indenting the upper plate south of the Nicoya peninsula (Figure 1). The subducting CNS crust is characterized by relatively high heat flow [*Vacquier et al.*, 1967; *Fisher et al.*, 2003], in general agreement with conductive lithospheric cooling models for crust of this age [*Parsons and Sclater*, 1977; *Stein and Stein*, 1994]. The EPR crust to the north is separated from the CNS crust by the trace of the triple junction [*Barckausen et al.*, 2001], which becomes a fracture zone near its intersection with the continent (Figure 2). *Werner et al.* [1999] documented a period of volcanic activity on the Cocos Ridge and seamounts with ages in the range of 13–14.5 Ma.

[5] ODP Leg 170 [*Kimura et al.*, 1997] drilled Site 1039 into the EPR crust in the trench just north of the intersection of the fracture zone separating the two crustal types (Figure 2). They recovered approximately 400 m of pelagic and hemipelagic sediment and bottomed in gabbroic sills (Figure 3). The sediment above the sills was dated at 16.5 Ma, and the crust below is dated magnetically at 24 Ma [*Barkausen et al.*, 2001]. Thus a sill event occurred in this region post 16.5 Ma, possibly 13–14.5 Ma – coincident with the ages of rocks dredged by *Werner et al.* [1999]. Surprisingly, even though the site was on EPR crust, as defined by magnetics, the gabbros were more similar geochemically to those found on the

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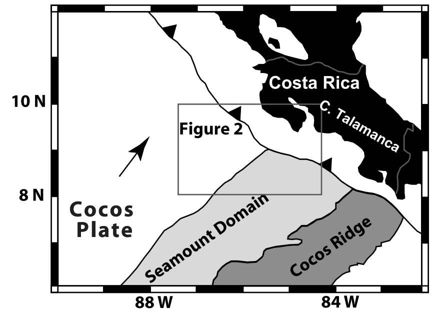

Figure 1. Map showing location of Cocos Ridge relative to Central America. Arrow gives direction of Cocos-Caribbean plate motion.

Galapagos and CNS than to those from the EPR [*Kimura et al.*, 1997].

3. Use of Seismic Correlation for Determining Ages

[6] Ages of events seen in the seismic records can be discerned through seismic correlation with ODP Site 1039 (Figure 3). Comparison of synthetic and actual seismograms and with core data shows a close correspondence between the seismic record and the cored sedimentary sequence. The first high amplitude reflection (Rl) in the synthetic seismogram occurs at the contact between units UIA and the UIB, in late Pleistocene diatom ooze with ash [*Kimura et al.*, 1997], located a few meters below the sea floor. The second high amplitude reflection (R2), traceable widely throughout the region, corresponds with the contact between units U3A (siliceous nanofossil ooze and clay) and U3B (siliceous nanofossil ooze). The strong reflection at this contact is preceded by a weak, parallel reflection, forming a distinctive doublet that can be followed widely. Around Site 1039 the hemipelagic units above U3A are weakly reflective, although farther to the west additional stronger

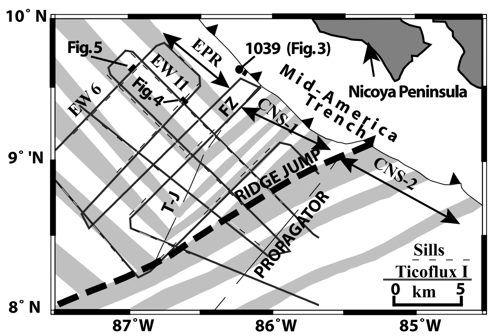

Figure 2. Seismic tracks of Ticoflux I survey, overlying the main tectonic features and magnetic anomaly pattern of the Cocos Plate off Costa Rica. Thick line segments are locations of Figures 3–5. Location of Site 1039 is shown. The region southeast of the triple junction (T-J) and ridge jump traces represents crust formed by the Cocos-Nazca Spreading Center (CNS), whereas the region to the NW was formed by the East Pacific Rise (EPR). Thicker dashes following track lines represent regions of sill intrusion inferred from the TF 1 seismic data. FZ, Fracture Zone.

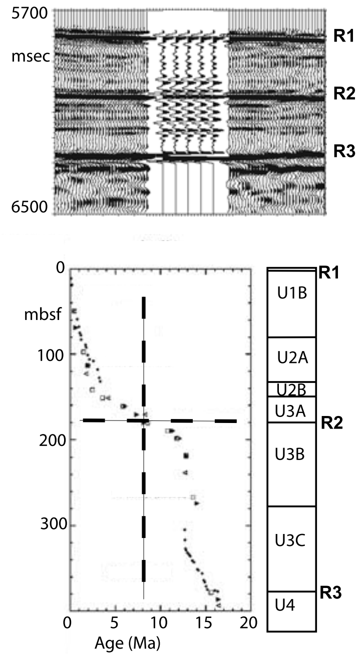

Figure 3. Seismic stratigraphy and age-depth relations for ODP Site 1039. Upper: Synthetic seismogram based on velocity and density logs from cores at Site 1039, shown next to seismic traces at the location of the site. Lower left: Age-depth relations for ODP Site 1039, showing data based on nanofossils, foraminifera, diatoms, and magnetic stratigraphy. Lower right: Stratigraphic units based on drilling. Materials forming these units discussed in text. Dashed lines locate the age of U3A-U3B boundary, marking the high amplitude reflection (R2) in the center of the seismic section (UTIG CR20). From *Kimura et al.* [1997].

reflections occur in this part of the section. While the synthetic seismograms show the dominance of the U3A-U3B boundary in the section (Figure 3), most seismic records produce an associated strong reflection 0.15 seconds beneath this boundary.

[7] Units U3B and U3C are weakly reflective and rest on the top of basement (R3), defined here as the base of the sedimentary section. Unit U3C consists of diatomaceous limestone, ooze and breccia and Unit U4, where drilled, consists of gabbroic sills. The base of the sediments is dated as lower middle Miocene. The R3 reflection often pairs with a lower (0.05 s) and less continuous high amplitude reflection, consisting of gabbroic sills in the Leg 170/205 region. The reflection character of events just above R3 is usually disturbed and weakly reflective.

[8] At Site 1039, we combine the drill and seismic data to determine seismic velocities of the hemipelagic (above reflection R2) and pelagic (below R2) layers. The former has a velocity of 1500 m/s and the latter 1583 m/s. These results are consistent with stacking velocities and allow us to constrain the depths to both the U3A-U3B and basement/sediment contacts away from the drill site throughout the survey region. Timing of tectonic events on the plate is best related to the U3A-U3B (R2) contact. Fossil ages using a combination of diatoms, foraminifera and nanofossils put the age of this boundary at 8 Ma, with an error of less than

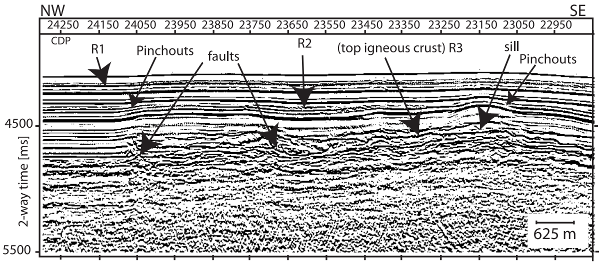

Figure 4. Migrated segment of seismic line EW11, showing sill intrusion and basement faults. Both features are inferred to have been active in the time period 8–10 Ma, based on sediment pinch-outs seen in this profile.

±1 Ma [*Kimura et al.*, 1997]. The very distinctive reflection at this 8 Ma contact provides an excellent, easily traceable datum throughout the survey region.

4. Seismic Correlation of Events

[9] Many of the major crustal features, such as seamounts, transform faults, ridge jumps and ridge propagators, formed early in the history of the Cocos Plate, but a significant number of events also occurred later. Later events include sill intrusion, faulting within the plate, and reactivation of earlier formed structures. Evidence for events during 8–10 Ma includes selective pinching out of strata of this age against faults, seamounts, ridges, or over sills, internal deformation, or faulting of strata through the 8–10 Ma interval. The well-dated reflection R2 (8 ± 1 Ma) is the upper limit of stratigraphy affected by many of these events.

[10] The propagator ridge (Figure 2) on the part of the plate formed by the Cocos-Nazca Spreading Center (CNS) is an early-formed feature, as demonstrated by the magnetic pattern [*Barckausen et al.*, 2001]. Each seismic crossing shows that the full sedimentary section laps undisturbed onto the southern part of the propagator ridge, illustrating an early origin. On some crossings to the north, however, reflection R2 lies unconformably on older units that pinch out against the northern propagator ridge, suggesting minor vertical movement on this part of the feature during 8–10 Ma. Thus, the propagator was formed early in the history of the plate but has had some later (R2) reactivation.

[11] Seismic lines crossing the trace of the triple junction show no sedimentary deformation and very minor reflectivity change in the basement. Thus the triple junction trace provided a smooth transition from CNS to EPR-derived lithosphere. Closer to shore, however, the continuation of this trace is marked by a fracture zone ~80 km long, sharply faulted on its southern edge. This fracture zone trace continues eastward across the Middle America trench and indents the margin bathymetrically [*von Huene et al.*, 2000].

5. Sill Intrusions

[12] Seismic line CR20 acquired by UTIG [*Shipley et al.*, 1992] crosses the location of drill site 1039 (Figure 1), and illustrates the structure of a large sill or zone of sills into which the drilling bottomed [*Kimura et al.*, 1997]. The oldest sediment above the sill is 16–17 Ma and the basement age, based on magnetic anomalies [*Barckausen et al.*, 2001], is 24 Ma. The sills are thus younger than 16–17 Ma, but clearly do not contribute heat at present to the sediments because the measured heat flow at this location is about 8 mW/m^2, based on borehole temperatures [*Kimura et al.*, 1997]. The reflection character of the sill is a high-amplitude, smooth reflection surface. The particular sill drilled in Site 1039 is underlain by another high-amplitude, smooth reflection from gabbroic sills, which has been drilled by ODP Leg 205. Thus we assume that the existence of high-amplitude, smooth, flat surfaces beneath the sedimentary section implies sill intrusion. We infer from the reflectivity character of the base of sediments that at least 75% of the area covered by the Ticoflux dataset consists of sill intrusion.

[13] We image a short, high amplitude reflection (probably a sill) on EWll (cdp 23150) associated with a broad fold in the sedimentary series above it (Figure 4). Sediments just below reflection R2 pinch out over the sill, suggesting an intrusion age of 8–10 Ma. A fault at cdp 24050 cuts the basement section and warps the sedimentary section above, also developing pinch-outs just below R2, suggesting that the fault and the sill were active at the same time.

[14] A short section of seismic line 6 crosses a local zone of erosion of a slope surface (cdp 5500), followed in time by infilling of a small basin (Figure 5). Upslope from this zone of infilling (cdp 5400) is a region of local erosion, likely the source of the in-filled material. This structure indicates local tectonic activity from approximately 10 Ma to 8 Ma, the latter well-constrained by reflection R2.

6. Discussions and Conclusions

[15] We have presented evidence for minor but widespread deformation offshore northern Costa Rica during 8–10 Ma. These movements include sill intrusions, local faulting, and tilting of ridges. A major change in Pacific-Cocos Plate motion occurred about 8 Ma [*Atwater and Stock*, 1998], which could have influenced the structural development of the Cocos Plate. Recently, *Abratis and Wörner* [2001] documented a change in geochemistry of lavas in the Cordillera Talamanca (Figure 1) of Costa Rica from calc-alkaline to alkaline at about 8 Ma. *Abratis and Wörner* [2001] suggested that this change coincides with the collision of the Cocos Ridge (Figure 1) and Costa Rica.

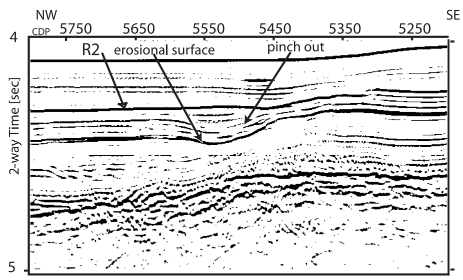

Figure 5. Migrated seismic section from the eastern part of EW6, showing 10 Ma erosional event and pinchout of 8–10 Ma strata. Note thinning of strata above the zone of pinchout and thickening of the same age material below, possibly due to local mass wasting.

They cite evidence for the timing of an effective biogeographic barrier between the Caribbean and Pacific oceans [*Collins et al.*, 1996] and the first unconformities appearing in local sedimentary basins of late Miocene age [*Krawinkel et al.*, 2000].

[16] Models for plate deformation associated with collision events classically focus on the upper plate, with the assumption that the lower plate colliders are rigid [e.g., *Tapponnier and Molnar*, 1976]. Rigidity, however, is a function of the thermal state of the lithosphere [e.g., *Davies*, 1999]. The age of the Cocos plate is 20–24 Ma based on magnetic anomalies, and would have been 12–16 Ma at the time of collision (8 Ma). This younger lithosphere would have been relatively thin and more susceptible to deformation. In addition, the presence of widespread sills having a maximum age of 16 Ma (and likely 13–14.5 Ma) would have produced a warming of the crust at that time, giving it a thermal age of between 5 and 8 Ma at the time of the collision.

[17] Although other factors, such as widespread change in plate motion, may have played a role in the deformation events of 8–10 Ma, we find the possibility of deformation associated with collision of the Cocos Plate, as proposed by *Abratis and Wörner* [2001], a most attractive solution to this problem. Some of the deformation results from reactivation of older tectonic features, such as propagators and fracture zones. Because the rate of convergence is high, this region would have been 500–600 km to the SW of its present location at 8 Ma, consistent with very minor structural features marking the deformation. Sill intrusion associated with activity on the Galapagos hotspot played a key role in both thermally weakening the lithosphere post 16 Ma and in deforming the sediments during the 8–10 Ma event.

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