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2017

Hamahashi, M., Sreaton, E., Tanikawa, W., Hashimoto, Y., Martin, K., Saito, S., & Kimura, G. (2017). Normal faulting and mass movement during ridge subduction inferred from porosity transition and zeolitization in the Costa Rica subduction zone. *Geochemistry, Geophysics, Geosystems*, 18(7), 2601-2616. doi:10.1002/2016gc006577

<https://hdl.handle.net/10356/143268>

<https://doi.org/10.1002/2016gc006577>

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RESEARCH ARTICLE

10.1002/2016GC006577

Special Section:

Subduction Processes in
Central America With an
Emphasis on CRISP Results

Key Points:

- Porosity transition across major seismic reflector in Costa Rica wedge slope was examined to evaluate mechanisms for sediment removal
- Porosity correction for zeolites formed by sediment-fluid interaction reduces estimated normal fault offset and mass movement
- Inferred mass movement, normal faulting, fluid flow, and uplift may be related to Cocos Ridge subduction

Supporting Information:

- Supporting Information S1
- Data Set S1
- Data Set S2
- Data Set S3
- Data Set S4

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Citation:

Hamahashi, M., E. Screaton, W. Tanikawa, Y. Hashimoto, K. Martin, S. Saito, and G. Kimura (2017), Normal faulting and mass movement during ridge subduction inferred from porosity transition and zeolitization in the Costa Rica subduction zone, *Geochem. Geophys. Geosyst.*, 18, 2601–2616, doi:10.1002/2016GC006577.

Received 8 AUG 2016

Accepted 12 JUN 2017

Accepted article online 16 JUN 2017

Published online 17 JUL 2017

Normal faulting and mass movement during ridge subduction inferred from porosity transition and zeolitization in the Costa Rica subduction zone

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Abstract Subduction of the buoyant Cocos Ridge offshore the Osa Peninsula, Costa Rica substantially affects the upper plate structure through a variety of processes, including outer forearc uplift, erosion, and focused fluid flow. To investigate the nature of a major seismic reflector (MSR) developed between slope sediments (late Pliocene-late Pleistocene silty clay) and underlying higher velocity upper plate materials (late Pliocene-early Pleistocene clayey siltstone), we infer possible mechanisms of sediment removal by examining the consolidation state, microstructure, and zeolite assemblages of sediments recovered from Integrated Ocean Drilling Program Expedition 344 Site U1380. Formation of Ca-type zeolites, laumontite and heulandite, inferred to form in the presence of Ca-rich fluids, has caused porosity reduction. We adjust measured porosity values for these pore-filling zeolites and evaluated the new porosity profile to estimate how much material was removed at the MSR. Based on the composite porosity-depth curve, we infer the past burial depth of the sediments directly below the MSR. The corrected and uncorrected porosity-depth curves yield values of 800 ± 70 m and 900 ± 70 m, respectively. We argue that deposition and removal of this entire estimated thickness in 0.49 Ma would require unrealistically large sedimentation rates and suggest that normal faulting at the MSR must contribute. The porosity offset could be explained with maximum 250 ± 70 m of normal fault throw, or 350 ± 70 m if the porosity were not corrected. The porosity correction significantly reduces the amount of sediment removal needed for the combination of mass movement and normal faulting that characterize the slope in this margin.

1. Introduction

The subduction zone offshore Costa Rica (Figure 1a) is an active margin with abundant seismicity, fluid seeps, and mud volcanoes [e.g., *Sahling et al.*, 2008; *Kluesner et al.*, 2013; *Arroyo et al.*, 2014] and is believed to be characterized by subduction erosion [e.g., *Ranero and von Huene*, 2000; *Vannucchi et al.*, 2003]. Offshore the western margin of Costa Rica, the oceanic Cocos Plate subducts under the Caribbean Plate at a convergence rate of ~ 90 mm/yr [DeMets, 2001]. The seafloor offshore the Osa Peninsula stands ~ 2.5 km higher than the surrounding seafloor [Barckhausen et al., 2001; Walther, 2003], due to the subduction of the aseismic Cocos Ridge, a 200 km wide and 1000 km long seamount chain formed at the Galapagos hot spot [Johnson and Lowrie, 1972; Werner et al., 2003] on the eastern edge of the Cocos Plate. The subduction of the buoyant Cocos Ridge has affected the upper plate structure, causing erosion of the outer forearc [Ranero and von Huene, 2000] and the uplift of the Osa Peninsula and the Quepos region [Gardner et al., 1992, 2013; Fisher et al., 1998; Sak et al., 2004].

Seismic reflection images indicate that the upper plate in this region has a densely fractured slope margin, and a widespread high-amplitude major seismic reflector (MSR) separates more intensely deformed material

below characterized by landward dipping reflectors, normal faults, thrusts, and folds, from younger slope sediments above where normal faults are abundant [Shipley *et al.*, 1992; McIntosh *et al.*, 1993; von Huene *et al.*, 2000; Bangs *et al.*, 2015, 2016] (Figures 1b and 1c). The MSR exists above lithified sediments offshore Osa Peninsula [Expedition 334 Scientists, 2012a; Harris *et al.*, 2013a, 2013b, 2013c] (Figures 1b and 1c), whereas the unconformity exists above mafic units offshore Nicoya Peninsula to the north [Kimura *et al.*, 1997; Vannucchi *et al.*, 2001]. Investigation of the nature of the MSR and upper plate structure and their differences along strike is important because these features potentially provide keys to understanding the tectonic and depositional history of the margin and the process of subduction erosion.

Seismic reflection, backscatter, and multibeam bathymetry studies have mapped multiple faults that cut through the MSR and identified potential seafloor seepage structures and fluid distribution below from high-backscatter anomalies, bathymetric expressions (e.g., pockmarks, mounds, and ridges), amplitude anomalies, and zones of seismic disturbance on the shelf and slope regions [Ranero *et al.*, 2008; Sahling *et al.*, 2008; Kluesner *et al.*, 2013]. These fluid seepage indicators lie along mapped fault traces and folds, suggesting that structurally controlled pathways allow fluids and gases to migrate through the margin slope and landward shelf [e.g., Kluesner *et al.*, 2013; Bangs *et al.*, 2015]. The inferred structurally controlled fluid flow may allow fluid escape from the plate boundary fault and thus increase effective stress and potentially affect the aseismic to seismogenic transition in the upper plate [e.g., Ranero *et al.*, 2008].

The Costa Rica Seismogenesis Project (CRISP) was designed to illuminate the factors that control nucleation and seismic rupture of large earthquakes at erosional subduction zones [Vannucchi *et al.*, 2012; Harris *et al.*, 2013a]. CRISP drilling penetrated the MSR offshore Osa Peninsula beneath the slope sediments at the upper slope Site U1379 during Integrated Ocean Drilling Program (IODP) Expedition 334, and at the middle slope Site U1380 during IODP Expedition 344 (Figure 1).

Vannucchi *et al.* [2013] inferred uplift based on benthic foraminifera distribution of abyssal species in the ~2.46–2.56 Ma lithified sediments below the MSR and beach species in the ~1.59 Ma slope sediments above the MSR at the upper slope Site U1379. Uplift, sedimentation, and subsidence must all have occurred quickly since the age gap across the MSR is < ~0.87 Ma. The rapid uplift from ~800 m seawater depth to near-shore conditions is suggested to have occurred in an older forearc basin in the early Pleistocene (2.3–2 Ma) [Vannucchi *et al.*, 2013, 2016]. This uplift is roughly coincident with the onset of Cocos Ridge subduction, which is reported to have begun 3–2 Ma [Morell, 2015] to 1 Ma [Lonsdale and Klitgord, 1978; Gardner *et al.*, 1992] based on plate reconstructions, chronostratigraphic records, and geophysical surveys.

In this paper, we investigate the nature of the MSR, fluid flow, and the physical property evolution in the upper plate. We use microstructural observation and X-ray fluorescence/diffraction analysis to examine the occurrence of zeolites across the MSR and to correct porosity values for pore-filling zeolites, focusing on the middle slope Site U1380. We then evaluate the porosity profile and compaction curve to infer how much material was removed at the MSR with and without the corrections for zeolites. Finally, we discuss possible mechanisms for the sediment removal (mass movement and normal faulting) based on estimated material flux and interpretations on seismic profiles.

2. Background of Study Area: CRISP Middle-Slope Site U1380

Site U1380 is located on the middle slope of the Costa Rica margin, 38 km offshore Osa Peninsula, and 24 km from Cano Island along seismic Line BGR99–7, penetrating down to 800 mbsf at a water depth of 502.7 m (Figure 1). The plate boundary is ~3.4 km below the seafloor in this area, and interplate earthquakes and geodetic measurements indicate that this site is seaward of the updip extent of plate interface

Figure 1. (a) Topographic and bathymetric map of the study area along the Middle America Trench offshore Costa Rica and the subducting Cocos Ridge, modified from Harris *et al.* [2013a]. The seafloor bathymetry presented here is based on satellite gravimetry and swath mapping [Barckhausen *et al.*, 2001; Fisher *et al.*, 2003; von Huene *et al.*, 2000]. Inset: The plate tectonics background of this region. NA: North American, CA: Caribbean, SA: South America, CO: Cocos Plate, PA: Pacific, EPR: East Pacific Rise, CNS: Cocos-Nazca Spreading Center, NZ: Nazca. (b) Seismic Line BGR99–7 along the drilling transect of Expedition 344 from C. R. Ranero, unpublished data reproduced in Harris *et al.* [2013a]. (c) Structural interpretation of the wedge based on the seismic image of Figure 1b. Black line: the major seismic reflector (MSR) beneath the slope. Purple line: the plate boundary. Shaded green: the wedge margin beneath the MSR. Green line: the land-ward dipping reflectors in the wedge margin beneath the MSR. Shaded yellow: the frontal accretionary prism. Orange line: the land-ward dipping reflectors in the frontal prism. Shaded light brown: the slope cover above the MSR. Shaded pink: the subducting Cocos Plate.

seismicity [e.g., Arroyo *et al.*, 2014]. In this study, we combine information from two holes at Site U1380 with information from one hole at Site 1378 [Expedition 334 Scientists, 2012b, 2012c; Harris *et al.*, 2013b] (Figures 1 and 2). Site U1378 is located ~0.9 km southwest of Site U1380 and provides data on the porosity of the uppermost ~400 m, which were not drilled at Site U1380.

At Site U1380, the upper plate material beneath the MSR at 551.48 mbsf is lithified, low porosity sediment consisting of clayey siltstone with medium to coarse sandstone of Unit 2 and silty claystone with fine sandstone of Unit 3 (Figure 2a). Above the MSR is the high porosity slope sediment of Unit 1 consisting of silty clay with fine sandstone (Figure 2a). In the upper portion of Unit 2, ~11.4 m of poorly consolidated sandstone layers partially lithified by cement containing abundant shell fragments are distributed. These coarser sand deposits in Unit 2 indicate a shelf sequence which may be associated with a change in depositional environment [Harris *et al.*, 2013b].

Foliation intensity, as characterized by preferred alignment of platy minerals, increases progressively downhole toward the MSR in Unit 1. A strongly foliated interval with abundant deformation bands and veins was identified in the recovered cores between 496.37 mbsf and ~2.5 m above the MSR (548.98 mbsf). This ~53 m thick damage zone contains slickenlines that are consistent with fault activity occurring at this horizon [Harris *et al.*, 2013b]. Shipboard fault kinematic analyses inferred a normal fault paleostress regime with σ_1 oriented vertically and σ_3 oriented in a northeast-southwest direction similar to the plate convergence direction [Harris *et al.*, 2013b]. This interpretation is consistent with the current stress state (maximum horizontal stress: NNE-SSW) inferred from borehole breakouts detected by logging-while-drilling and wireline downhole measurements within the deepest intervals at Site U1379 [Malinverno *et al.*, 2016]. In contrast, borehole breakouts suggest a maximum horizontal stress oriented NNW-SSE in the shallow portion at Site U1378.

Based on calcareous nannofossil zonation schemes from Martini [1971], Bukry [1973, 1975], and Okada and Bukry [1980], the sediments above and below the MSR were both assigned to the NN 18 zone, indicating an age between 2.44 and 1.95 Ma [Harris *et al.*, 2013b] (Figure 2a). Sediments in this zone are 272 m thick and sedimentation rates of ~555 m/Ma (272 m/0.49 Ma) were calculated [Harris *et al.*, 2013b]. Any age gap across the MSR must also be within the 0.49 Ma window (2.44–1.95 Ma).

Heavy hydrocarbons are present in pore waters from ~450 to 551.48 mbsf of Unit 1. Elevated Li values and low concentrations of Cl were also measured, suggesting fluid migration from a deeper region with temperatures high enough to allow smectite dehydration and thermogenic hydrocarbon generation. This interval of fluid migration may be related to the strongly foliated zone described between 496.37 and 548.98 mbsf [Harris *et al.*, 2013b]. Below the MSR (552 mbsf), heavy hydrocarbons are not present and Li decreases sharply [Harris *et al.*, 2013b]. Cl shows a slight increase in concentration, but is still dilute relative to seawater. Interpreted temperatures of the fluid source are between 60°C and 80°C to allow smectite dehydration but no thermogenic hydrocarbons [Harris *et al.*, 2013b]. Ca concentrations increase from below seawater values at ~450 mbsf to ~3 times seawater values at the base of the drilled section [Harris *et al.*, 2013b].

Sharp boundaries in shipboard measurements of porosity and P-wave velocity between Units 1 and 2 correspond to the MSR shown in the seismic profile [Harris *et al.*, 2013b] (Figure 2b). Units 2 and 3 have lower porosity (~22–37%) than Unit 1 (~41–71%), and P-wave velocities measured from discrete samples in Unit 1 (~1540–1920 m/s) are lower than that in Unit 2 (~2060–2560 m/s) (Figure 2b). Coincident with porosity, sample bulk density is lower (~1460–2040 kg/m³) in Unit 1 than Units 2 and 3 (~2070–2280 kg/m³), while grain density is relatively consistent throughout Units 1–3.

3. Laboratory Methods

3.1. Resistivity Measurement and Physical Property Cross-Correlation

To examine the consolidation trend of the sediments, electrical resistivity was measured with an Agilent 4294A component analyzer (Agilent Technologies, USA) using the bridge method with a two-terminal circuit for cubic samples (supporting information Text S2). Twenty five discrete sediment samples from Site U1380 were cut in specimen cubes parallel to the depth (z) direction of the borehole, and the horizontal plane was polished for measurement. Samples were impregnated with seawater for 10 h until sample mass

Figure 2. (a; left) Prestack time-migrated depth section along the seismic Line BGR99-7 centered at Site U1380 [C. R. Ranero, unpublished data reproduced in Harris *et al.*, 2013b] (black box). Yellow dotted line: MSR. Blue dotted line: the drilled range at Site U1380 during Expedition 344. (right) Lithostratigraphic summary of Site U1380C and representative image of sediment drill cores from Units 1, 2, and 3 from Harris *et al.* [2013b]. Biostratigraphic zones determined by nannofossil content and paleomagnetostratigraphy (Black: normal polarity, white: reversed polarity, gray: uncertain polarity) during Expedition 344. (b; left) Close-up section of seismic Line BGR99-7 at Site U1380. Red bar: MSR. Blue bars: landward-dipping reflectors. (right) Physical property results obtained during Expedition 344 [Harris *et al.*, 2013b]: Discrete sample porosity, grain density, wet bulk density, and P-wave velocity measured on split cores perpendicular to the core axis. Red and blue horizontal lines: the lithostratigraphic unit boundaries and physical transitions that correlate with the seismic reflectors at this horizon.

stabilized and resistivity was measured every ~ 1.5 h. The magnitude ($|Z|$) and phase (θ) of the complex impedance were measured at 10 kHz and 1000 mV by the inductance (L), capacitance (C), and resistance (R) (LCR) meter between opposite cube faces sandwiched with brass electrodes and insulated rubber pads. Electrical resistivity in the z direction was computed from the measured complex impedance and sample dimension defined by face lengths.

We used cross-plots of porosity and resistivity to determine the cementation exponent and consolidation state of sediments [e.g., *Ewing and Hunt, 2006; Montaron, 2009; Kozlov et al., 2012*] across the lithologic units. The approximate correlation between porosity and resistivity is known as Archie's law [*Archie, 1942*]:

$$F = R_{\text{eff}} / R_f = b \varphi^{-m} \quad (1)$$

where F is the formation factor, R_{eff} is the resistivity of fluid-saturated rock, R_f is the resistivity of the fluid within the rock, φ is the porosity of the rock, b and m ("cementation exponent") are fitting parameters.

3.2. Optical Microscopy, Field Emission Scanning Electron Microscopy (FE-SEM), Energy Dispersive X-Ray Spectrometry (EDS), and Particle-Size Analysis

Oriented samples were impregnated with resin and polished and made into thin sections for microstructural observation (supporting information Text S2) in the vertical and horizontal direction for each sample. Sixty samples from Site U1380 were examined on an optical microscope (BX51TRD, OLYMPUS Corporation, Japan). Fourteen samples were examined on a Hitachi S-4500 (Hitachi High-Technologies Corporation, Japan) field emission scanning electron microscope (FE-SEM). Standard operating conditions were 15 kV acceleration voltage and 15 μA emission current. Secondary electron (SEM) and backscattered electron (BSE) imaging was used to determine mineralogy and texture. Qualitative and quantitative elemental analyses of selected phases were performed using an energy-dispersive X-ray spectrometer (EDS). Thirty nine samples were analyzed for particle size measurement using the Malvern Mastersizer 2000 laser diffraction particle size analyzer (Malvern Instruments Ltd, UK).

3.3. X-Ray Fluorescence Analysis (XRF) and X-Ray Diffraction Analysis (XRD)

The concentration of 10 major elements for 38 samples from Site U1380 were determined by X-ray fluorescence (XRF) analysis of fused glass disks, using an XRF spectrometer PANalytical Axios (PANalytical, The Netherlands) equipped with Rh tube (supporting information Text S2). The measurement settings were at 60 kV and 66 mA for Fe_2O_3 and MnO , at 40 kV and 100 mA for TiO_2 , and at 32 kV and 125 mA for SiO_2 , Al_2O_3 , MgO , CaO , Na_2O , K_2O , and P_2O_5 .

Relative mineral proportions in thirty seven bulk samples recovered from Site U1380 and five samples from Site U1413 were examined from powder X-ray diffraction (XRD) patterns which were recorded using a PANalytical X'Pert PRO MPD X-ray diffractometer system (PANalytical, The Netherlands) with $\text{CuK}\alpha$ radiation (supporting information Text S2). The measurements were taken at 45 kV and 40 mA, with 0.8 mm-thick 0.25° and 0.3 mm-thick 0.125° divergence slits, a 6 mm-thick antiscattering slit and a receiving slit, at a scan rate of 0.006° per minute at a scan step of 0.008° in 2θ , over a 4° – 34° 2θ range. Diagnostic reflections from individual mineral species were processed using the standard PANalytical peak analysis software. To distinguish the peak between heulandite and clinoptilolite at $9.91^\circ 2\theta$, and laumontite and plagioclase at $12.45^\circ 2\theta$, bulk powders were heated in an oven at 350°C for 8 h, and XRD patterns for the heated and non-heated samples were compared [e.g., *Alietti, 1972*]. For the clay mineral analysis, bulk powders were gently crushed, dispersed ultrasonically in distilled water, and the clay fraction ($<2.0 \mu\text{m}$) was separated by centrifugation. The expandability of smectite was determined from the saddle/peak ratio of 001 reflection in ethylene-glycol-treated XRD pattern. XRD patterns for the oriented mounts were recorded at a scan rate of 0.03° per minute over 3 – $23^\circ 2\theta$ range.

For the quantitative analysis of XRD patterns of zeolites, we prepared 83 samples from Site 1380 mixed individually with standards of analcime, laumontite, and heulandite of known weight, and conducted XRD using the natural samples and standard-mixed samples. The zeolite abundance in each natural sample was obtained from the relationship between the intensity of diagnostic reflection and the weight % of each zeolite by plotting the results from the standard-mixed samples and natural samples.

4. Results

4.1. Consolidation Trend Based on Microstructural Observation and Physical Properties

Based on microstructural observation of representative samples from Site U1380, Unit 1 sediments consist of large particle-sized lithic fragments, with various major minerals such as smectite, chlorite, quartz, plagioclase, calcite, and zeolites (Figure 3, supporting information Figure S1). Sand tends to increase in abundance and particle size with depth in Unit 1.

Across the MSR, where porosity decreases significantly in Unit 2, a sharp contrast in microstructure is observed (Figure 3, supporting information Figure S2). Siltstone, sandstone, and conglomerate layers are moderately cemented by calcite, and the coarse-grained lithic and biogenic materials tend to build cohesive microstructures where they are common. Lithic fragments become smaller and form more cohesive structures with depth in Unit 2 (Figure 3, supporting information Figure S3). The microstructure of representative samples from Unit 3 gradually changes to a more homogeneously dense texture formed by smaller lithic fragments, where coarse sands are less abundant and grains are more well-sorted with depth (Figure 3, supporting information Figure S3).

The average grain size of the sediments obtained from the particle size analyses does not vary significantly between Units 1 and 2 across the MSR, indicating that the effect of grain-size difference on the porosity-depth transition is minimal at this horizon (Figure 3, supporting information Data Set S1). The overall

Figure 3. (left) Results of the measured average particle size of Site U1380 sediments in this study. Clay, silt, sand volume% were derived from the particle size fraction. Red-dotted lines: lithostratigraphic unit boundaries. (right) Representative optical microscopic images of the sediments. Depths of imaged samples are shown in white.

volume % of clay, silt, and sand in the sediments derived from particle size analysis range from ~60%–75%, ~25%–30%, and ~10%–25%, respectively in Units 1, 2, and 3 (Figure 3).

4.1.1. Cross Correlation of Resistivity, P-Wave Velocity, and Porosity

To determine the relationship between the geophysical signatures and lithologic units, we examined the cross-plot between shipboard porosity and P-wave velocity (Figure 4). The velocity values of Unit 1 can be fit by the empirical relationship described by *Hoffman and Tobin* [2004] from the underthrust sediments in the Shikoku basin of the Nankai Trough drilled during Ocean Drilling Program Legs 131, 190, and 196 (Figure 4a). In contrast, the values of Units 2 and 3 mostly plot above the curve (Figure 4a).

Figure 4. (a) Cross-correlation between the shipboard discrete sample porosity and P-wave velocity measurements for sediments recovered from Site U1380. Open circles: Unit 1. Closed circles: Units 2 and 3. Dotted lines: the approximate curve derived from the Shikoku Basin sediments from *Hoffman and Tobin* [2004] for comparison. (b) Results of the resistivity measurements obtained from Site U1380 in this study. Open diamond: Unit 1. Closed diamonds: Units 2 and 3. (c) Cross-correlation between shipboard porosity and measured resistivity (b) in this study. Black approximate line: the exponential curve of Archie's law at Site U1380 ($m = 1.36$) with reference to the curves for the Japan Trench Site 438A (DSDP Leg 57) ($m = 1.09$) and Nankai Trough Kumano Site C0002B (IODP Exp. 315) ($m = 1.06$) [Shipboard Scientific Party, 1980; Expedition 315 Scientists, 2009].

The electrical resistivity values obtained from the discrete sample measurement in the present study are higher in Units 2 and 3 (~ 1.62 – $4.28 \Omega\text{m}$) compared to Unit 1 at 474.6 mbsf ($\sim 1.53 \Omega\text{m}$) (Figure 4b, supporting information Data Set S2). The best fit to Archie's law (equation (1)) yields $m = 1.36$ and $b = 1219$ ($R^2 = 0.44$) (Figure 4c). The relatively high m value suggests a high consolidation trend (high resistivity increase) in the porosity range of $\sim 20\%$ – 55% .

4.2. Element and Mineral Composition of the Sediments: Zeolite Assemblage and Their Weight Percentage

The results from XRF analysis reveal that Al_2O_3 , K_2O , and TiO_2 are more abundant in the higher porosity sediments of Unit 1, whereas SiO_2 , CaO , P_2O_5 , MgO , Na_2O , and MnO are higher in the lower porosity sediments of Units 2 and 3 (Figure 5, supporting information Data Set S3). The transitions in element composition between Units 1 and 2 are likely to reflect the trends in mineral assemblage of the sediments.

Major mineral components of the sediments revealed from XRD are phyllosilicates including chlorite and smectite, quartz, plagioclase, calcite, and zeolite (supporting information Figure S5, Data Set S4). The mineral components across the MSR are marked by the transitions in zeolite composition among the Na-type zeolite analcime ($\text{NaAlSi}_2\text{O}_6 \cdot \text{H}_2\text{O}$), the Na/Ca-type zeolite heulandite ($(\text{Ca}, \text{Na}_2)\text{Al}_2\text{Si}_7\text{O}_{18} \cdot 6\text{H}_2\text{O}$), and the Ca-type zeolite laumontite ($\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 4\text{H}_2\text{O}$) (Figure 5). The zeolite composition in Unit 1 consists mainly of heulandite and laumontite, and below the MSR in Unit 2, the sediments consist of heulandite, laumontite, and analcime (Figure 5). Beneath the porosity increase in Units 2 and 3, laumontite is less abundant, and heulandite and analcime become the major zeolites. The quantitative bulk analyses for the zeolites revealed that the weight percentages of heulandite and laumontite in Unit 1 range from 0.5% to 1.8% and from 0% to 4.5%, respectively, whereas those of analcime, heulandite, and laumontite in Unit 2 are 2.8%–23%, 0.6%–2.1%, 0%–4.2%, respectively (Figure 5). In Unit 3, the weight percentages of analcime, heulandite, and laumontite are 6.8%–7.9%, $\sim 1.2\%$ – 1.7% , and 0%–3.1%, respectively (Figure 5). From the clay fraction XRD analysis, smectite and chlorite were identified in all samples. Other than the changes described for the zeolites, the sediments do not exhibit significant changes in mineral assemblage.

4.2.1. Zeolite Occurrence and Implied Conditions

The observations of zeolites and whether they are detrital or authigenic provide insight to the conditions of zeolite formation experienced in the sediments and the effect of mineral precipitation on porosity. The

Figure 5. Major element (SiO_2 , Al_2O_3 , Fe_2O_3 , MnO , MgO , CaO , Na_2O , and K_2O) weight percent (%) from XRF analysis and weight percent (%) of heulandite, laumontite, and analcime from bulk XRD quantitative analysis of sediment samples at Site U1380. Red-dotted lines: lithostratigraphic unit boundaries. Arrows: transitions in element composition.

analclime in Units 2 and 3 is observed mainly as $\sim 50 \mu\text{m}$ -sized particles among lithic fragments under the optical microscope and are not likely to be filling the pores, indicating that they may be detrital (supporting information Figure S4). In contrast, the laumontite and heulandite in Units 1, 2, and 3 are present within biogenic shells, pores, and partial veins, and are likely to be pore-filling rather than detrital (supporting information Figure S4). The laumontite and heulandite have much smaller crystal sizes ($< 50 \mu\text{m}$) as compared to analclime, especially in Units 2 and 3.

Generally, Na/Ca-type zeolite heulandite and Ca-type zeolite laumontite transforms from clinoptilolite by an interaction with plagioclase, Ca-rich pore water, and/or dissolved carbonates through microdissolution-precipitation, initiated by the geochemistry of pore fluid and/or increase in temperature [e.g., Coombs *et al.*, 1959; Iijima and Utada, 1972; Boles, 1971; Iijima, 1986; Yoshimura, 1994; Ogiwara, 1996]. The authigenic zeolites heulandite and laumontite in Units 1, 2, and 3 (Figure 5) are likely to have formed through interaction with Ca-rich pore fluid originating from silicic volcanic glass and clinoptilolite. Shipboard pore water geochemistry results show Ca rising to 3 times seawater values between 450 mbsf and the base of the borehole (section 2) [Expedition 334 Scientists, 2012b; Harris *et al.*, 2013b; Ross *et al.*, 2015]. The zeolite distribution in this study and the pore water geochemistry results both support focused Ca-rich fluid flow across the MSR. Heulandite and laumontite were also present at the interval between 40 and 582.2 mbsf at the upper slope Site U1413 based on XRD measurements in this study (supporting information Text S1, Figure S6), also supporting possible migration of Ca-rich fluids that are consistent with shipboard pore water geochemistry (supporting information Text S1) [Harris *et al.*, 2013c].

4.2.2. The Effect of Zeolite Precipitation on the Porosity Decrease at the MSR

Secondary consolidation across the MSR due to pore-filling laumontite and heulandite will reduce sediment porosity. The value of porosity filled by fluid-interacted zeolites can be calculated from the weight and density of the zeolites (equation (2)).

$$\varphi_z = V_z \div V_B \times 100 = (W_z \div D_z) \div (100 \div D_B) \times 100 \quad (2)$$

where φ_z is the porosity (%) filled by zeolite, V_z is the volume of zeolite, V_B is the total bulk volume, W_z is the weight percentage of zeolite, D_z is the density of zeolite, and D_B is the bulk density of the sediments.

We quantified the porosity φ_z filled by laumontite and heulandite using W_z obtained from the quantitative bulk XRD analyses (section 4.2 above), the D_z values of laumontite (2.3 g/cc) and heulandite (2.2 g/cc) referring to Anthony *et al.* [2016], and the D_B obtained from the shipboard measurements (~ 1.9 – 2.2 g/cc). The results from representative samples reveal that the porosity filled by laumontite is 0%–3.8% in Unit 1, 1.9%–4.0% in Unit 2, and 0%–2.6% in Unit 3, whereas heulandite fills 0.5%–1.8% in Unit 1, 0.6%–2.1% in Unit 2, and 1.2%–1.7% in Unit 3. The total amount of filled porosity due to zeolite formed during the sediment-fluid interaction (i.e., laumontite and heulandite) is 0.5%–4.8% in Unit 1, 0.8%–4.7% in Unit 2, and 1.7%–4.3% in Unit 3. The correction shifts the compaction curve to higher porosity above and below the MSR, increases the slope/inclination of the porosity-depth curve in Unit 1 and decreases the porosity gap across the MSR by $\sim 1.8\%$ (Figure 6).

4.3. Inferred Sediment Removal and Past Burial Depth Across the MSR

A significant porosity gap between Units 1 and 2 across the MSR remains after correction for zeolite precipitation (Figure 6). Although rapid sedimentation could cause undercompaction, it cannot explain the sharp porosity difference between Units 1 and 2. Thus, to explain the difference in consolidation across the MSR, there must have been material removed between Units 1 and 2.

The consistent burial compaction trend after correcting for the effect of secondary consolidation by zeolites (section 4.2.2) allows us to assume a composite porosity-depth curve among Units 1, 2, and 3, and assess the initial burial depth and thickness of sediment removal from the porosity gap across the MSR (Figure 7a). The porosity-depth curve of the sediments corrected for zeolites is best-fit by an exponential curve ($y = 67e^{-0.0007x}$, $R = 0.90$) (Figure 7a). The initial burial depth range is inferred as 800 ± 70 m from the depth where the approximate curve and its 95% confidence band intersect with the mean porosity range of $37.8\% \pm 1.2\%$ (95% confidence interval) below the MSR at the top of Unit 2 (Figure 7a). If the materials were removed completely above this past burial depth prior to deposition of Unit 1, the thickness of missing sediments would range 800 ± 70 m.

Figure 6. Porosity-depth profile of the sediments at Site U1380. Red circles show the shipboard porosity data and yellow circles show the porosity data corrected for the effect of zeolites due to fluid-sediment interaction (laumontite and heulandite) in this study. Black-dotted line: location of the MSR between Units 1 and 2.

In contrast, when using the porosity-depth curve that is not corrected for zeolites, the intersection between the approximate curve of Unit 1 ($y = 68e^{-0.0008x}$, $R = 0.93$) and the mean porosity range directly below the MSR ($33.4\% \pm 1.2\%$) infers the past burial depth range of 900 ± 70 m in Unit 2 (Figure 7b). This indicates a larger removal of sediments compared to the result corrected for zeolites above.

5. Discussions

5.1. Possible Mechanisms for Sediment Removal Across the MSR

The initial burial depth of sediments below the MSR was inferred from the porosity-depth curve corrected for the effect of secondary consolidation by zeolites (section 4.3). This allows estimation of the thickness of sediment removed. One possibility for the mechanism of sediment removal across the MSR is mass movement that exposed Unit 2 at the seafloor. However, additional considerations suggest that it is unlikely that the entire differ-

ence in consolidation can be attributed to seafloor removal. If the 800 ± 70 m thick sediments derived from corrected porosity were to have deposited and removed completely by a marine mass movement within the age gap of $< \sim 0.49$ Ma, unrealistically high sedimentation rates of at least 1640 ± 150 m/Ma at Site U1380 (800 ± 70 m/ 0.49 Ma) would be required. We suggest instead that sediment removal was caused partly by younger sediments sliding downward due to normal fault displacement across the MSR during or after the deposition of Unit 1 after the mass movements above Unit 2. With complete mass removal, all the material above the MSR would have been removed and then 551.48 m of sediments deposited. In contrast, normal fault movement requires less deposition of sediments within the age gap because the footwall is still overlain by some hanging wall sediments.

If the entire exhumation suggested from the porosity-depth curve is due to normal faulting, the normal fault displacement would be 250 ± 70 m (1100 ± 740 m parallel to the fault plane given a dip angle of $\sim 10^\circ$ – 30°), which is obtained by subtracting the maximum sediment removal (800 ± 70 m) by the current thickness of Unit 1: 551.48 m above the MSR. This assumes that the normal fault slip occurred after the full deposition of Unit 1. If the normal faulting occurred earlier before full deposition of Unit 1, the throw must be greater to allow the 800 ± 70 m burial of Unit 2.

In contrast, the inferred sediment removal derived from uncorrected porosity (900 ± 70 m) would require normal faulting with a larger offset (350 ± 70 m), obtained by the same method as above. The porosity correction in this study helps to better constrain sediment removal and initial burial depth and to test whether normal fault displacement is required to explain the observed porosity difference across the MSR.

Figure 7. Porosity-depth relationship of Site U1380 Units 1, 2, and 3 sediments. (a) Black dots: porosity corrected for the effects of zeolites due to fluid-sediment interaction (laumontite and heulandite) in Unit 1 ($y = 67e^{-0.0007x}$, $R = 0.90$). Red line: Approximate curve for the corrected porosity of Unit 1. Green lines: 95% confidence band for the porosity of Unit 1. Green-dotted lines: the estimated extension of the 95% confidence band. Gray dots: porosity corrected for the zeolites in Units 2 and 3, shifted to its inferred initial burial depth. Blue bar: 95% confidence interval of the porosity ($37.8\% \pm 1.2\%$) of Unit 2 directly below the MSR. Gray-colored bar: the estimated initial burial depth of Unit 2 below the MSR (800 ± 70 mbsf) and its error range, derived from the intersection of the porosity range of Unit 2 directly below the MSR and the approximate curve of Unit 1. (b) Black dots: uncorrected porosity in Unit 1. Red line: Approximate curve for the uncorrected porosity of Unit 1 ($y = 68e^{-0.0008x}$, $R = 0.93$). Green lines: 95% confidence band for the porosity of Unit 1. Green-dotted lines: the estimated extension of the 95% confidence band. Gray dots: uncorrected porosity in Units 2 and 3, shifted to its inferred initial burial depth. Blue bar: 95% confidence interval of the porosity ($33.4\% \pm 1.2\%$) of Unit 2 directly below the MSR. Gray-colored bar: the estimated initial burial depth of Unit 2 below the MSR (900 ± 70 mbsf) and its error range, derived from the intersection of the porosity range of Unit 2 directly below the MSR and the approximate curve of Unit 1.

Although we do not have the zeolite information to correct the Site U1379 porosity profile, we can compare the shipboard porosities. The shipboard porosity gap ($\sim 16\%$) observed at Site U1379 at 879.90–881.75 mbsf across the MSR is 6% larger than the shipboard porosity gap at Site U1380 ($\sim 10\%$) (supporting information Text S1, Figure S7). The larger porosity gap at Site U1379 suggests a greater initial burial depth and a larger amount of sediment removal in the upper slope than in the middle slope, which may indicate that normal fault displacement must also contribute to the porosity gap in the upper slope.

5.2. Integration of Results With the Structures From the 2-D Seismic Profile BGR99-7 at Site U1380

Normal faulting is supported by the structure of the fault zones and normal fault stress regime observed from the drilled cores [Harris *et al.*, 2013b] and is also consistent with the dense pattern of interpreted normal faults in the outer shelf based on multibeam bathymetry, backscatter, and 3-D seismic data [Kluesner *et al.*, 2013; Bangs *et al.*, 2015, 2016]. The missing material (800 ± 70 m) across the MSR (section 5.1) could possibly all be due to normal fault offset (250 ± 70 m) with no mass movement. However, from the enlarged prestack time-migrated seismic Line BGR99-7 near the middle-slope Site U1380 [C. R. Ranero, unpublished data reproduced in Harris *et al.*, 2013b] (Figure 8a), we infer uplift and seafloor erosion across the MSR based on the

seismically imaged erosional contact that cuts the landward-dipping reflectors in the margin wedge below (Figure 8a). Above the MSR, zones of disrupted and poorly defined seismic reflections may represent mass transport deposits (shaded blue in Figure 8a). Mass movement, possibly induced by uplift events, likely occurred along the slope, although the offset is difficult to decipher from the seismic image (Figure 8a).

Figure 8. (a) Structures interpreted from the enlarged prestack time-migrated seismic Line BGR99-7 near the middle-slope Site U1380 [Harris *et al.*, 2013b] in this study (Figure 2). (b–d: left) Inferred structural development in the order of occurrence with progressing time (t1–t4). (right) Schematic cartoon showing evolution of porosity-depth profile of sediments with time. Brown box: sediment column. Blue line: porosity-depth curve. Red dot: sediments directly beneath the current MSR. Red line: normal fault cutting across the MSR. (b) Uplift and erosion of the wedge (shaded green) involved mass movement, creating the MSR (black line) and cutting the land-ward dipping reflectors (green lines) below. (c) Slope sediments (colored orange) and mass transport material (colored blue) were deposited above the MSR and formed porosity transition. The mass movement (along the red-dotted line) may have created additional erosion (blue-dotted line) followed by slope sediment deposition. Mass movements have also occurred in the shallow portion of the slope. (d) The MSR and sedimentary layers were cut by abundant normal faulting (red lines) and formed the current porosity gap between Units 1 and 2. In later stage, sediments incur folding.

The multiple normal faults that are occasionally cutting across and distributed near the MSR (shown in red lines in Figure 8a; vertical exaggeration: ~ 200) also dip near-horizontally with vertical lengths of ~ 100 – 400 m and vertical offset of each fault that range ~ 10 – 30 m. These individual amounts of vertical throw are smaller than the normal fault displacement derived in the current study, which may suggest that movement by multiple faults accumulated to cause the porosity difference across the MSR, rather than a single fault.

By integrating the results from the drill cores in this study and the inferred structures from seismic Line BGR99-7, we suggest the following structural development of the wedge slope, in accordance with the porosity evolution of the sediments (Figures 8b–8d). The sediments of Unit 2 and 3 were compacted and uplifted, and overlying materials were partly removed due to mass movement (Figure 8b). This mass movement was followed by deposition of Unit 1 sediments associated with mass transport deposits in the slope, attributing to porosity transition across the MSR (Figure 8c). Later, abundant normal faulting cut across the MSR, and the combined effect of mass movement and fault displacement caused the current porosity difference between Units 1 and 2 (Figure 8d). The Ca-rich fluid is inferred to have flowed from depth focused by fault zones across the MSR [Expedition 334 Scientists, 2012b; Harris et al., 2013b; Ross et al., 2015], and formed the heulandite and laumontite causing secondary consolidation of the sediments.

Tectonic uplift is inferred by Vannucchi et al. [2013] to have occurred 2.3–2 Ma. The distribution of the ~ 11.4 m thick, coarser grained unconsolidated sand layer containing abundant shell fragments in the upper section of Unit 2 [Harris et al., 2013b] indicates that the sediment removal occurred in a near-shore shelf environment, associated with the inferred uplift. Mass movement in the slope may have occurred due to gravity collapse during uplift and heterogeneous slope angle as inferred from the differences in the depth of the MSR between Sites U1380 and U1379. Normal faulting in the shallow portion of the wedge is probably due to the extensional stress regime that initiated during these events.

From the seismic data, zones of poorly defined reflection layers are interpreted as mass transport deposits in the shallower regions of the slope (Figure 8c), suggesting that multiple events of mass movement occurred, accompanied by normal faulting along nearly horizontal planes, although there is no significant porosity gap within Unit 1. These erosional contacts may be related to uplift events in the past 1.9 Ma and 0.5 Ma based on benthic foraminifera inferred by Vannucchi et al. [2013] at Sites U1379 and U1378, respectively. The MSR and sedimentary layers were later folded by recent compression, cut by and associated with abundant faults (Figure 8d).

The mass movement, fluid flow, and faulting across the MSR inferred from the upper and middle slopes offshore Osa Peninsula may have been regional rather than rearranging sediments locally. The time range of the sediment removal (2.20–0.25 Ma) inferred from nannofossil age of the sediments between Units 1 and 2 are consistent with the timing of the arrival of the Cocos Ridge offshore the Osa Peninsula, i.e., ~ 3 – 1 Ma, as reported from on-land chronological studies and recent modern plate reconstructions [e.g., Morell, 2015]. Thus, the subduction of the Cocos Ridge and other associated seamounts could provide the mechanism for the mass movement, normal faulting, uplift, and fluid flow in the slope of the upper plate inferred from the present study.

The sediment-dominated upper plate offshore Osa Peninsula hosts a complex system evolving through these multiple-phased events of uplift, erosion, and recent compression [e.g., Bangs et al., 2016; Vannucchi et al., 2016] that are well recorded near the MSR as examined in this paper. The MSR offshore Osa is distinct from the unconformity developed above the mafic units offshore Nicoya Peninsula to the north [e.g., Kimura et al., 1997; Vannucchi et al., 2001], and the variability along the trench could possibly be due in part to the effect of Cocos Ridge subduction to the south. This fractured margin is also an active region of vigorous fluid flow focused along faults and permeable zones inferred from geophysical surveys [e.g., Ranero et al., 2008; Sahling et al., 2008; Kluesner et al., 2013], pore water geochemistry studies [e.g., Vannucchi et al., 2012; Harris et al., 2013b, 2013c], and the zeolite assemblages in this study. This paper has tested and revealed the impact of pore-filling minerals (e.g., zeolite) resulting from this fluid flow on the sediment consolidation and porosity difference across the MSR. This work quantitatively constrains the mechanisms responsible for sediment removal and clarifies the combined effect of normal faulting and mass movement that characterize the major geologic events in this region.

6. Conclusions

Various tectonic events and Cocos Ridge subduction have altered the upper plate of the Costa Rica subduction zone offshore Osa Peninsula through uplift, erosion, faulting, and focused fluid flow. These events are

well-recorded near the major seismic reflector (MSR) that bound the slope sediments (late Pliocene-late Pleistocene silty clay) and underlying higher velocity upper plate materials (late Pliocene-early Pleistocene clayey siltstone). In this paper, to identify possible mechanisms of sediment removal across the MSR, we studied the sediment microstructure, consolidation state, and fluid-interacted zeolites using samples recovered from middle slope Site 1380 by IODP Expedition 344. We examined the occurrence of zeolites across the MSR, corrected porosity values for pore-filling zeolites, and evaluated the porosity profile to infer how much material was removed at the MSR with and without the porosity correction for zeolites. Across the MSR, Ca-type zeolites laumontite and heulandite are inferred to have formed due to interaction with Ca-rich fluids that have flowed at this horizon. Based on a composite porosity-depth curve corrected for zeolites, we estimated the past burial depth of the sediments directly below the MSR. The corrected and uncorrected porosity-depth curves yield depths of 800 ± 70 m and 900 ± 70 m, respectively. We argue that deposition and removal of this entire estimated thickness in 0.49 Ma would require unrealistically large sedimentation rates and suggest that normal faulting at the MSR must contribute. The porosity offset could be explained with maximum 250 ± 70 m of normal fault throw, or 350 ± 70 m if the porosity were not corrected. The porosity correction in this study significantly reduces the amount of sediment removal needed for the combination of mass movement and normal faulting that characterize the upper plate slope in this margin.

Acknowledgments

This research used samples and data provided by the Integrated Ocean Drilling Program (IODP). This work was supported by JSPS Grant-in-Aid for Scientific Research Fellowship for Young Scientists 02610283, Grant-in-Aid for Scientific Research (S) 15H05717 IODP Exp. 344 After Cruise Research Program, JAMSTEC, JAMSTEC Research Student System, Tokyo Tech/Univ. Tokyo Global COE Program (GCOE), and Univ. Tokyo Graduate COE Program. Extended geologic background, methodology and supporting data for measurements of particle size, resistivity, XRF, XRD, and microstructural observation conducted in this study are provided as two texts, seven figures, and four data sets in supporting information files. Shipboard porosity, density, P-wave velocity, thermal conductivity, and temperature data from IODP Exp. 334 and 344 are accessible from the IODP-USIO Laboratory Information Management System (LIMS) Web Tabular Report (<http://web.iodp.tamu.edu/WTR/html/sci-data.html>).

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