Tectonic history of the northern Peru convergent margin during the past 400 ka

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ABSTRACT

The late Pleistocene tectonic history of the northern Peru convergent margin can be retraced using data collected during deep-sea dives of the submersible *Nautile* combined with a recent Hydrosweep survey conducted off Peru at lat 5°–6°S by the R/V *Sonne*. During the past 400 ka, a broad rollover fold formed in the middle slope area, in association with a major seaward-dipping detachment fault. A catastrophic debris avalanche occurred as the result of oversteepening of the landward flank of the rollover fold. The gravity failure of the slope, previously recognized by SeaBeam mapping, occurred at 13.8 ±2.7 ka and produced a destructive tsunami.

INTRODUCTION

Tsunamis generated at convergent plate boundaries may be caused by gravity slides of large amounts of sediment combined with relatively low magnitude earthquakes (Kanamori, 1972; Beck and Nishenko, 1990). Deep-sea dives conducted with the submersible *Nautile* along the northern margin of Peru during the NAUTIPERC (NAUTile dives in the PERu-Chile Trench) cruise in March–April 1991 (Fig. 1) have provided new insight into the tectonic processes that allow massive gravity failure at convergent margins (von Huene et al., 1989), failure great enough to cause tsunamis.

The primary objectives of the NAUTIPERC cruise included geological observations and chemical studies of venting fluids at a convergent margin that is devoid of an accretionary prism and where subduction erosion is active (Scholl et al., 1980; Hussong and Wipperman, 1981; Aubouin et al., 1984; Bourgois et al., 1990; von Huene and Scholl, 1992). Normal faulting and massive subsidence are characteristic of the northern Peru margin (Kulm et al., 1984, 1988; Suess, von Huene et al., 1988a, 1988b; von Huene, Suess et al., 1988; Resig, 1989).

We report herein the main geological results of submersible observations conducted in the Paita dive area (Fig. 1). The geological data collected in situ from the submersible are combined with the results of a recent hydrosweep bathymetric survey by the R/V *Sonne* (cruise 78, March–April 1992) conducted off northern Peru. These data provide detailed geomorphic information and allow us to propose a tectonic history for the past 400 ka (Bourgois et al., 1992).

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PREVIOUS STUDIES OF THE PERU MARGIN OFF PAITA

Three multichannel seismic lines, trending east-west, were shot during the Nazca plate project (Kulm et al., 1981) in an area of the landward slope of the Peru-Chile Trench between 5° and 12°S. From the interpretation of one of these lines (line CDP3, offshore Paita), Sheperd and Moberly (1981) concluded that the upper slope is deformed by block faulting and that the lower slope exhibits the diffraction pattern of an accretionary prism. Reprocessing of the line and comparison with data from on-shore industry wells allowed von Huene et al. (1986) to project geological data from the shelf to the middle slope area.

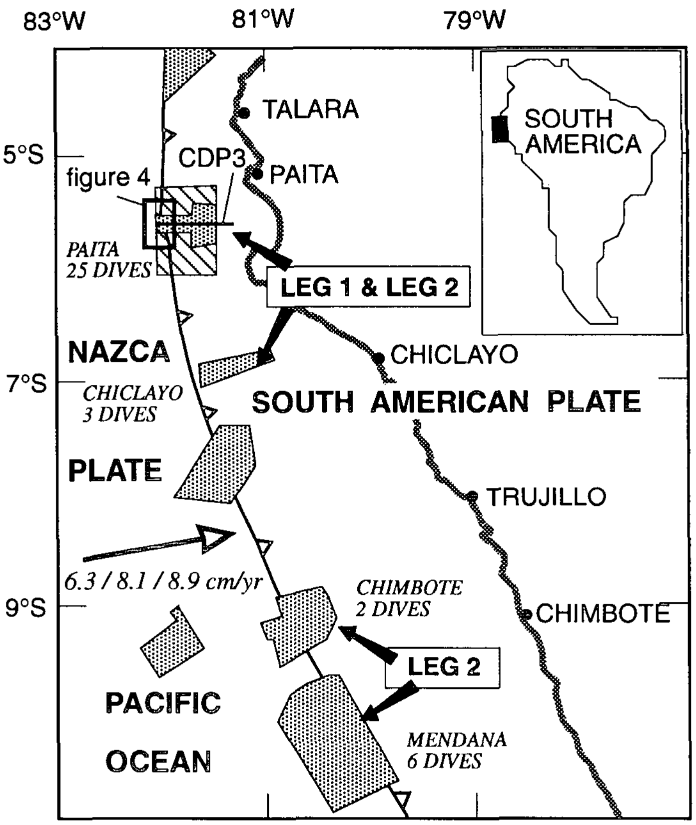

Figure 1. Location of dives during NAUTIPERC cruise (March 7–April 22, 1991). Toothed line indicates Peru-Chile Trench convergence zone. Main diving area discussed in this paper is that of Leg 1, off Paita. Large, open-head arrow shows direction of convergence of Nazca plate relative to South American plate. Numbers under arrow are convergence rates (see text). Patterned areas represent SeaBeam survey (R/V *Jean Charcot*, Seaperc cruise, 1986). Diagonal-rule pattern represents area of Hydrosweep survey (R/V *Sonne*, 1992).

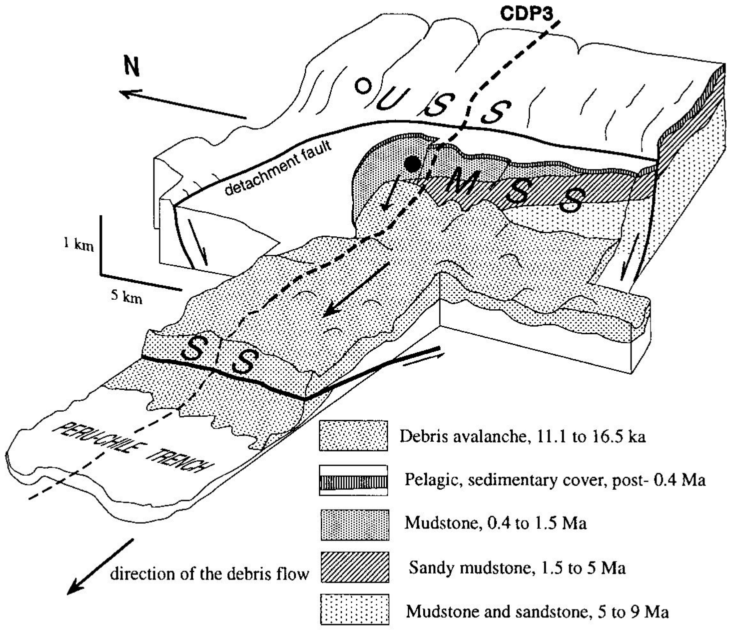

Figure 2. Three-dimensional diagram showing main geologic and tectonic features identified in Paita area. USS—Upper slope scarp; MSS—middle slope scarp; SS—subduction scarp. Diagram is from mesh-net perspective diagram of SeaBeam bathymetry (Bourgois et al., 1988). Solid circle and open circle indicate locations of A and B, respectively, of Figure 3. Thick part of dashed line along CDP3 profile refers to section in Figure 5C. Thick line under SS represents decollement.

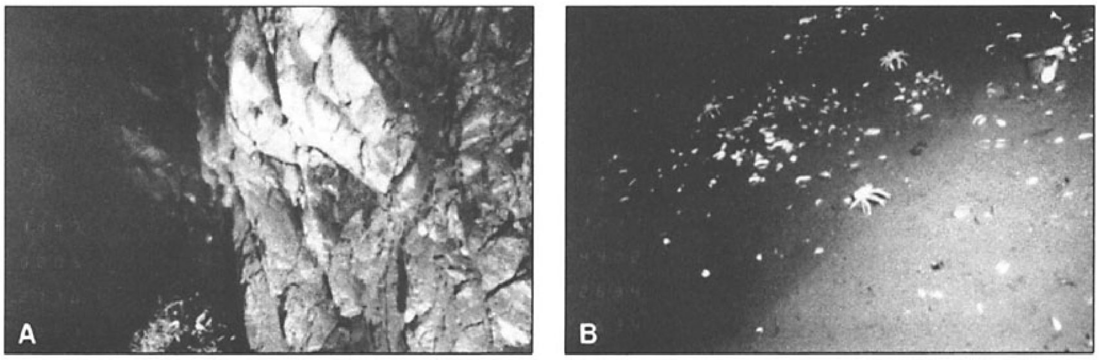

Figure 3. A: Middle slope scarp exhibits bare-rock outcrop without any pelagic deposit. Scarp is very fresh scar. Active fluid venting associated with clam colonies, bacterium patches, serpulid thickets, and thick barite deposits occurs along scarp. B: Upper slope scarp is covered by pelagic sediment and contrasts with typical aspect of middle slope scarp.

In 1986, in preparation for Ocean Drilling Program (ODP) Leg 112, information on the structure of the middle slope area was greatly improved by SeaBeam bathymetry (Fig. 1) that was acquired simultaneously with four multichannel seismic profiles (von Huene et al., 1989) shot perpendicular to the CDP3 line. Several main morphological features have been distinguished in the surveyed area. (1) A 400–700-m-high scarp (upper slope scarp; Fig. 2) separates the upper slope from the middle slope. The seismic data show that this scarp is a major detachment fault dipping 45° seaward. The fault penetrates deeply into the continental margin down to 3–5 km below the sea floor (Bourgois et al., 1988; von Huene et al., 1989). (2) A 1000–1200-m-high scarp (middle slope scarp; Fig. 2) is located 10 km seaward from the upper slope scarp. (3) A 300–500-m-high scarp (subduction scarp; Fig. 2) is located at the base of the lower slope. (4) A chaotic topography, with closed highs and lows, between the middle slope scarp and subduction scarp is the surface of a debris avalanche originating from the middle slope scarp. (5) Isolated mounds on the flat floor of the trench indicate that the debris avalanche traveled seaward to the trench axis.

In 1989, von Huene et al. proposed that the upper and the middle slope scarps bound a landward-tilted block detached along a listric fault and that the middle slope scarp represents an area voided by slumping. They emphasized that the detachment of the block (20 × 33 km) was catastrophic. It produced the debris avalanche that covered the lower slope and stored enough gravity energy to travel across the trench axis. The 400–450 km^3 of displaced material is thought to be sufficient to produce a destructive tsunami.

MIDDLE SLOPE SCARP

The 84 samples of fossiliferous sediment collected along the middle slope scarp delineate the geology of the area (Fig. 2). The reconstructed lithostratigraphic succession of the middle slope area consists of, from bottom to top, (1) a 400-m-thick section of upper Miocene mudstone and sandstone, deposited between 9 and 5 Ma; (2) a 300–400-m-thick section of massive siltstone and sandy mudstone of earliest Pliocene (5.3 to 4.5 Ma) to latest Pliocene (2.3 to 1.8 Ma) age; (3) a 0 to 500 m sequence of diatom- and radiolarian-bearing mudstone of Quaternary age (1.5 to 0.4 Ma); and (4) a 50–75-m-thick sequence of pelagic diatom ooze of late Pleistocene age; on the basis of the presence of *Lamprocyrtis nigriniae* (Johnson and Nigrini, 1985) and the latest presence of *Stylatractus universus* (Morley and Shackleton, 1978), this sequence is younger than 0.4 Ma. The late Pleistocene sequence unconformably overlies the older sequences.

The 16 dives along the middle slope scarp explored a succession of small cliffs exposing bare-rock outcrops (Fig. 3A) separated by narrow steps covered with Holocene pelagic sediment. Fresh talus is present at the foot of small cliffs. Rock outcrops exhibit a dense network of fractures. Talus and fractures are associated commonly with clam colonies and serpulid thickets related to fluid vents. In general, the freshness of the outcrops (Fig. 3A) suggests that the surface failure that produced the middle slope scarp was catastrophic and recent.

Two dives along the westernmost east-west–trending section of the middle slope scarp observed beds dipping 12° to 15° seaward, whereas the four dives along the north-south–trending section of the middle slope scarp observed stratification dipping 2° to 5° landward. This is at variance with the dip expected from the "landward-tilted block" model of von Huene et al. (1989) that would predict a 5° landward rotation for the middle slope scarp area. The middle slope area is not a simple, rigid, tilted block, but a broad anticline with a north-south–trending axis, bordered upslope by a detachment fault that drops the antiformal structure toward the trench (Fig. 2). The pelagic diatom ooze cover (Fig. 2) younger than 0.4 Ma accumulated during the time that the anticlinal structure formed.

UPPER SLOPE SCARP

Two deeply incised canyons, which were explored during three dives, cut through the upper slope scarp at the upper-middle slope boundary. Two main observations are important to note. (1) In contrast to the surface of the middle slope scarp, the post–0.4 Ma pelagic sedimentary cover over the upper slope scarp is very thick (up to 75 m), leading to a smooth topography and indicating that the detachment-fault scarp is totally buried (Fig. 3B). (2) Active fluid vents (Fig. 3B) are found along the upper slope scarp, which is the sediment-draped footwall of the detachment fault.

According to von Huene et al. (1989), the detachment along the fault of the upper slope scarp was catastrophic and occurred shortly before (or after) the failure that formed the middle slope scarp. The upper slope scarp should therefore exhibit morphological characteristics similar to those of the middle slope scarp.

The major detachment fault related to the upper slope scarp (Bourgois et al., 1988; von Huene et al., 1989) cuts the upper plate down to a subsurface depth of 5 km (von Huene et al., 1989). We assume that the anticline that extends seaward across the middle slope area is linked to the detachment fault, and thus would be a rollover fold. The time when the rollover began to form can be estimated. Multichannel seismic data (von Huene et al., 1989) establish that the detachment cuts the Quaternary sequence (1.5 to 0.4 Ma). The detachment scarp was covered progressively by the post–0.4 Ma pelagic sediment as the middle slope area subsided; therefore, we believe that the detachment and the related middle-slope rollover fold began to form at 0.4 Ma.

DISCUSSION

Age of the Debris Slide

The date of the debris avalanche is inferred in the following way. If it is assumed that the debris flow traveled across the trench floor to the seaward wall of the trench and that the front of the debris flow moved east by plate convergence, the age of the avalanche can be determined as a function of the distance between the front of the debris flow today and its original position. Hydrosweep bathymetric data (R/V *Sonne* cruise 78, March–April 1992) establish that the western border of the chaotic zone, representing the frontal part of the debris avalanche in the trench, extends farther seaward south of the area mapped during the R/V *Jean Charcot* cruise in 1986 (Figs. 1 and 4). Between 5°45′ and 5°50′S, the debris front is 1 km away from the 150-m-high scarp of the normal fault that bounds the western side of the trench (Fig. 4). If we assume that (1) the debris flow stopped against such a buttress fault scarp (Fig. 4) and (2) the trench floor has maintained a constant width in two-dimensional cross section along a specific transect as it evolved through time, we can infer that the front of the slide debris has traveled landward 1 km. According to different authors, plate convergence rates in this area range between 6 and 8.9 cm/yr (6.3 ±0.3 cm/yr in the model of Smith et al., 1990; 8.1 cm/yr in the model of DeMets et al., 1990; and 8.9 cm/yr in the model of Minster and Jordan, 1987). Taking into account the assumptions presented above, we thus conclude that the slide occurred between 16.5 and 11.1 ka.

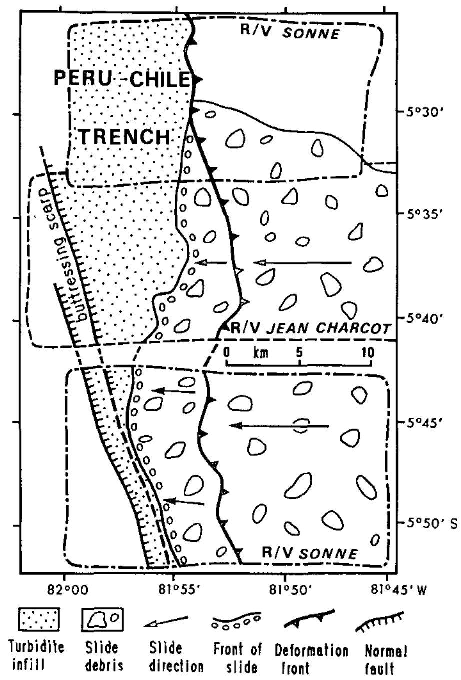

Figure 4. Hydrosweep (R/V *Sonne* cruise 78, March–April 1992) and Sea-Beam (Seaperc cruise of R/V *Jean Charcot*, July 1986) surveys of Peru-Chile Trench off Paita (see Fig. 1 for location). Slide debris traveled across flat trench floor to seaward slope and was subsequently carried back toward deformation front by plate convergence. Mass wasting occurred at 13.8 ±2.7 ka. Heavy dashed line represents buttress fault scarp buried under turbidite infill of trench.

Evolution of the Margin

The predetachment topography (Fig. 5A) of the slope landward of the middle slope scarp was reconstructed (von Huene et al., 1989) by matching the subsurface geology and aligning the sea-floor topography along the CDP3 line (Fig. 2). A complementary constraint was determined by aligning landward-dipping reflectors cut by the detachment fault at 5 km depth. Thus, from 400 ka, when the detachment fault began to form, to the present time, the landward flank of the middle slope rollover fold rotated 5° landward and downward. The slope angle in this area evolved from 7° to 2° and became more stable (Fig. 5, B and C). During the same time, the seaward flank of the middle slope rollover fold rotated 5° seaward (Fig. 5B). The restored slope of the seaward flank dips 12°, slightly more than the 11° critical slope angle of gravity stability as determined from the slope angle of the northern intact part of the seaward flank of the middle slope rollover fold. Thus, the slope in this area oversteepened (Fig. 5B) dramatically to the point of gravity failure. The catastrophic debris avalanche that occurred between 16.5 and 11.1 ka removed the seaward flank of the middle slope rollover fold (Fig. 5C). The volume of material involved in the avalanche debris (>400 km^3) was sufficient to generate a large tsunami. The tectonic processes that would generate such a large tsunami include (1) a major seaward-dipping detachment fault located at the upper middle slope boundary and (2) the consequent formation of an 18-km-wide rollover fold in the middle slope area. The strain released along the detachment fault was stored partly along the middle slope rollover fold during the past 400 ka and then was released catastrophically through the gravity failure of the middle slope area. Subduction erosion at depth, change in the angle of subduction, development of relief on the subducting plate, and compressional forces within the sedimentary sequence of the margin may have acted separately or together to increase the slope angle of the middle slope area.

The unloading induced by the catastrophic failure and the subsequent avalanche debris would diminish pore-fluid pressure arising from lithostatic overburden and accelerate the upward migration of fluid. A major zone of fluid vents occurs at the intersection between the north-south– and east-west–trending sections of the middle slope scarp (Fig. 2). Murauchi and Ludwig (1980) suggested that the

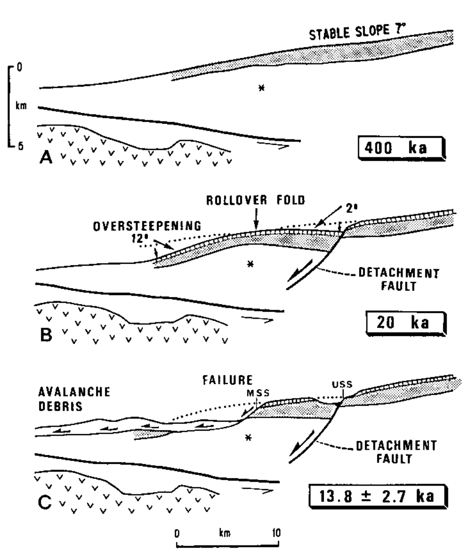

Figure 5. Tectonic evolution of middle slope area during past 400 ka. A: Slope in stable condition prior to start of detachment faulting (slope angle = 7°) along middle slope area. B: Downslope slip movement along detachment fault was accommodated seaward by rollover fold that extends throughout middle slope area. Landward flank of rollover fold subsided 800 m. Seaward flank was greatly oversteepened to critical slope angle (11°–12°) of gravity stability. C: Failure of seaward flank of rollover fold. Asterisk shows approximate position of oldest collected sample. Diagonal-rule pattern = pelagic sedimentary cover post–0.4 Ma. Stippled pattern = mudstone, 0.4 to 1.5 Ma. V pattern = oceanic crust. Thick line above V pattern represents decollement. MSS is middle slope scarp; USS is upper slope scarp.

mechanism of upward migration of fluid released during subduction is capable of weakening the base of the upper plate. Such weakening might contribute to the subduction erosion of this base. Therefore, the catastrophic failure of the middle slope area is a process that may locally increase the rate of subduction erosion.

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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. 87, p. 111–126.

Beck, S.L., and Nishenko, S.P., 1990, Variations in the mode of great earthquake rupture along the central Peru subduction zone: Geophysical Research Letters, v. 17, p. 1969–1972.

Bourgois, J., and 11 others, 1988, SeaBeam and seismic reflection imaging of the tectonic regime of the Andean continental margin off Peru (4°S to 10°S): Earth and Planetary Science Letters, v. 87, p. 111–126.

Bourgois, J., Huchon, P., and Pautot, G., 1990, Tectonics of the Peru active margin, *in* Aubouin, J., and Bourgois, J., eds., Tectonics of the circum-Pacific continental margins: International Geological Congress, 28th, Washington, D.C., Proceedings, p. 77–137.

Bourgois, J., and 17 others, 1992, Northern Peru convergent margin: Massive slides from the upper plate into the trench axis observed from a submersible: Eos (Transactions, American Geophysical Union), v. 73, p. 152.

DeMets, C., Gordon, R.G., Argus, D.F., and Stein, S., 1990, Current plate motions: Geophysical Journal International, v. 101, p. 425–478.

Hussong, D.M., and Wipperman, L.K., 1981, Vertical movement and tectonic erosion of the continental wall of the Peru-Chile Trench near 11°30′S latitude, *in* Kulm, L.D., et al., eds., Nazca plate: Crustal formation and Andean convergence: Geological Society of America Memoir 154, p. 509–524.

Johnson, D.A., and Nigrini, C., 1985, Synchronous and time-transgressive Neogene radiolarian datum levels in the equatorial Indian and Pacific oceans: Marine Micropaleontology, v. 9, p. 489–524.

Kanamori, H., 1972, Mechanism of tsunami earthquakes: Physics of the Earth and Planetary Interiors, v. 5, p. 346–359.

Kulm, L.D., Dymond, J., Dasch, E.J., Hussong, D.M., and Roderick, R., 1981, Nazca plate: Crustal formation and Andean convergence: Geological Society of America Memoir 154, 824 p.

Kulm, L.D., Suess, E., and Thornburg, T.M., 1984, Dolomites in organic-rich muds of the Peru forearc basins: Analogue to the Monterey Formation, *in* Garrison, R.E., et al., eds., Dolomites of the Monterey Formation and other organic-rich units: Pacific Section, Society of Economic Paleontologists and Mineralogists Special Publication 41, p. 29–47.

Kulm, L.D., Thornburg, T.M., Suess, E., Resig, J., and Fryer, P., 1988, Clastic, diagenetic, and metamorphic lithologies of a subsiding continental block: Central Peru forearc, *in* Suess, E., and von Huene, R., Proceedings, Ocean Drilling Program, initial reports, Volume 112: College Station, Texas, Ocean Drilling Program, p. 91–107.

Minster, J.B., and Jordan, T.H., 1987, Present-day plate motions: Journal of Geophysical Research, v. 92, p. 4798–4804.

Morley, J.J., and Shackleton, N.J., 1978, Extension of the Radiolarian *Stylatractus universus* as a biostratigraphic datum to the Atlantic Ocean: Geology, v. 6, p. 309–311.

Murauchi, S., and Ludwig, W.J., 1980, Crustal structure of the Japan Trench: The effect of subduction of ocean crust, *in* Langseth, M., and Okada, H., Initial reports of the Deep Sea Drilling Project, Volumes 56 and 57 (part 1): Washington, D.C., U.S. Government Printing Office, p. 463–469.

Resig, J., 1989, Benthic foraminiferal stratigraphy and paleoenvironment off Peru, Ocean Drilling Program Leg 112, *in* von Huene, R., and Suess, E., Proceedings, Ocean Drilling Program, scientific results: College Station, Texas, Ocean Drilling Program, p. 203–235.

Scholl, W.D., von Huene, R., Vallier, T.L., and Howell, D.G., 1980, Sedimentary masses and concepts about tectonic processes at underthrust ocean margins: Geology, v. 8, p. 564–568.

Sheperd, G.L., and Moberly, R., 1981, Coastal structure of the continental margin, northward Peru and southwest Ecuador, *in* Kulm, L.D., et al., eds., Nazca plate: Crustal formation and Andean convergence: Geological Society of America Memoir 154, p. 551–591.

Smith, D.E., and nine others, 1990, Tectonic motion and deformation from the Satellite Laser Ranging to LAGEOS: Journal of Geophysical Research, v. 95, p. 22,013–22,041.

Suess, E., von Huene, R., et al., 1988a, Proceedings, Ocean Drilling Program, initial reports, Volume 112: College Station, Texas, Ocean Drilling Program, 1015 p.

Suess, E., von Huene, R., and Leg 112 shipboard scientists, 1988b, Ocean Drilling Program Leg 112, Peru continental margin: Part 2, Sedimentary history and diagenesis in a coastal upwelling environment: Geology, v. 16, p. 939–943.

von Huene, R., and Scholl, D.W., 1992, 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., Kulm, L., Miller, J., and Hussong, D., 1986, The Peru continental margin, record sections 2 and 3, *in* von Huene, R., ed., Seismic images of modern convergent margin tectonic structure: American Association of Petroleum Geologists Studies in Geology 26, p. 37–40.

von Huene, R., Suess, E., and Leg 112 shipboard scientists, 1988, Ocean Drilling Program Leg 112, Peru continental margin: Part 1, Tectonic history: Geology, v. 16, p. 934–938.

von Huene, R., Bourgois, J., Miller, J., and Pautot, G., 1989, A large tsunamogenic landslide and debris flow along the Peru Trench: Journal of Geophysical Research, v. 94, p. 1703–1714.

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