Long Term Subduction Erosion along the Middle America Trench offshore Guatemala

Long-term subduction-erosion along the Guatemalan margin of the Middle America Trench

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ABSTRACT

A new analysis of Deep Sea Drilling Project (DSDP) Leg 84 data demonstrates that the dominant process controlling the Guatemala margin tectonic evolution since ca. 25 Ma is subduction-erosion. Data from benthic foraminifera, assemblages from upper-slope DSDP Sites 568, 569, and 570 indicate long-term, progressive subsidence from upper to middle bathyal depths (600–1000 m) ca. 19 Ma to modern abyssal depths (>2000 m). Rapid subsidence migrated landward starting at the Oligocene-Miocene boundary time under the current middle slope, where it increased sharply ca. 19 Ma, reached the current upper slope by ca. 15 Ma, and arrived at the uppermost slope ca. 2 Ma. Subsidence indicates crustal thinning by basal tectonic erosion of mass from the underside of the upper plate. Under the assumption that, in the Miocene, the morphology of the forearc was similar to that of today, landward migration of the trench was at a rate of 0.8–0.9 km/m.y. This linear rate corresponds to a tectonic erosion rate of the submerged forearc of 11.3–13.1 $km^3 \cdot m.y.^{-1} \cdot km^{-1}$. The evolution of arc magmatism and superfast spreading at the East Pacific Rise since early Miocene time may have caused slab shallowing and tectonic erosion that readjusted the forearc geometry.

Keywords: subduction-erosion, convergent margins, benthic foraminifera, Guatemala, Middle America Trench.

INTRODUCTION

Subduction-erosion is a prominent process in most convergent-margin systems (von Huene and Scholl, 1991; Clift and Vannucchi, 2004), but is difficult to study because destruction of the forearc greatly limits the investigation of geologic evidence on land. Conventional ocean drilling is not able to reach the plate boundary, where seismic records show truncated upper-plate reflections and other signs of erosion along the base of the upper plate (Ranero and von Huene, 2000). Consequently, subduction-erosion is inferred from other evidence, the most indicative for the submerged forearc being (1) long-term subsidence and tilting of the continental slope, (2) regional tectonic extension of the slope apron, and (3) disrupted topography across the lower slope and in the wake of subducted ocean-floor relief (von Huene and Lallemand, 1990; von Huene et al., 2000; Vannucchi et al., 2001). Evidence of margin subsidence—as revealed particularly by the paleodepths inferred by benthic foraminifera in slope sediment—helps in estimating crustal thinning of the forearc, subduction-erosion rates, and the amount of upper-plate material removed (Vannucchi et al., 2003).

Here we focus on evidence for subsidence offshore Guatemala, an area drilled during Deep Sea Drilling Project (DSDP) Legs 67 and 84 (Aubouin et al., 1984; von Huene et al., 1985a) to investigate subduction accretion processes (Fig. 1). Prior to drilling, accretion was proposed as the principal process shaping the margin, as inferred from landward-dipping seismic reflections (Seely et al., 1974). DSDP Legs 67 and 84 sites were drilled in a transect across the continental slope within and adjacent to San José Canyon (Fig. 1). No accreted oceanic sediment was encountered, although DSDP Leg 84 recovered the margin's igneous basement, Late Cretaceous–Eocene sediment, and the overlying late Oligocene to Quaternary slope-apron sequence. However, the tectonic history was poorly constrained. These studies, together with seismic and bathymetric data (Moore et al., 1986), characterized the Guatemalan margin as subducting trench sediment, and the uppermost slope being uplifted because of compressional deformation, limited underplating, or strike-slip transport (Moore et al., 1986; von Huene, 1989). In this paper we report an analysis of the Guatemalan margin vertical movement history, the best proxy, in the absence of modern seismic profiles, for infering subduction erosion, in analogy with the nearby Costa Rica margin (Vannucchi et al., 2001, 2003). The analysis demonstrates a long-term subsidence of the Guatemalan mar-

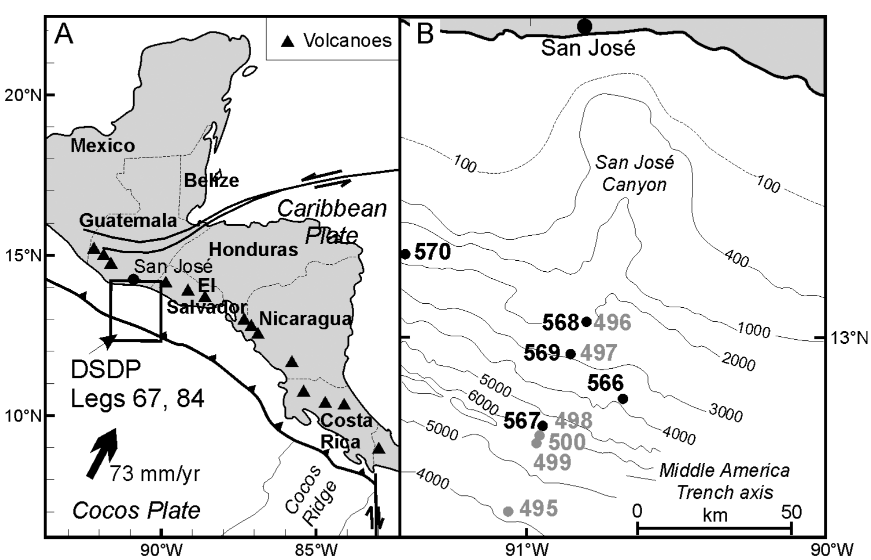

Figure 1. A: Tectonics of Middle America Trench. B: Map of sites of Deep Sea Drilling Project (DSDP) Legs 67 (in gray) and 84 (in black) across Guatemalan continental slope offshore San José.

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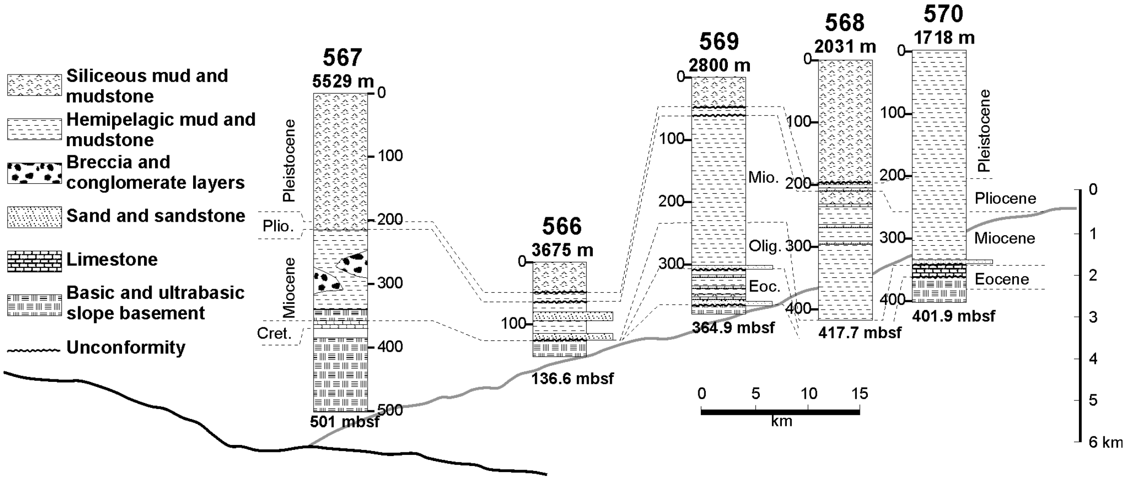

Figure 2. Stratigraphic columns, location, and bathymetric distribution of Deep Sea Drilling Project Leg 84 Guatemala Trench sites (mbsf—meters below seafloor).

gin that shifts the tectonic interpretation from nonaccretionary to clearly erosional.

BENTHIC FORAMINIFERA AS PALEOBATHYMETRIC TRACERS

Along the DSDP transect, the Neogene–Quaternary sediment thickness (Fig. 2) varies because of rough basement topography (von Huene et al., 1985b) and unconformities, some of which are interpreted as recording localized downslope sediment movement (Baltuck et al., 1985); others, such as the prominent early Miocene unconformity, extend over much of the margin (von Huene, 1989).

The ubiquitous mixing of benthic foraminiferal assemblages from upslope, together with poorly reflective slope deposits cut by small canyons in the upper slope, led Baltuck et al. (1985) to conclude that mass wasting was the dominant process on the Guatemalan margin. Nonetheless, Miocene–Pleistocene benthic foraminifera were locally interpreted as indicating gradual uplift of the margin, together with vertical migrations of water masses (McDougall, 1985).

In this study, the benthic foraminifera distributions from DSDP Sites 568, 569, and 570 were analyzed by using the benthic foraminifera data of McDougall (1985). For each site, benthic assemblages were extracted by Q-mode principal component analysis (PCA) performed on centered data after exclusion of both rare species and samples with fewer than 40 specimens. Loading scores of dominant and important associated taxa of the PCA assemblage obtained from the three sites are reported in Table DR1.[1] Following Van Morkhoven et al. (1986) and through assemblage comparisons with Holocene equivalents from similar environments (McDougall, 1985; Murray, 1991; Schmiedl et al., 1997), we determined the bathymetric significance of the taxa dominating the PCA assemblages. Variations through time of the first three principal components allow interpretation of the paleobathymetry evolution at the three sites (Fig. 3). We reconstructed long-term deepening of the depositional setting from an upper to middle bathyal depth (600–1000 m) during the Miocene to a modern lower bathyal to abyssal depth (≥2000 m) (Fig. 3).

We considered the possibility, suggested by McDougall (1985), that the trend in benthic foraminiferal assemblages reflects vertical migrations of different water masses, rather than bathymetric changes. However, this hypothesis can be discounted for two reasons: (1) If the successive emplacement of different bottom-water masses was the primary factor influencing the distribution of benthic foraminifera, then the successive phases of shoaling and deepening of different bottom-water masses proposed by McDougall (1985) would not be reflected in a progressive deepening signature. (2) DSDP Sites 568 and 569, although at different water depths, record synchronous bottom-water changes, so if the benthic foraminiferal distribution was reflecting water-mass properties rather than paleodepth, they would still result in coeval changes in the record of bathymetric indices.

Using the age assignments of Aubouin et al. (1985), we compare the bathymetric evolution of the three sites. On the upper slope to uppermost slope (DSDP Site 570), the PCA assemblage indicates a major deepening during the Pleistocene, when increased proportions of middle and middle to lower bathyal assemblages were recorded (Fig. 3). At this site, the increasing scores of upper bathyal forms associated with relatively stable values of PCA1 (lower bathyal) and PCA3 (upper to middle bathyal) assemblages may indicate a moderate shallowing during the late Pliocene and part of the Pleistocene. However, the same trend may indicate the increase in the amount of downslope-transported material shown by higher sand contents (from 6%–12% to 22%–24%) and the presence of slumping during this interval (von Huene et al., 1985a).

PCA assemblages from DSDP Site 568 show two clear subsidence phases. Subsidence at the Pliocene-Pleistocene boundary (ca. 2 Ma) is well constrained by a decrease in middle bathyal assemblages and a contemporaneous increase in middle to lower bathyal assemblages. Unfortunately, the low number of specimens from samples between 250 and 200 m below seafloor precludes accurate dating. A second deepening step is observed in the Pleistocene samples, wherein loading scores of the PCA2 assemblage increase sharply (Fig. 3). Using one-dimensional backstripping analysis (Sclater and Christie, 1980), it was possible to isolate the tectonic—as opposed to the sediment loading—component of the basement subsidence. In deep-water settings such as the Guatemala margin, the bulk of the subsidence follows water-depth changes as the trend observed in PCA assemblages. Backstripping at DSDP Site 568 improved the resolution of the slow beginning of subsidence, in the middle Miocene (ca. 15 Ma; Fig. 3).

At DSDP Site 569 the trend is similar to that observed at DSDP Site 568. However, the benthic foraminiferal record suggests that initial deepening occurred at DSDP Site 569 during the early Miocene (ca. 19 Ma); an increase in the proportion of the lower bathyal taxa is shown by the statistical analysis (Fig. 3). This predates the deepening observed at the Miocene-Pliocene transition at DSDP Site 568, where a second stage of deepening from lower bathyal to abyssal depth is well constrained by a sharp increase in the proportion of abyssal taxa. Backstripping shows that subsidence predated the deepening signature recorded by benthic

[1]GSA Data Repository item 2004099, Table DR1, composition and bathymetric significance of principal component analysis data, Appendix 1, tectonic erosion rate calculations, and Figure 4, calculation of volume lost, is available online at www.geosociety.org/pubs/ft2004.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

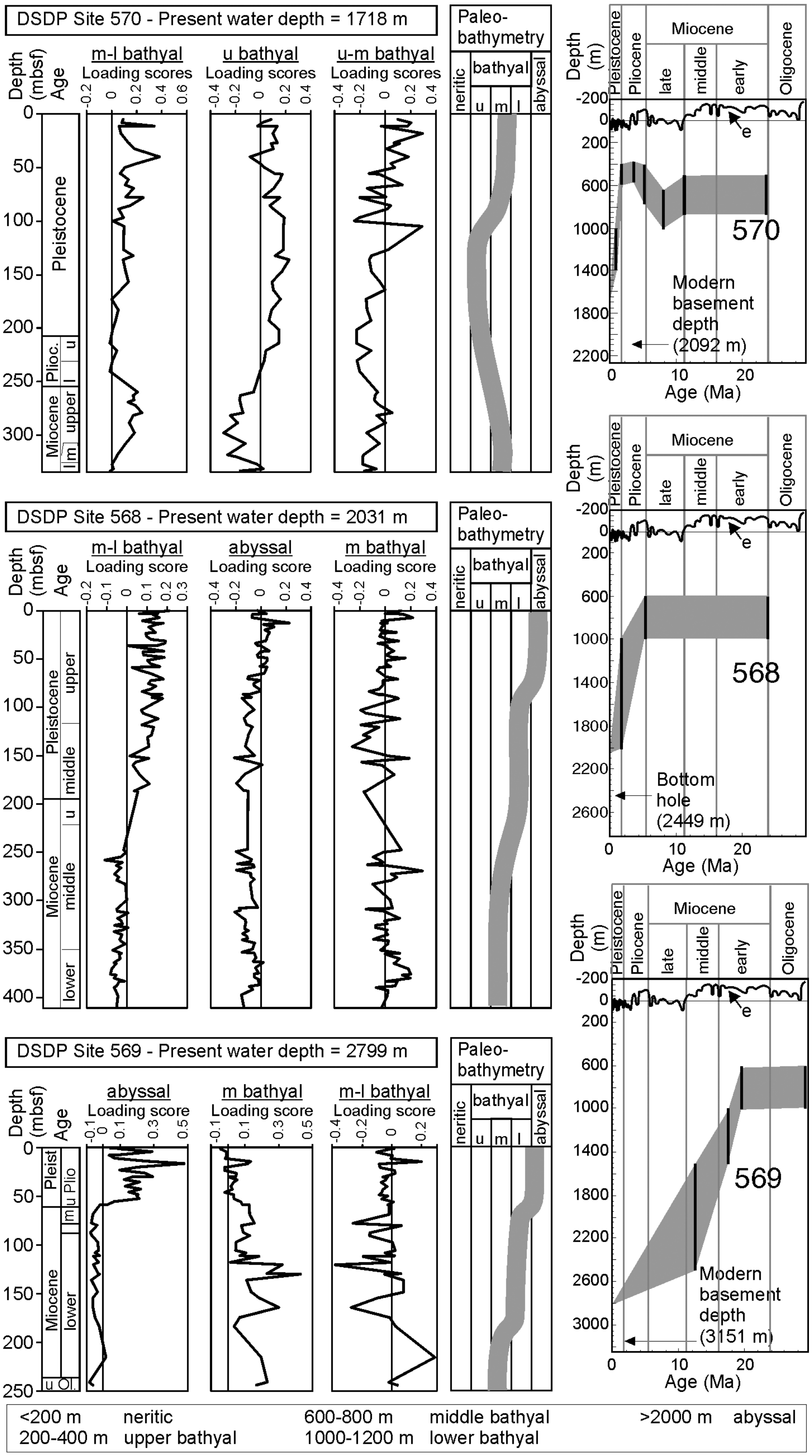

Figure 3. Q-mode benthic foraminiferal assemblages from Deep Sea Drilling Project (DSDP) Sites 568, 569, and 570. Paleoenvironmental significance of first three axes is inferred from highest loading scores in r-mode principal component axis (Table DR1; see footnote 1). Depth classification is after Van Morkhoven et al. (1986). Sediment-unloaded depths to basement at Sites 568, 569, and 570 were calculated after unloading sedimentary sections using one-dimensional backstripping method of Sclater and Christie (1980) and accounting for changes in sea level by using reconstruction of Haq et al. (1987). Eustatic curve is indicated with "e" in figure. u—upper; l—lower; m—middle; mbsf—meters below seafloor. This method effectively isolates subsidence component that is not caused by sediment loading and compaction or by eustatic sea-level change and is thus interpreted as having tectonic origin.

foraminifera starting at the Oligocene-Miocene boundary (Fig. 3).

DISCUSSION AND CONCLUSIONS

Benthic foraminifera assemblages indicate that the 600-m-deep Guatemalan shelf subsided to 1000 m upper-slope depth ca. 19 Ma and subsequently subsided to >2000 m (Fig. 3). Middle-slope subsidence may have started after 28 Ma, but it accelerated after ca. 19 Ma. Upper-slope deepening, first seen between 11 and 16 Ma, migrated landward, reaching the uppermost slope after 2 Ma. The long-term deepening rates average 80 m/m.y. for the middle- to upper-slope sites and 550–600 m/m.y. for the uppermost slope site. Rapid subsidence of the middle- to upper-slope DSDP Sites 568 and 569 coincides with a lithologic break from calcareous to siliceous oozes, indicating a major environmental change. The consistent subsidence-rate differences between the middle- to upper-slope sites and the uppermost slope may indicate a transition from constant to very fast subsidence in the Pliocene–Pleistocene (DSDP Site 570) (Fig. 3). Subsidence due to the normal faulting inferred from early seismic records (Aubouin et al., 1984) and later documented in reprocessed records is much less than that resolved from biostratigraphy.

Assuming that the Miocene forearc was configured as currently known, tectonic erosion rate can be estimated for the Guatemalan sector of the Middle America Trench. The absence of modern seismic data leaves uncertainties in the crustal thickness beneath the upper-slope sites, producing an uncertainty in the rate of erosion of ~10%. DSDP Site 569 reached the forearc basement and can be used to calculate forearc crustal-volume loss. Because the Guatemalan Trench has a forearc slope angle of ~5.5° and DSDP Site 569, 32 km from the trench axis, has subsided ~1500 m since the early Miocene, a maximum of 16 km of frontal erosion since 19 Ma is implied. This results in an average trench-retreat rate of ~0.8 km/m.y. The corresponding rate of crustal loss from the submerged forearc is ~11.3 $km^3 \cdot m.y.^{-1} \cdot km^{-1}$ (see explanation in Appendix 1; see footnote 1), much less than farther south off the Nicoya Peninsula of northern Costa Rica, where the long-term erosion rate since 16 Ma is ~45 $km^3 \cdot m.y.^{-1} \cdot km^{-1}$ (Vannucchi et al., 2001, 2003). Recent analysis shows that major tectonic erosion in that region increased after 6.5 Ma to a rate of 107–123 $km^3 \cdot m.y.^{-1} \cdot km^{-1}$, coeval with initial subduction of the Cocos Ridge (Vannucchi et al., 2003).

Subduction erosion affected the middle slope of the Guatemalan margin from Oligocene–early Miocene (ca. 25 Ma) time, although subsidence may have started even earlier closer to the trench axis. The presence of calc-alkaline ash layers in upper Oligocene sediment indicates that subduction was active at this time, possibly starting in the Late Cretaceous (Hoernle et al., 2002). However, moderate rates of subsidence, at least before the Pliocene–Pleistocene (Fig. 3), suggest a slow, quasi-stable tectonic erosion not accelerated by collision of seamounts or ridges, in accordance with the absence of such features on the incoming plate.

Early Miocene plate development reorganized the Cocos plate. Magnetic anomalies from the Cocos plate and corresponding regions of the Pacific plate demonstrate that East Pacific Rise spreading during the middle Miocene was ~200 mm/yr, ~30%–40% faster than the fastest modern spreading rate (Wilson, 1996). The end of this episode of fast spreading was 18 Ma; initiation can reasonably be estimated as 24–25 Ma (Wilson, 1996), followed by the breakup of the Farallon plate at 23 Ma. That event led to the initiation of the Cocos-Nazca spreading center (Barckhausen et al., 2001) and caused subduction below Central America to change from eastward to more northeastward (Barckhausen et al., 2001). The plate-tectonic configuration change is coincident with a peak of explosive volcanism in Guatemala and Honduras (Sigurdsson et al., 2000) that produced the silicic ignimbrites, tuffs, ash, and related pyroclastic sediment known as the Chalatenango Formation and Padre Miguel Group (Reynolds, 1980, 1987). A connection between the two episodes is unclear (Sigurdsson et al., 2000), but the high rates of explosive volcanism can be related to increased availability of subducted continental material removed from the upper plate by slab shallowing and consequent subduction-erosion. In Guatemala, as in Nicaragua (Ranero et al., 2000), reorganization of the Cocos plate is inferred to have caused the subduction of progressively younger lithosphere that led to shallowing of the angle of the subducting slab and thus faster subduction-erosion rates.

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REFERENCES CITED

Aubouin, J., Bourgois, J., and Azema, J., 1984, A new type of active margin; the convergent-extensional margin, as exemplified by the Middle America Trench off Guatemala: Earth and Planetary Science Letters, v. 97, p. 211–218.

Aubouin, J., von Huene, R., Azema, J., Coulbourn, W.T., Cowan, D.S., Curiale, J.A., Dengo, C.A., Faas, R.W., Harrison, W.E., Hesse, R., Ladd, J.W., Muzylov, N., Shiki, T., Thomson, P.R., and Westberg, M.J., 1985, Initial reports of the Deep Sea Drilling Project, Volume 67: Washington, D.C., U.S. Government Printing Office, 799 p.

Baltuck, M., Taylor, E., and McDougall, K., 1985, Mass movement along the inner wall of the Middle America Trench, Costa Rica, *in* von Huene, R., and Aubouin, J., Initial reports of the Deep Sea Drilling Project, Volume 84: Washington, D.C., U.S. Government Printing Office, p. 551–570.

Barckhausen, U., Ranero, C.R., von Huene, R., Cande, S.C., and Roeser, H.A., 2001, Revised tectonic boundaries in the Cocos plate off Costa Rica: Implications for the segmentation of the convergent margin and for plate tectonic models: Journal of Geophysical Research, v. 106, p. 19,207–19,220.

Clift, P.D., and Vannucchi, P., 2004, Controls on tectonic accretion versus erosion in subduction zones: Implications for the origin and recycling of the continental crust: Reviews of Geophysics (in press).

Haq, B.U., Hardenbol, J., and Vail, P.R., 1987, Chronology of fluctuating sea levels since the Triassic: Science, v. 235, p. 1156–1167.

Hoernle, K., van den Bogaard, P., Werner, R., Lissinna, B., Hauff, F., Alvarado, G., and Garbe-Schonberg, D., 2002, Missing history (16–71 Ma) of the Galápagos hotspot: Implications for the tectonic and biological evolution of the Americas: Geology, v. 30, p. 795–798.

McDougall, K., 1985, Miocene to Pleistocene benthic foraminifers and paleoceanography of the Middle America slope, DSDP Leg 84, *in* von Huene, R., and Aubouin, J., Initial reports of the Deep Sea Drilling Project, Volume 84: Washington, D.C., U.S. Government Printing Office, p. 363–418.

Moore, G.F., Shipley, T.H., and Lonsdale, P.F., 1986, Subduction erosion versus sediment offscraping at the toe of the Middle America Trench off Guatemala: Tectonics, v. 5, p. 513–523.

Murray, J.W., 1991, Ecology and paleoecology of benthic foraminifera: London, UK, Longman Scientific and Technical, 397 p.

Ranero, C.R., and von Huene, R., 2000, Subduction erosion along the Middle America convergent margin: Nature, v. 404, p. 748–752.

Ranero, C.R., von Huene, R., Flueh, E., Duarte, M., Baca, D., and McIntosh, K., 2000, A cross section of the convergent Pacific margin of Nicaragua: Tectonics, v. 19, p. 335–357.

Reynolds, J.H., 1980, Late Tertiary volcanic stratigraphy of northern Central America: Bulletin of Volcanology, v. 43, p. 601–607.

Reynolds, J.H., 1987, Timing and sources of Neogene and Quaternary volcanism in south-central Guatemala: Journal of Volcanology and Geothermal Research, v. 33, p. 9–22.

Schmiedl, G., Mackensen, A., and Müller, P.J., 1997, Recent benthic foraminifera from the eastern South Atlantic Ocean: Dependence on food supply and water masses: Marine Micropaleontology, v. 32, p. 249–287.

Sclater, J.G., and Christie, P.A.F., 1980, Continental stretching: An explanation of the post–mid-Cretaceous subsidence of the central North Sea basin: Journal of Geophysical Research, v. 85, p. 3711–3739.

Seely, D.R., Vail, P.R., and Walton, G.G., 1974, Trench slope model, *in* Burk, C.A., and Drake, C.L., eds., The geology of continental margins: New York, Springer Verlag, p. 249–260.

Sigurdsson, H., Kelley, S., Leckie, R., Carey, S., Bralower, T., and King, J., 2000, History of circum-Caribbean explosive volcanism: $^{40}Ar/^{39}Ar$ dating of tephra layers, *in* Leckie, R., and Sigurdsson, H., eds., Proceedings of the Ocean Drilling Program, Scientific results, Volume 165: College Station, Texas, Ocean Drilling Program, p. 299–314.

Van Morkhoven, F.P.C.M., Berggren, W.A., and Edwards, A.S., 1986, Cenozoic cosmopolitan deep-water benthic foraminifera: Bulletin des Centres de Recherches Exploration-Production Elf-Aquitaine, v. 11, p. 421.

Vannucchi, P., Scholl, D.W., Meschede, M., and McDougall-Reid, K., 2001, Tectonic erosion and consequent collapse of the Pacific margin of Costa Rica: Combined implications from ODP Leg 170, seismic offshore data, and regional geology of the Nicoya Peninsula: Tectonics, v. 20, p. 649–668.

Vannucchi, P., Ranero, C.R., Galeotti, S., Straub, S.M., Scholl, D.W., and McDougall-Ried, K., 2003, Fast rates of subduction erosion along the Costa Rica Pacific margin: Implications for nonsteady rates of crustal recycling at subduction zones: Journal of Geophysical Research, v. 108, 2511, doi: 10. 1029/2002JB002207.

von Huene, R., 1989, The middle America convergent plate boundary, Guatemala, *in* Winterer, E.L., et al., eds., The eastern Pacific Ocean and Hawaii: Boulder, Colorado, Geological Society of America, Geology of North America, v. N, p. 535–550.

von Huene, R., and Lallemand, S., 1990, Tectonic erosion along the Japan and Peru convergent margins: Geological Society of America Bulletin, v. 102, p. 704–720.

von Huene, R., and Scholl, D.W., 1991, Observations at convergent margins concerning sediment subduction, subduction erosion, and the growth of continental crust: Reviews of Geophysics, v. 29, p. 279–316.

von Huene, R., Aubouin, J., Arnott, R.J., Baltuck, M., Bourgois, J., Helm, R., Ogawa, Y., Kvenvolden, K.A., McDonald, T.J., Taylor, E., McDougall, K., Filewicz, M.V., Winsborough, B., and Lienert, B., 1985a, Initial reports of the Deep Sea Drilling Project, Volume 84: Washington, D.C., U.S. Government Printing Office, 967 p.

von Huene, R., Miller, J., Taylor, D., and Blackman, D., 1985b, A study of geophysical data along the Deep Sea Drilling Project active margin transect off Guatemala, *in* von Huene, R., and Aubouin, J., Initial reports of the Deep Sea Drilling Project, Volume 84: Washington, D.C., U.S. Government Printing Office, p. 895–909.

von Huene, R., Ranero, C.R., Weinrebe, W., and Hinz, K., 2000, Quaternary convergent margin tectonics of Costa Rica, segmentation of the Cocos plate, and Central American volcanism: Tectonics, v. 19, p. 314–334.

Wilson, D.S., 1996, Fastest known spreading on the Miocene Cocos-Pacific plate boundary: Geophysical Research Letters, v. 23, p. 3003–3006.

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