Shear-zone thickness and the seismicity of Chilean- and Marianas-type subduction zones

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ABSTRACT

Chilean-type convergent margins have many large (M > 7.6) earthquakes, whereas Marianas-type ones do not. This dichotomy is enigmatic if the plate interface is viewed as a thin frictional decollement, whereas it becomes understandable if it is viewed as a relatively thick, sediment-filled shear zone, which thins or thickens arcward depending on subduction speed and sediment supply. Chilean-type margins have thick trench fills, and their shear zones generally thin arcward from inlets as much as several thousand metres high, the most pronounced thinning being located near backstops. Tall (up to several kilometres) seamounts are subducted essentially intact to relatively great depths and confining pressures before jamming into the roof of the channel and becoming seismogenic asperities. Their near-basal ruptures can generate large thrust-type earthquakes, mainly concentrated in seismic fronts near backstops. Marianas-type margins, in contrast, have thin trench fills, and their shear zones generally thicken arcward from inlets that can be as little as 300 m high. Seamounts are truncated near the inlet at low confining pressures and generate only small earthquakes. After passing the inlet, they do not touch the roof and therefore cannot generate large earthquakes. A similar mechanism may explain seismic gaps at sediment-poor regions of subduction zones.

INTRODUCTION

Approximately 80% of the world's seismic energy release occurs as subduction-zone (Fig. 1) thrust-type events shallower than 60 km (Scholtz, 1990, p. 280); with the sizes and numbers of events vary greatly from zone to zone, and even as seismic gaps within zones (Kanamori, 1971; Lay et al., 1982; Habermann et al., 1986; Heaton and Hartzell, 1986; Zhang and Schwartz, 1992; Pacheco et al., 1993). Uyeda and Kanamori (1979) were among the first to generalize the variation by classifying subduction zones as either Chilean type, if they have numerous large (M > 7.6) thrust-type earthquakes, or Marianas type if they do not. Chilean-type margins typically have thick trench fills and broad (tens of kilometres wide) accretionary prisms, whereas Marianas-type ones have thin trench fills and narrow, or even nonexistent, accretionary prisms.

The large thrust-type earthquakes of Chilean-type margins nucleate at depths of ~15–65 km (Scholz, 1990; Zhang and Schwartz, 1992; Tichelaar and Ruff, 1993). Very few, if any, M > 5.5 events occur beneath accretionary prisms (Chen et al., 1982; Frohlich et al., 1982; Shimamoto et al., 1993), and an abrupt seismic front (Byrne et al., 1988) marks the transition to seismogenic stick slip arcward of it, except in seismic gaps.

Most workers view subduction-zone interplate motion as frictional slip along a relatively thin, if not vanishingly thin, decollement (Wang, 1980; Davis et al., 1983; Vrolijk, 1990; Le Pichon et al., 1993) and regard the associated thrust-type seismicity as localized stick slip (Shimamoto, 1985; Byrne et al., 1988; Scholz, 1990). But why should the stick-slip properties of interplate subduction-zone faults vary so greatly from Chilean- to Marianas-type margins? Why, given that the ambient temperature, hence rock ductility, generally increases arcward, should seismic fronts occur? And what causes seismic gaps?

PERCENTAGE OF SEISMIC SLIP

Kanamori (1971, 1977) concluded that seismic slip does not account for the total interplate slip in subduction zones. Lay et al. (1982) estimated that it is 30% to 60% of the total at most sites, but <10% at Izu-Bonin-

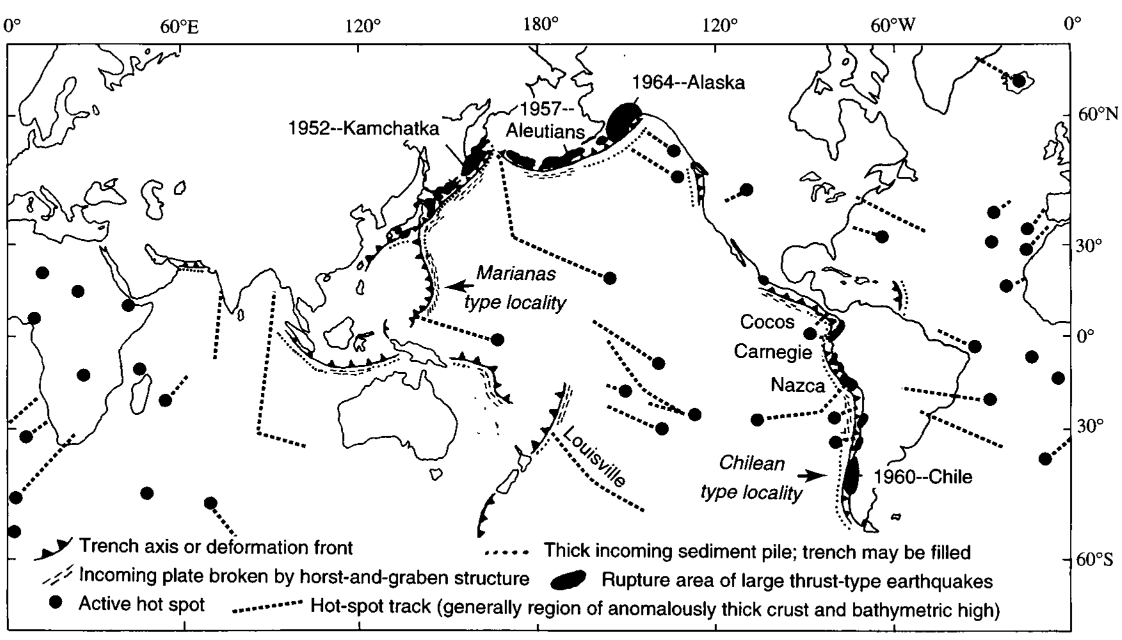

Figure 1. Subduction zones with convergence speeds >3 cm/yr. Thick trench fill and horst-and-graben structure after Hilde (1983). Rupture areas from Kanamori (1986). Active hotspots and tracks from Crough (1983).

Mariana, Java, and Ryukyu. Peterson and Seno (1984) found that from 1904 to 1980 it was <50% at 20 of 24 margins they analyzed and <10% at many of them. The exceptions were the ones with the four largest recent earthquakes. Byrne et al. (1988) concluded that seismic slip is a negligible fraction of the total interplate slip beneath accretionary prisms but is ~100% of it in the seismogenic thrust region at depths of 20–60 km. Pacheco et al. (1993) concluded that in the seismogenic regions of 18 subduction zone segments during 1900–1989 it typically was <50% and commonly <10%. For Java-Sumatra and Bonin-Marianas it was <1%.

SEISMOGENIC ASPERITIES AND TRENCH FILL

Most of the short-period body waves radiated during large earthquakes come from small areas of the rupture plane, termed "asperities" (Lay and Kanamori, 1980; 1981; Ruff and Kanamori, 1983). Although asperities must be involved in thrust-type subduction-zone earthquakes, their presence does not in itself account for the contrast between the Chilean- and Marianas-type earthquakes.

Kanamori (1986) speculated that the thickness of the incoming trench sediment must also be a factor; Ruff (1989) noted that 13 of the 19 largest recorded subduction-zone earthquakes occurred where "excess trench sediment" buries horst-and-graben topography formed on the incoming plate where it bends downward. Ruff speculated that subduction of thick sediment somehow forms a strong interplate contact zone in which ruptures initiated at asperities become extensive, producing large earthquakes.

Thatcher (1990) concluded that the main-shock epicenters of great circum-Pacific earthquakes tend to occur near previous similar events, that large earthquakes are due to rupture of high-shear-strength asperities, and that comparable amounts of slip occur in successive events. The extent of rupture varies in successive events, however, because the weaker regions surrounding the asperities not only deform rapidly during earthquakes, but also creep slowly between them.

Zhang and Schwartz (1992) found that for M 5–7 earthquakes at 23 margins during 1977–1990 the depth encompassing 50% of the cumulative seismic moment release significantly increased with increasing convergence speed or trench-axis sediment thickness. They attributed the influence of thicker sediment to inhibition of seismic failure at shallow depths by stable sliding properties and high pore-fluid pressures, although they found this influence "difficult to interpret" (Zhang and Schwartz, 1992, p. 543).

SUBDUCTION ACCRETION AND EROSION

Subduction accretion occurs by offscraping and underplating (see review by Cloos and Shreve, 1988a). It enlarges accretionary prisms and diminishes the amount of sediment moving downward. Hence, it generally tends to decrease the thickness of the subducting layer, although, because of mechanical requirements, it can never reduce it to zero (Shreve and Cloos, 1986).

Accretion is not the only fate of the incoming sediment at subduction zones. Long-term mass balances based on deep-sea drilling transects at several margins indicate that substantial amounts of sediment must have been subducted to great depths (Scholl et al., 1980; Cloos and Shreve, 1988a; von Huene and Scholl, 1991). The presence of ^{10}Be in some volcanic arcs (Tera et al., 1986) indicates that clay-bearing oceanic sediment <10 Ma was involved in magma genesis. Thus, the top, and hence all, of the incoming sediment at these arcs was subducted to the depth of magma genesis.

In addition, at a few margins, such as Marianas, northeast Japan, Guatemala, and Peru (Scholl et al., 1980; Hilde, 1983; von Huene and Lallemand, 1990; Lallemand et al., 1992), subduction erosion has removed the toe and base of the overriding block. In fact, global mass balance indicates that erosion is just as important as accretion at convergent plate margins (von Huene and Scholl, 1991); it apparently prevails wherever the trench sediment thickness is <500 m (Le Pichon et al., 1993, p. 328). Although its mechanism is unknown, because it destroys rather than creates a rock record, it clearly augments the amount of material moving downward, and hence will generally tend to increase the thickness of the subducting layer.

The presence of early Tertiary rocks on the lowermost trench slope of the Marianas margin (Hussong and Uyeda, 1982) indicates that it has undergone long-term subduction erosion. If the plate interface is viewed as a relatively thin frictional fault between the overriding crystalline block and the downgoing basaltic slab, the lack of large earthquakes seems highly problematical, not only at Marianas but along the entire 3000-km-long Izu-Bonin-Marianas margin.

SUBDUCTION-CHANNEL MODEL

The subduction-channel model accounts quantitatively for sediment subduction, prism accretion, and melange formation (Shreve and Cloos, 1986), and qualitatively for a wide variety of subduction-zone phenomena (Cloos and Shreve, 1988b). Its basic premise is that, taken as a whole, unconsolidated sediment with near-lithostatic pore-fluid pressure deforms like a very viscous fluid (see Cloos and Shreve, 1988a, p. 485). An important consequence is that some sediment is always dragged downward between the plates, so that they are separated not by a relatively thin frictional fault, or decollement, but by a relatively thick shear zone, or "subduction channel."

Offscraping occurs where the sediment supply exceeds the capacity of the inlet of the subduction channel. Underplating occurs where, because of sufficiently low shear stresses, the sediment (or, in certain cases, upwelling melange) near the roof of the channel loses pore water to the hanging wall, becomes markedly more viscous, and attaches to the hanging wall (see Cloos and Shreve, 1988b, p. 520). Subduction erosion occurs where sufficiently high stresses detach pieces of the hanging wall, which become exotic blocks in the sediment (or melange) filling the channel.

NUCLEATION OF EARTHQUAKES

Because the interface between the converging plates is lubricated by a layer of underconsolidated sediment, the generation of large thrust-type earthquakes requires nucleation by asperities. One of us (Cloos, 1992) proposed that nucleation mainly occurs by near-basal rupture of >1000–2000-m-high basaltic seamounts when they jam against the roof of the subduction channel, and noted that their basal areas are comparable to the areas of asperities as determined from seismological studies. The number of suitable seamounts seems sufficient, inasmuch as on each 10^6 km^2 of sea floor there are on average 5 seamounts taller than 2 km and 165 taller than 1 km (Smith and Jordan, 1988).

The subduction-channel model (Shreve and Cloos, 1986) predicts profiles of the thickness of the sediment-filled shear zone. The computed thicknesses at five widely differing sites range from as little as ~250 m at Marianas, with no accretion, to locally as much as ~5000 m at northeast Japan. At Marianas the thickness gradually increases arcward, whereas at the other sites it is less regular but generally decreases arcward, especially at the "backstops" bounding the arcward sides of accretionary prisms.

Subduction erosion of the overriding block, as at Marianas, increases the amount of material being subducted and hence generally thickens the shear zone. Von Huene and Lallemand (1990) concluded that during the Tertiary the fore-arc blocks at north-

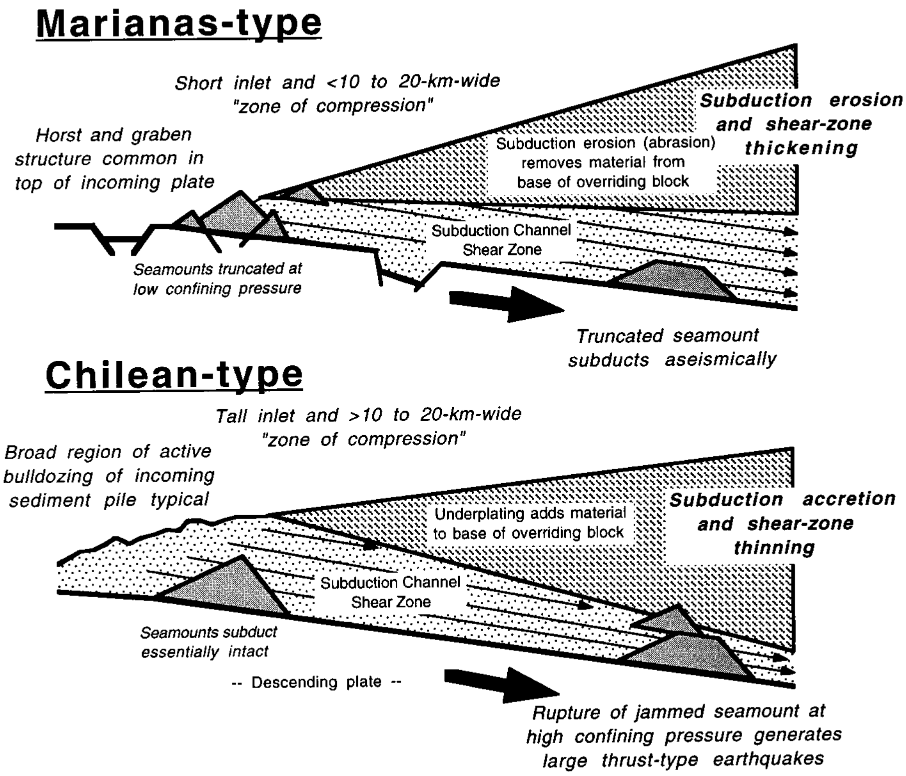

Figure 2. Schematic illustration of differences between Chilean- and Marianas-type margins. At Chilean-type margins, the sediment-filled subduction shear zone thins to arcward, hence large, thrust-type earthquakes occur, because seamounts are subducted nearly intact to high confining pressures before jamming against overriding plate. At Marianas-type margins, it thickens to arcward, hence no large earthquakes occur because seamounts are truncated at low confining pressure near inlet and never touch overriding plate farther arcward.

east Japan and Peru were removed by subduction erosion at rates of ~30–60 km^2/m.y. A comparable rate at Marianas, where the incoming sediment is ~150 m thick and the subduction speed including backarc spreading is ~8 cm/yr, would double the amount of subducting material in the arcward parts of the shear zone, increasing the thickness there to perhaps 600 m.

SUBDUCTION-ZONE SEISMICITY

The subduction channels of Chilean-type zones generally thin arcward from inlets that can be as high as several thousand metres, the most pronounced thinning being near crystalline backstops at the rear of accretionary prisms. Thus, tall subducted seamounts travel essentially intact to relatively great depths before jamming into the roof of the channel and becoming asperities (Fig. 2). Their near-basal detachment at high confining pressure generates large thrust-type earthquakes concentrated in distinct seismic fronts where the channel thins most abruptly.

The subduction channels of Marianas-type subduction zones, in contrast, generally thicken arcward from inlets that can be as little as 300 m high. Subducted seamounts, which may be "prefractured" by bending-induced normal faulting (Hilde, 1983) before reaching the inlet (Fryer and Hussong, 1985; Kobayashi et al., 1987), are truncated at low confining pressure as they enter the inlet (Fig. 2), and the associated earthquakes are small. Past the inlet, they cease being asperities and hence do not generate large earthquakes.

SEISMIC GAP HYPOTHESIS

Similar considerations bear on the debate (Kagan and Jackson, 1991, 1993, 1995; Stein, 1992; Nishenko and Sykes, 1993) about earthquake predictions made using the seismic-gap hypothesis of Sykes (1971), Kelleher et al. (1973), and McCann et al. (1979). The essence of the hypothesis is that seismic gaps are the most likely places for future large earthquakes. We suggest, however, that some seismic gaps may exist simply because the trench axis sediment is locally thin, subduction erosion occurs, and therefore shear-zone thickening downdip of the inlet precludes subducted seamounts from becoming seismogenic asperities.

Subducting bathymetric highs (e.g., the Carnegie and Louisville Ridges), which Kelleher and McCann (1976, p. 4885) long ago recognized as "zones of anomalous quiescence," in particular strongly reduce trench-axis sediment thickness by diverting sedimentary flows to either side. Other causes can be trapping of sediment in forearc basins, influx of sediment from major submarine canyons, damming of trench-axis turbidity currents by topographic barriers, such as subducting transform scarps, and even local climatic variations that control the supply of sediment. Large variations in sediment thickness in the Peru-Chile trench have been well documented by Schweller et al. (1981, p. 329, Fig. 4).

CONCLUSIONS

The presence of a relatively thick, sediment-filled shear zone, or subduction channel, that thins or thickens arcward depending on subduction speed and sediment supply, as opposed to a relatively thin fault, or decollement, readily explains the association of some seismic gaps with sediment-poor regions of subduction zones and the striking difference in seismic behavior between the Chilean- and Marianas-type subduction zones.

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