

Geodynamics of flat subduction: Seismicity and tomographic constraints from the Andean margin

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Abstract. The cause and geodynamic impact of flat subduction are investigated. First, the 1500 km long Peru flat slab segment is examined. Earthquake hypocenter data image two morphologic highs in the subducting Nazca Plate which correlate with the positions of subducted oceanic plateaus. Travel time tomographic images confirm the three-dimensional slab geometry and suggest a lithospheric tear may bound the NW edge of the flat slab segment, with possible slab detachment occurring down dip as well. Other flat slab regions worldwide are discussed: central Chile, Ecuador, NW Colombia, Costa Rica, Mexico, southern Alaska, SW Japan, and western New Guinea. Flat subduction is shown to be a widespread phenomenon, occurring in 10% of modern convergent margins. In nearly all these cases, as a spatial and temporal correlation is observed between subducting oceanic plateaus and flat subduction, we conclude that flat subduction is caused primarily by (1) the buoyancy of thickened oceanic crust of moderate to young age and (2) a delay in the basalt to eclogite transition due to the cool thermal structure of two overlapping lithospheres. A statistical analysis of seismicity along the entire length of the Andes demonstrates that seismic energy release in the upper plate at a distance of 250-800 km from the trench is on average 3-5 times greater above flat slab segments than for adjacent steep slab segments. We propose this is due to higher interplate coupling and the cold, strong rheology of the overriding lithosphere which thus enables stress and deformation to be transmitted hundreds of kilometers into the heart of the upper plate.

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1. Introduction

The 1500 km long segment of flat subduction beneath Peru and the associated volcanic gap have remained a puzzling phenomenon ever since their discovery [Barazangi and Isacks, 1976; Pilger, 1981; Hasegawa and Sacks, 1981]. During the past 20 years, various explanations have been offered for the unusual geometry of the Peru and other flat slab regions. These will be discussed in detail below. The geometry of the Nazca Plate beneath southern Peru, initially descending at an angle of 30° down to a depth of 100 km, before proceeding horizontally for several hundred km, was first constrained by a local seismic network [Hasegawa and Sacks, 1981; Boyd *et al.*, 1984; James and Snoke, 1994]. While the subduction of Nazca Ridge correlates spatially and temporally with this southern portion of the flat slab segment [Pilger, 1981; Nur and Ben-Avraham, 1981; McGeary *et al.*, 1985; von Huene *et al.*, 1996], its vast northward extent remained unexplained until the recent evidence for a second subducted plateau beneath northern Peru was put forward [Gutscher *et al.*, 1999a] (Figure 1). Thus the Peru segment is, in effect, composed of two adjacent flat slab regions. The combined buoyancy of Nazca Ridge and the completely subducted Inca Plateau support a 1500 km long segment of the Nazca Plate with an intervening lithospheric sag.

This paper investigates the fine three-dimensional structure, geodynamic development, and governing mechanism causing flat subduction beneath Peru, the Andean margin, and elsewhere. This phenomenon not only has direct implications for the seismicity and tectonics of Peru, but also, since a similar flat slab episode has been proposed during the North American Sevier-Laramide orogeny [Jordan *et al.*, 1983; Bird, 1984, 1988; Dumitru *et al.*, 1991], bears strongly on such models. Furthermore, the thermal and mechanical evolution of a slab undergoing flat subduction can be expected to govern the rheology and thus style of deformation in

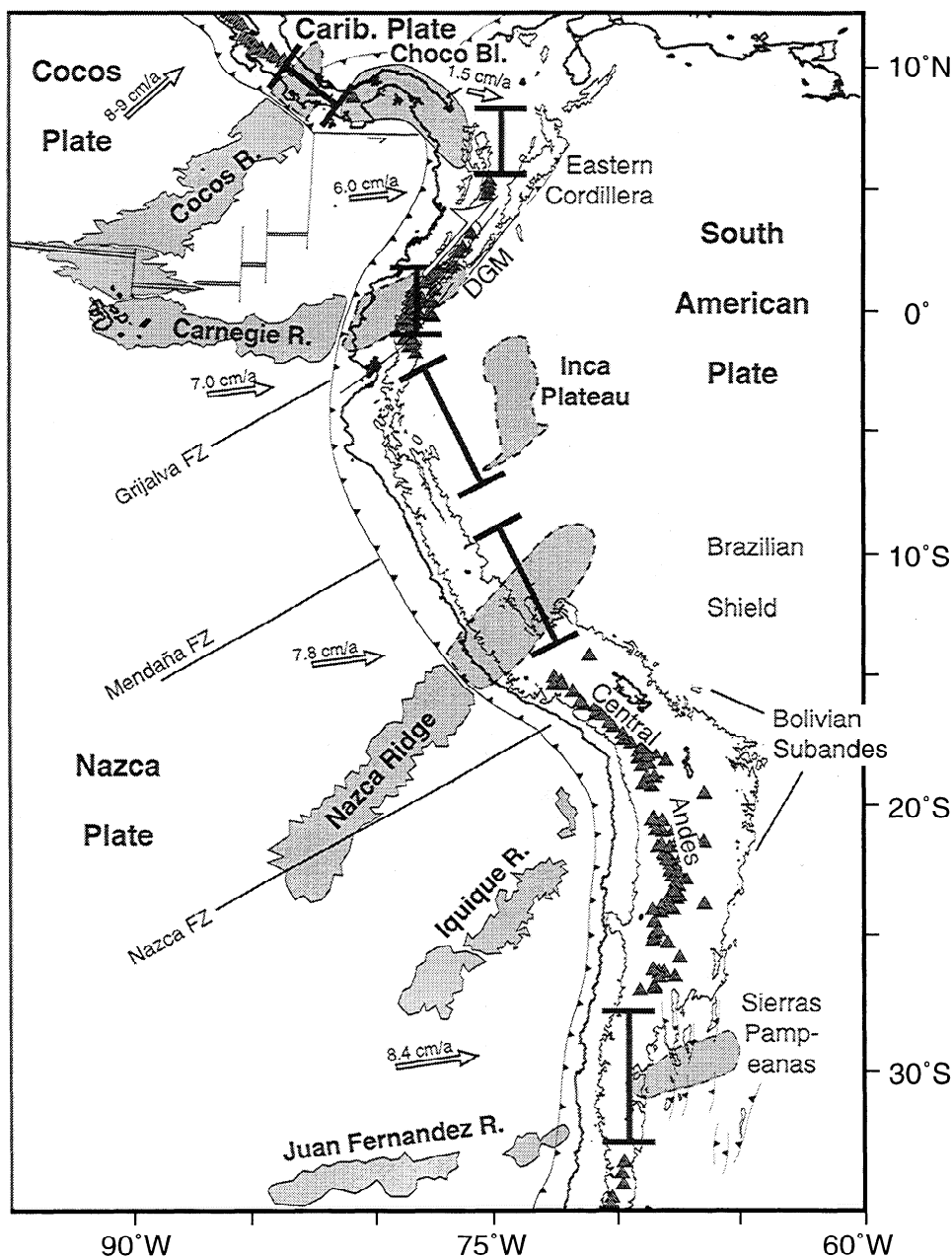


Figure 1. Tectonic setting of the Andean margin with flat slab segments indicated by thick brackets and subducting oceanic plateaus shaded gray. Andes are defined by the 2000 m contour with active volcanoes shown as black triangles. Inferred subducted plateaus (Inca Plateau) and uncertain continuations (e.g., Cocos, Carnegie, Nazca, and Juan Fernandez Ridges) are dashed. DGM is the Dolores-Guayaquil Megashear. Plate convergence vectors are based on a global kinematic model [DeMets *et al.*, 1990].

the upper plate giving rise to strong segmentation along strike [Jordan *et al.*, 1983; Isacks, 1988; Dumitru *et al.*, 1991]. The remarkable coincidence that the highest and broadest part of the orogen, the central Andes (including Puna and Altiplano, with a several hundred kilometer wide fold and thrust belt in the Bolivian Subandes), is flanked both to the north and to the south

by flat slab segments [Isacks, 1988; Gephart, 1994] suggests a causal, subduction-related mechanism linking these phenomena. Finally, it has been proposed that flat subduction may have been widespread during early stages in the Earth's history and contributed greatly to the process of continental growth in the Proterozoic and Archean [Vlaar, 1983; Vlaar, 1985; Abbott *et al.*, 1994].

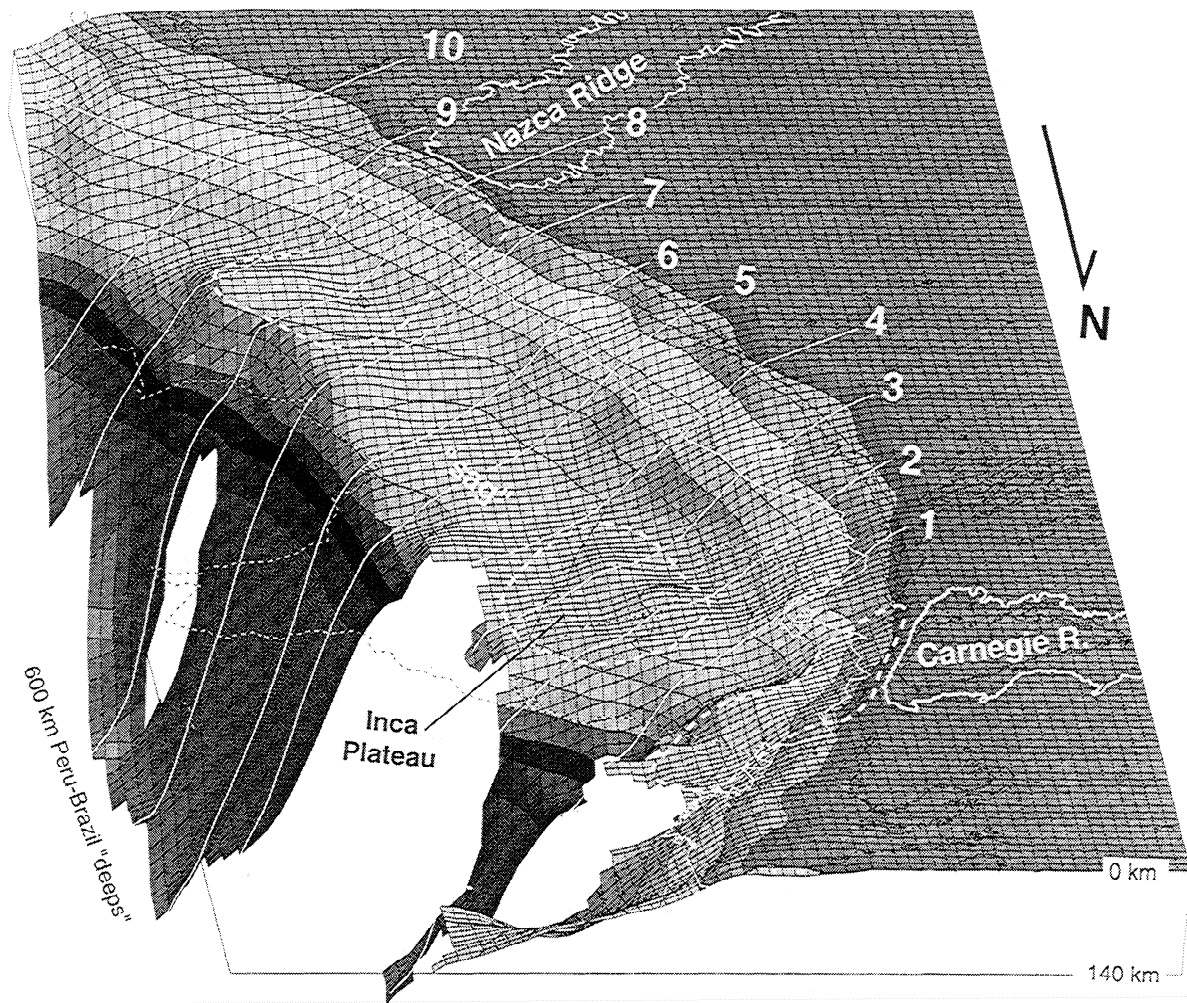


Figure 2. Three-dimensional view (looking south) of the subducted Nazca slab surface as determined from gridding of earthquake hypocenters. The location of oceanic plateaus at the surface and their estimated subducted positions (dashed) are shown. Two morphologic highs can be seen with an intervening “sag”. The highs correspond to the subducted continuation of Nazca Ridge and to the subducted Inca Plateau [Gutscher *et al.*, 1999a].

Indeed, recently published deep seismic data (SNORCLE) from the 1.9 G yr old, NW Canadian Slave Region image an accreted slab at 70 km depth, which appears to be a fossil flat slab [van der Velden and Cook, 1999].

2. Three-Dimensional Structure of the Subducted Nazca Plate

2.1. Seismicity Data

Relocated earthquake hypocenters [Engdahl *et al.*, 1998] were used to constrain the geometry of the subducting Nazca Plate in three-dimensions. A 3-D perspective view of the subducting Nazca Plate was obtained by gridding the location of earthquakes hypocenters along the Wadati-Benioff zone (Figure 2). This was achieved by filtering out upper plate seismicity (i.e.,

above 70 km beyond 200 km from the trench) and then applying a gridding algorithm with Generic Mapping Tools (GMT) software [Wessel and Smith, 1991]. The traces of 10 seismological cross sections (Figure 3) as well as the estimated positions of subducted oceanic plateaus are shown. The 3-D view clearly images two morphologic highs in the Nazca Plate beneath Peru, one corresponding to the subducted continuation of Nazca Ridge and one corresponding to the predicted position of the subducted Inca Plateau based on plate kinematic reconstructions [Gutscher *et al.*, 1999a]. Between these two highs is a saddle-shaped lithospheric sag between 5° and 8°S. This is consistent with the recent interpretation of the 1500 km long Peru flat slab as a “double flat slab”, with two light bodies each supporting approximately 500 km of the Nazca Plate [Gutscher *et al.*, 1999a].

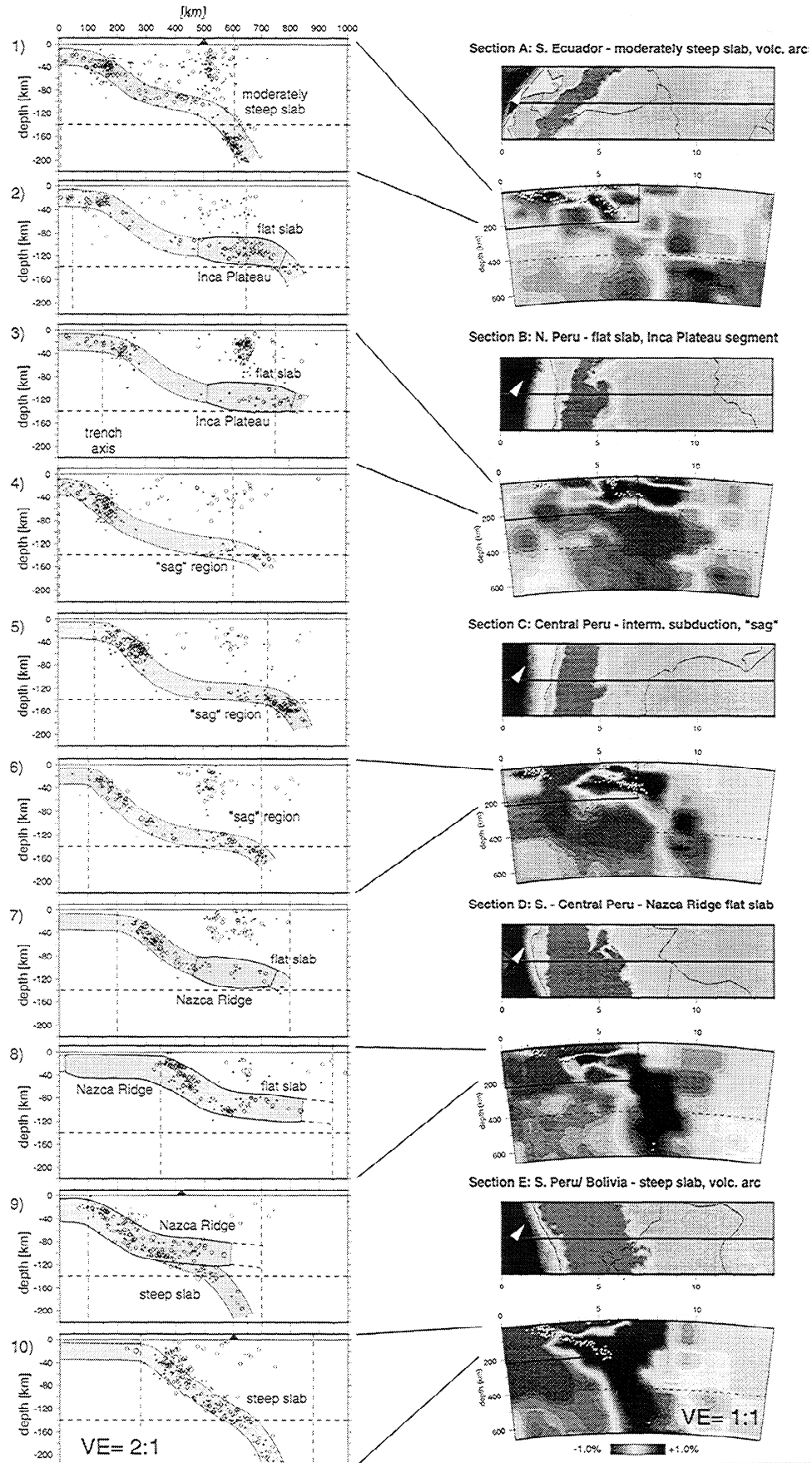


Figure 3.

A series of 10 ENE oriented 2-D cross sections perpendicular to the trench and to the Andes are presented in Figure 3 (left), each with a sampling width of 1° latitude. They cover, from north to south, a moderately steep slab in southern Ecuador (section 1), the flat slab due to Inca Plateau (sections 2 and 3), the sag region (sections 4-6), the flat slab due to Nazca Ridge (sections 7 and 8) and the steep slab in southern Peru/Bolivia (sections 9 and 10). While the sag is not a major first-order feature, earthquakes in this region are roughly 20 km deeper than those in the flat slab to the north (Inca Plateau) and 40 km deeper than in the flat slab to the south (Nazca Ridge). The maximum distance of penetration of the horizontal slab corresponds to the northern Inca plateau. Here the horizontal plate bends down steeply or “resubducts” some 700 km from the trench (section 2), whereas in the sag region (section 6) resubduction occurs 500-600 km from the trench. Although the continuation of Nazca Ridge represents the shallowest portion of the flat slab, at depths between 80 and 100 km (sections 8 and 9), it is not possible to determine the distance of penetration based on hypocenters alone, owing to the seismic gap here, though the tomographic image (Figure 3, section D, see also below) suggests penetration of up to 800 km.

2.2. Tomographic Model

Tomographic models can reveal information about lithospheric and mantle structure at great depths and in regions where no information is available from in situ seismicity [Engdahl *et al.*, 1995]. Improvements in the inversion techniques of global earthquake travel time data now allow resolution comparable to regional tomographic studies [Bijwaard *et al.*, 1998]. The tomographic velocity model is a global model obtained by a travel time inversion based on 82,000 well-constrained earthquakes from a global relocated hypocenter data set [Engdahl *et al.*, 1998], using 7.6 million P and pP arrivals with absolute residuals <7.5 s. The descending oceanic lithosphere can be seen as zones of higher seismic velocities (darkest shading) due to the colder,

denser material. Earthquakes are shown as small white circles.

The vertical cross sections (Figure 3, right) constrain the geometry of the downgoing Nazca Plate in three dimensions. They correspond to seismicity sections 1, 3, 6, 8 and 10 respectively. In southern Ecuador (Figure 3, section A) the Nazca Plate dips moderately steeply toward the NE, curving gently down to a depth of 600 km, where the great 1970 Colombia earthquake occurred. In northern Peru the flat slab near Inca Plateau is sampled and is shown to “underslide” the South American lithosphere horizontally for roughly 800 km (Figure 3, section B). The lack of continuity between this flat slab portion and the subducted lithosphere at 500-600 km depth suggests slab detachment has likely occurred here, perhaps along an age discontinuity as described by previous authors [Vlaar and Wortel, 1976; Wortel, 1984]. Spike tests (not shown) indicate moderate resolution at these depths (200-400 km) and suggest the slab detachment imaged is not an artifact. In the sag region (Figure 3, section C) the overall plate dip is transitional between the flat slab north and south. Here the Nazca Plate curves gently, becoming steeper as it descends and is relatively continuous. Near Nazca Ridge (Figure 3, section D) the slab is again shown to proceed horizontally, undersliding the South American lithosphere over 500 km before bending sharply at a nearly 90° angle and descending almost vertically to the 670 km discontinuity. Finally, the section beneath southern Peru reveals a steep slab segment, descending continuously and curving smoothly toward the 670 km discontinuity (Figure 3, section E).

The horizontal sections (Figures 4a-4d) reveal velocity variations in layers of 50 km thickness. Wadati-Benioff contours are also shown based on an analysis of hypocenters [Gutscher *et al.*, 1999a] and correlate well with the depth range of the high-velocity anomalies. The abrupt northern termination of the flat lying lithospheric slab (top left corner of Figure 4b) suggests slower, warmer material to the NW and supports the hypothesis of a lithospheric tear beneath south-

Figure 3. left: ten seismicity cross sections perpendicular to the trench using relocated hypocenter data, scaled by magnitude. Each section has a sampling width of 1° . The vertical dashed lines represent the trench axis and the position 600 km inboard. (vertical exaggeration) VE = 2:1. The sections sample, from north to south, the steep slab in southern Ecuador (section 1), the flat slab due to Inca Plateau (sections 2 and 3), the intervening sag (sections 4-6), the flat slab due to Nazca Ridge (sections 7 and 8) and the steep slab in southernmost Peru (sections 9 and 10). Right: Tomographic images, cross sections: section A, southern Ecuador, moderately steep NE dipping slab, volcanic arc; section B, northern Peru flat slab, Inca Plateau segment, no volcanic arc, with possible slab detachment; section C, “sag” region, no volcanic arc; section D, Nazca Ridge flat slab segment, shallowest region, no volcanic arc, sharp kink; section E, southern Peru steep slab, volcanic arc. (no vertical exaggeration) VE = 1:1. Here and in Figures 4 and 5, darkest shading = fast velocities = dense, cold lithosphere, medium gray (see gray scale) = slow velocities = hot, light material (below 100 km depth typically asthenosphere).

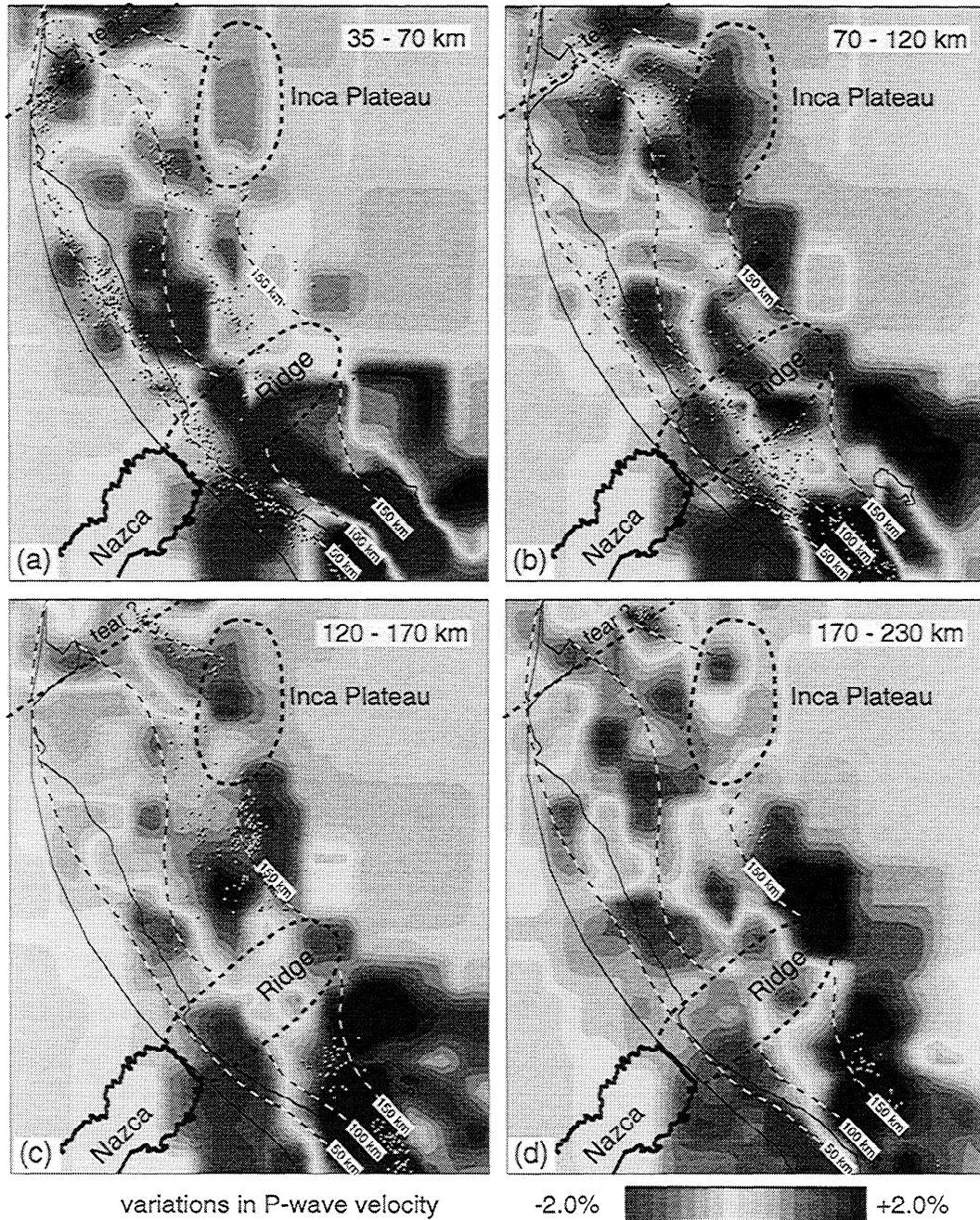


Figure 4. Tomographic images, horizontal layers: (a):35-70 km; b: 70-120 km; c: 120-170 km; 170-230 km. Positions of known (solid) and inferred (dashed) subducted oceanic plateaus shown.

ern Ecuador along the continuation of the ENE trending Grijalva fracture zone [Pennington, 1981; Hall and Wood, 1985; Gutscher et al., 1999b].

3. Discussion

3.1. Flat Subduction: Other Regions

Before addressing the question, What causes flat subduction?, it is useful to examine other regions where this phenomenon is observed and thus gain insights through

comparative analysis. While the Peru flat slab segment is by far the longest, the central Chile flat slab segment extending from 28° to 32°S is equally well documented [Pilger, 1981; Smalley and Isacks, 1987; Cahill and Isacks, 1992; Kay and Abbruzzi, 1996]. Here the Juan Fernandez Ridge is currently subducting below the margin at 31°S [Pilger, 1981; 1984; von Huene et al., 1997]. In contrast to Peru, only one buoyant structure is present, and accordingly, the flat slab segment and volcanic gap are only 500 km in width. As in Peru

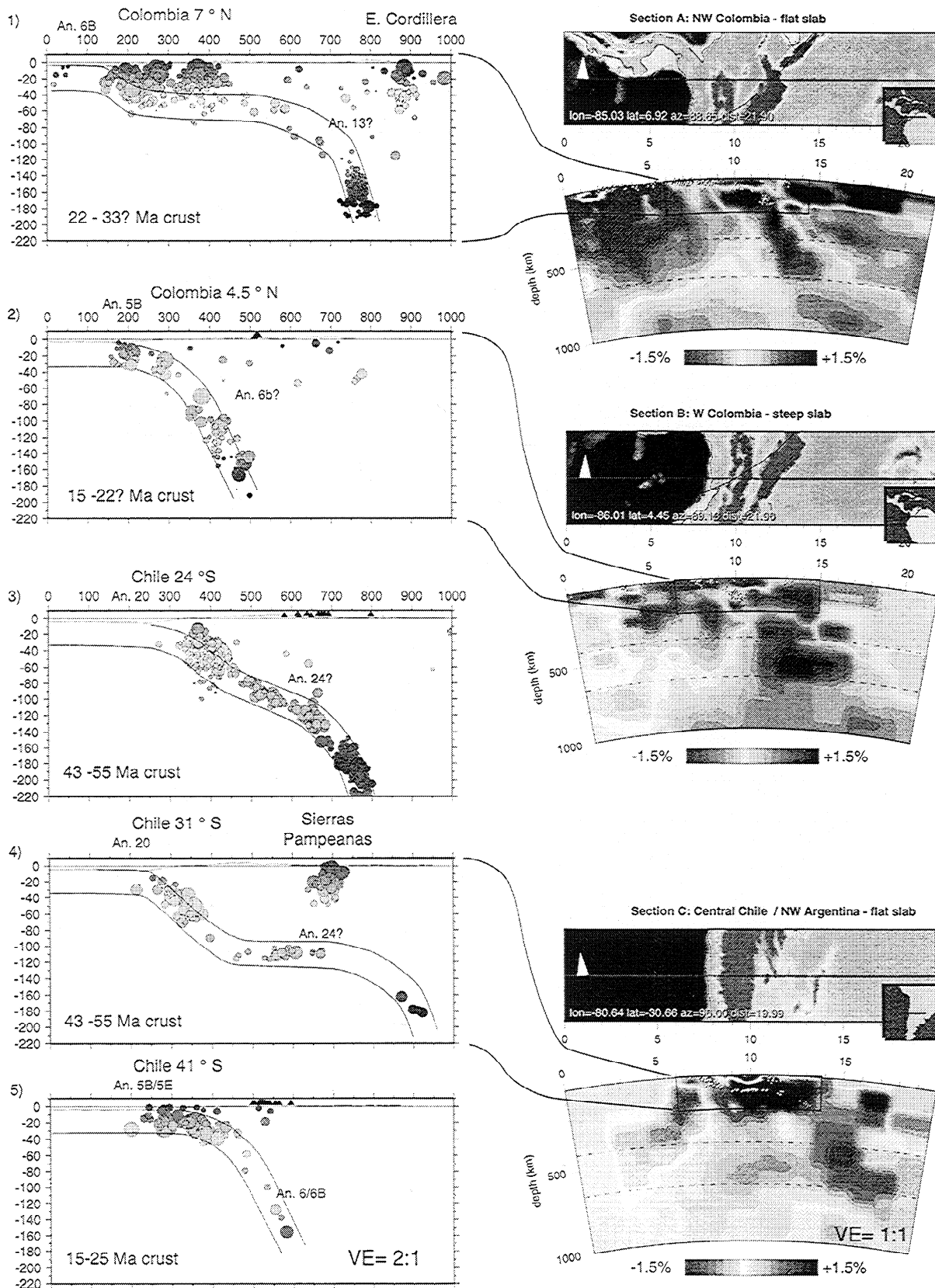


Figure 5. (left) Five representative seismicity cross sections from several different steep and flat slab segments along the Andes with known age of subducting oceanic lithosphere at the trench and estimated age beneath the arc (when present). $VE = 2:1$. Note there is no direct correlation between young lithosphere and flat subduction. (right) Tomographic images, cross sections: section A, NW Colombia flat slab, no volcanic arc; section B, western Colombia steep slab, volcanic arc; section C, central Chile / NW Argentina flat slab, no volcanic arc. $VE = 1:1$.

Table 1. Flat Slab Segments Worldwide

	Region ^a	L, ^b km	Thickened Crust?	Age, ^c m.y.	V, ^d cm/a	Arc ^e	Adk, ^f m.y.	Deform. ^g
1	Chile (28°-33°S)	550	Juan-Fernandez R.	43	8.4	no	4-7	C
2	Peru (2°-15°S)	1500	Nazca R., Inca Plat.	30-43	7.8	no	3-6	C, SS, E
3	Ecuador (1°S-2°N)	350	Carnegie Ridge	16-24	7	yes	0-3	C, SS
4	Colombia (6°-9°N)	350	Choco / Carib. Plat.	20	6	no	-	C, SS
5	Costa Rica (82°-84°W)	250	Cocos Ridge	14-20	8-9	no	1-3	C
6	Mexico (96°-100°W)	400	Tehuantepec R.	13-20	6-8	yes	-	minor
7	Cascadia (46°-49°N)	350	-	8	4	yes	0	C
8	Alaska (145°-150°W)	500	Yakutat Terrane	45	6	no	0	C, SS
9	SW Japan (132°-137°E)	600	Izu-Bon., Pal.-Ky. R.	15-20	4	yes	0	SS
10	New Guinea (136°-142°E)	550	Euripik Ridge	20	4-9	no	2-4	C, SS

^aSources: 1, *Pilger* [1981], *Cande and Haxby* [1991], and *Kay and Abbruzzi* [1996]; 2, *Barazangi and Isacks* [1976], *Petford and Atherton* [1996], and *Gutscher et al.* [1999a]; 3, *Lonsdale and Klitgord* [1978], *Monzier et al.* [1997], and *Gutscher et al.*, [1999b]; 4, *Pennington* [1981], *Hardy* [1991], and *van der Hilst and Mann* [1994]; 5, *Defant et al.* [1993] and *Protti et al.*, [1994]; 6, *McGeary et al.* [1985], *Suarez et al.* [1990], and *Singh and Mortera* [1991]; 7, *Crosson and Owens*, [1987] and *Defant and Drummond* [1993]; 8, *Pennington*, [1984] and *Brocher et al.* [1994]; 9, *Hirahara* [1981], *Morris* [1995], and *Gutscher and Lallemand* [1999]; 10, *McGeary et al.* [1985], *Pubellier et al.* [1998], and *Okal*, [1999]

^bLength of flat slab segment, along trench. Cumulative length is 5400 km, or 10% of modern convergent margins.

^cAge of the subducting oceanic lithosphere at trench.

^dRelative plate velocity.

^ePresence of Quaternary volcanic arc.

^fAge of adakitic volcanism, if present. A zero indicates adakitic geochemical signature in modern arc magmas.

^gUpper plate deformation based on earthquake focal mechanisms. C, compressional (thrusting); SS, strike-slip; E, extensional (normal). In most cases the P axes are aligned parallel to the relative plate motion (i.e., see Figure 9).

the Nazca Plate proceeds subhorizontally for 300 km at a depth of about 100 km (Figure 5). The tomographic image from central Chile confirms this well established flat slab geometry (Figure 5, section C).

There are several other subduction zones worldwide exhibiting an "abnormal" flat to low-angle subduction geometry. In general, these are not as well constrained as central Chile or Peru and subsequently, are less well known. In nearly all these cases, as in Peru and Chile, subducting plateaus or arcs are associated spatially and temporally with this anomalous style of subduction (Table 1). In Ecuador, Carnegie Ridge subducts beneath the northern Andes [*Pennington*, 1981; *Gutscher et al.*, 1999b] (Figure 1). In NW Colombia, the Panama/Choco Block is colliding with South America [*Pennington*, 1981; *McGeary et al.*, 1985]. A portion of the Caribbean Plateau is subducting along the North Colombia Deformed Zone toward the SE while others portions may currently be undersliding Colombia from the west [*van der Hilst and Mann*, 1994] (Figure 1). The tomographic image (Figure 5, section A) supports this flat slab interpretation for NW Colombia. In Costa Rica, Cocos Ridge subducts at the termination of the Middle America Trench [*Gardner et al.*, 1992; *Protti et al.*, 1994, 1995; *Kolarsky et al.*, 1995] (Figure 1). In southern Mexico a short flat slab segment (200-300 km downdip length) appears to bottom out at a shallow depth of only 50 km, implying an unusually thin continental

lithosphere [*Suarez et al.*, 1990; *Singh and Mortera*, 1991]. In southern Alaska the accretion of the Yakutat Terrane, a buoyant block of thickened crust, along the easternmost Aleutian Trench causes a remarkable flattening of the angle of subduction as constrained by the great trench arc gap of 600 km, by abundant earthquake hypocenters, and by wide-angle seismic data [*Pennington*, 1984; *Brocher et al.*, 1994]. The Juan de Fuca slab beneath Cascadia also descends at a very shallow angle [*Crosson and Owens*, 1987], although in this case, no thickened crustal block has been identified at present. At the Nankai trough, oceanic lithosphere flanked by the Izu-Bonin Arc and Palau-Kyushu Ridge underslides SW Japan at 50-70 km depth [*Hirahara*, 1981; *Sacks*, 1983; *Morris*, 1995; *Gutscher and Lallemand*, 1999; *Gutscher*, 2000]. Finally, there is the New Guinea thrust beneath Irian Jaya [*Okal*, 1999]. This subduction system, with no known arc volcanism, also appears to exhibit flat slab behavior, likely related to the subducting Euripik Ridge, a 2 km high oceanic plateau [*McGeary et al.*, 1985].

In many cases of flat subduction an intermediate depth seismic gap is present [*McGeary et al.*, 1985; *McCann and Habermann*, 1989], and thus the geometry of the slab below 60 km depth must be constrained by indirect observation (e.g., tomographic, volcanological, etc.). In Colombia and Costa Rica a volcanic gap correlates with the position of the subducting arc or

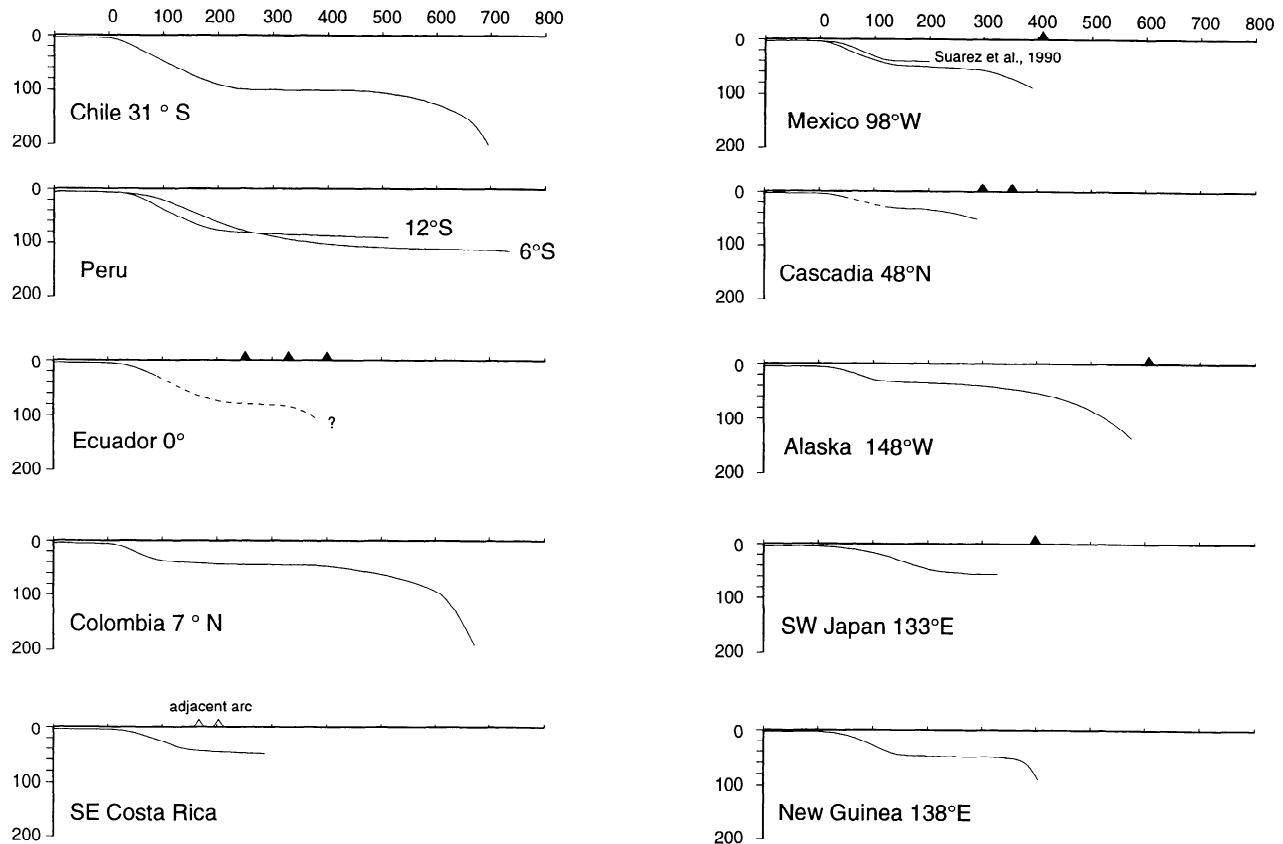


Figure 6. Slab geometries from all 10 flat slab regions worldwide based on our analysis of hypocenter data. All sections are shown at the same scale, VE = 1:1. In Alaska [Brocher *et al.*, 1994], Cascadia [Parsons *et al.*, 1998], Costa Rica [Bialas *et al.*, 1999], and SW Japan [Kodaira *et al.*, 2000] constraints on the upper 20-30 km are available from wide angle seismic data. Note there are typically up to three inflection points as the slab steepens at the trench, flattens for one to several hundred km and then finally steepens again.

ridge, while in Ecuador a broad arc is present. In Costa Rica/Panama, Ecuador, and SW Japan, anomalous “adakitic” geochemical signatures are found in relic or present-day arc magmas [Defant *et al.*, 1993; Monzier *et al.*, 1997; Morris, 1995]. In central Chile, adakitic signatures were found in the relic (6-12 Ma) arc and attributed to the shallowing of the subducting slab [Kay and Abbruzzi, 1996]. Such adakitic magmas have been attributed to partial melting of very young (<10 m.y. old) oceanic crust [Defant and Drummond, 1990; Peacock *et al.*, 1994], although paradoxically, they are commonly found in many arcs where crust of moderate age (45-10 m.y. old) is subducting (Table 1). This intriguing correlation between adakitic magmas and many flat slab segments suggests a possible link to the evolution of flat subduction, but this subject is beyond the scope of this paper and is discussed elsewhere [Gutscher *et al.*, 2000].

The global tomographic model [Bijwaard *et al.*, 1998] has been examined for the subduction zones listed in Table 1, interpreted to exhibit flat to low-angle subduc-

tion behavior. For Peru (Figure 3, sections B and D), central Chile (Figure 5, section C), NW Columbia (Figure 5, section A) and southern Alaska (not shown) the tomographic images confirm an underthrusting of the oceanic plate over several hundred kilometers at a low angle as constrained by the hypocenter data. In regions where relatively young, thus warm, oceanic lithosphere is subducting (Ecuador, Costa Rica, Mexico, Cascadia, and SW Japan), no flat slab is clearly visible. This may be attributed to lack of resolution in the upper 100 km and/or the possibility that a relatively warm slab may not possess sufficient seismic velocity contrast with respect to the ambient mantle. In other regions (e.g., western New Guinea) the spatial resolution is too poor to draw inferences. In all cases, however, the tomographic model does not exclude the presence of a flat slab. On the basis of our analysis of (1) earthquake hypocenter data [Engdahl *et al.*, 1998], (2) the tomographic images discussed above, and (3) published deep seismic data, simplified sections of the subducting slab geometry have been compiled for all 10 of these regions

(Figure 6) at the same scale, without vertical exaggeration. This allows an objective assessment of slab dip while illustrating the range of observed flat subduction geometries. Typically, up to three inflection points are present, and it is immediately apparent that this complex curvature cannot be accurately described with a single value for slab dip.

3.2. What Causes Flat Subduction?

Let us examine some of the models previously proposed to explain the phenomenon of flat subduction. For the particular case of Peru the large northward extent of the flat slab region was proposed to be caused by other unknown plateaus. One suggestion was an offset continuation of Carnegie Ridge [Pennington, 1981]. This is not easily ruled out, but there are no compelling arguments to support it. It further necessitates that the Carnegie Ridge trace be older than the breakup of the Farallon Plate into Cocos and Nazca Plates at 25 Ma [Hey, 1977; Lonsdale and Klitgord, 1978]. Finally, if this were the cause, then why is there a short section of steep slab (between 1° and 2°S) between the proposed subducted offset continuation and the portion of Carnegie Ridge currently subducting at the trench? A second suggestion was a northward kink in the subducted portion of Nazca Ridge [Pilger, 1981]. This is not supported by recent kinematic reconstructions [Cande and Haxby, 1991; Gutscher et al., 1999a]. More importantly, the prominent intermediate depth seismic gap and the shallowest portion of the flat slab (<100 km depth) and the low velocity region imaged in the tomography (Figure 4c) are directly in line with the trend of Nazca Ridge at the trench, thus contradicting this model.

The following hypotheses have also been put forth to explain flat subduction in general.

1. The first is interplate hydrostatic suction [Jischke, 1975]. This may contribute once two lithospheres are in contact, but since this force could potentially act everywhere where one plate subducts beneath another it does not answer the question, Why does flat subduction occur in Peru and central Chile (and elsewhere) and why not everywhere?

2. The second is subduction of very young, warm and thus buoyant lithosphere [Vlaar and Wortel, 1976; Wortel and Vlaar, 1978; Vlaar, 1983; Sacks, 1983; Cloos, 1993; Abbott et al., 1994]. Age certainly is an integral part of buoyancy and for extreme cases (i.e., <5 m.y. old lithosphere) may induce flat subduction. However, age alone seems insufficient to explain most areas of flat subduction. Counter-examples include western Colombia between (3°-5°N) [Pennington, 1981; Gutscher et al., 1999b] and south central Chile (40°-42°S), where moderately young oceanic lithosphere 15-25 m.y. old (magnetic anomalies 5 - 6) subducts steeply to >150 km beneath an active volcanic arc (Figure 5). A further

counterexample is Mexico (105°-103°W), where very young oceanic lithosphere 3-10 m.y. old (directly adjacent to the East Pacific Rise) subducts steeply to the north. The plate dip is well constrained by intermediate depth seismicity and by the narrow 150-200 km trench arc gap [Singh and Mortera, 1991]. Contrary to these areas, the age of the oceanic crust at the Peru trench is 30-43 m.y. old (magnetic anomalies 10-20) [Gutscher et al., 1999a] and for the central Chile flat slab is 43 m.y. (anomaly 20) [Cande and Haxby, 1991] (Figure 5). Thus, while lithospheric age influences the buoyancy, it does not seem to be the primary controlling factor.

3. A third hypothesis is a delay in the basalt to eclogite transition [Sacks, 1983; Pennington, 1984]. Thermal shielding occurring as a result of superposition of two lithospheres can delay the temperature- and pressure-dependent metamorphic reactions involved in the transformation of basalt amphibolite to the 15% denser garnet eclogite phase. This appears to be a both logical and necessary factor contributing to the development of flat subduction. Like hypothesis 1, it does not directly answer the question, Why here?, but [Sacks, 1983] adds "the buoyant zones contain aseismic ridges." We agree with this analysis.

4. A fourth suggestion is the curvature of the margin [Bevis, 1986; Cahill and Isacks, 1992; Gephart, 1994]. While the Peru margin exhibits an overall gentle convex shape, the sharpest curve is around Ecuador, where a moderately steep subduction segment and narrow arc are observed between 1° and 2°S [Pennington, 1981; Gutscher et al., 1999b]. Furthermore, the central Chile flat slab occurs along a straight section of margin with almost no curvature. There are other convex margins all around the world where 20-50 m.y. old oceanic lithosphere (comparable to the ages of Andean flat slab lithosphere) descends at a steep angle (e.g., Sandwich Arc, New Hebrides Arc, Ryukyu Arc). Thus the predictions of this model are not borne out by the observations. Such "membrane forces" may play a role when very young, neutrally buoyant crust is subducted and has been suggested to explain shallow subduction beneath northern Cascadia [Crosson and Owens, 1987].

5. A fifth hypothesis is rapid absolute motion of the upper plate, which is considered to override the oceanic lithosphere faster than the latter can sink [Cross and Pilger, 1982; Olbertz et al., 1997]. This is the case with South America in general, which is sweeping west in response to the opening of the South Atlantic at an absolute velocity of 3-4 cm/a. This has often been invoked to explain the difference between the supposed Chilean or Andean (low angle) style of subduction versus the Marianas (steep) style of subduction [Uyeda and Kanamori, 1979]. A careful examination of the Andean margin, however, shows this terminology to be inappropriate. As shown in Figure 5 and Figure 1, there are at least 5

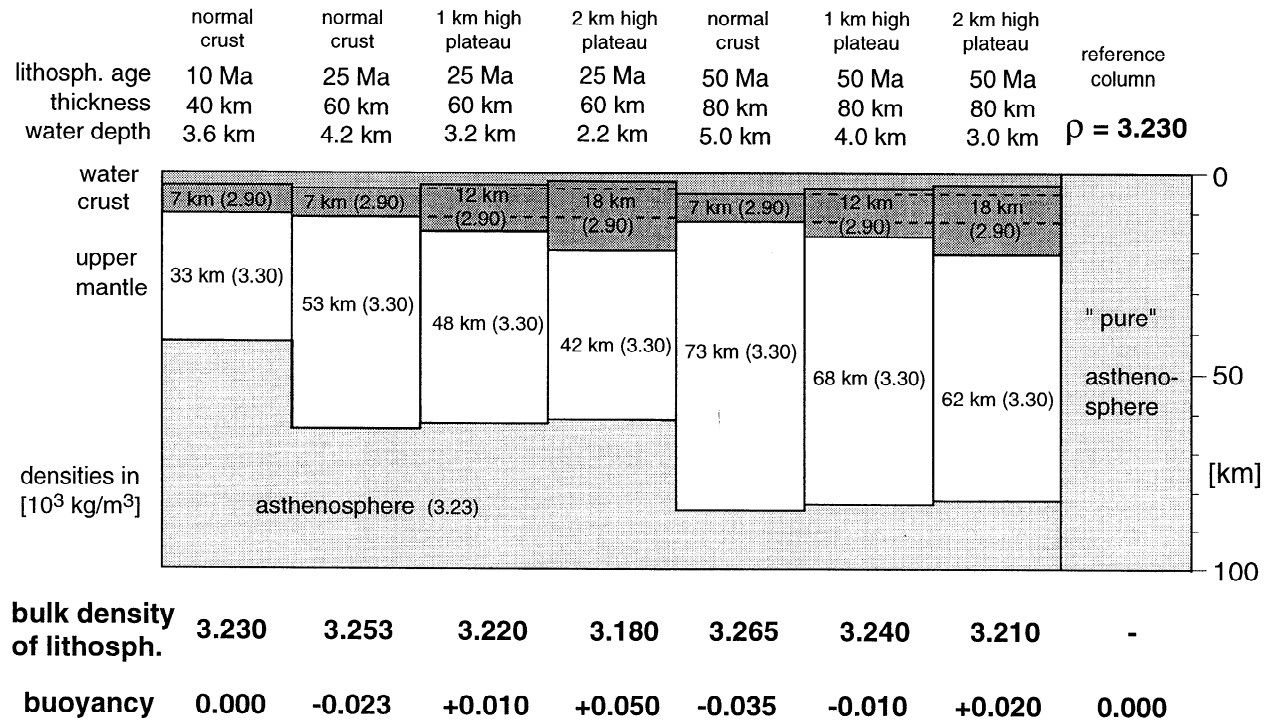


Figure 7. Buoyancy of plateaus and oceanic crust. Isostatic columns for 10–50 m.y. old oceanic lithosphere are compared to a 100 km deep reference column of asthenosphere assuming no eclogitization. (see text for discussion).

abrupt changes in subduction style along the length of the Andes from flat to steep to flat to steep, and so on. Colombia (4°N), Bolivia, and south central Chile (34°–42°S) with subduction angles of 20°–30°, are most certainly Andean and not low angle subduction. A general tendency towards low angle subduction as a result of rapid absolute upper plate motion may be accentuated by the other factors discussed above: along-strike variation in lithospheric age (and thus buoyancy) of the subducted slab, variations in relative plate motions (caused by along strike variations of the margin geometry) and the positive buoyancy of oceanic plateaus. Thus, we cannot exclude a contribution of absolute motion to (regional) flatness of subduction. Further, we cannot exclude dynamic effects from along strike variations in regional mantle convection, e.g., local upwelling, downwelling, or horizontal currents.

Summing up, while a variety of factors may contribute, the one perturbing element which seems to be involved in nearly all cases of flat subduction is the presence of overthickened oceanic crust. Thus, on the basis of this comparative analysis it would appear that the simplest explanation, crustal buoyancy, is the best candidate to explain flat subduction.

Therefore let us examine the buoyancy forces involved in the subduction of an oceanic plateau in order to determine whether these are sufficient to inhibit normal

step subduction. Assuming the simplest case of Airy isostasy, a uniform crustal density of 2900 kg/m³, and a density contrast of 400 kg/m³ at the crust mantle boundary, then a 1 km high plateau in isostatic equilibrium corresponds to an anomalous oceanic crust 12 km thick, and a 2 km high plateau corresponds to an 18 km thick crust (Figure 7). Upon subduction the entire lithosphere (plateau/crust and uppermost mantle), is “immersed in asthenosphere” and the buoyancy (i.e., subductability) is simply a measure of the mean bulk density of the subducted lithosphere compared to the surrounding asthenosphere. The isostatic and buoyancy calculations presented here are based largely on a similar analysis [Cloos, 1993] but are targeted more to the question of subduction of overthickened (plateau or arc) oceanic crust.

Our calculations demonstrate that for reasonable crustal, mantle and asthenosphere densities, a 2 km high, 18 km thick oceanic plateau is sufficiently buoyant to support itself and an adjacent portion of slab of comparable width for lithospheric ages of up to 50 m.y. (those encountered in known flat slab segments). For example a 200 km wide, 18 km thick plateau and 110 km of normal 50 m.y. old oceanic lithosphere, taken together will have a neutral buoyancy and will likely produce a 310 km wide flat slab segment. A more modest 1 km high, 12 km thick plateau can barely

support itself for 25 m.y. old lithosphere, and for 50 m.y. old lithosphere, the column is denser than the surrounding asthenosphere and will thus subduct normally. This appears to be the case for the 10-15 km thick Hikurangi Plateau, embedded in Cretaceous age lithosphere and therefore subducting beneath North Island New Zealand at a steep angle [Davy and Wood, 1994; Eberhart-Phillips and Reyners, 1997]. Conversely, thicker plateaus will presumably be able to support even wider flat slab segments. The above values correspond to the range of crustal thicknesses reported for several oceanic plateaus worldwide, Galapagos (14-18 km) [Feighner and Richards, 1994], Tuamotu (30-32 km) [Talandier and Okal, 1987], Cocos Ridge (18 km) [Bialas et al., 1999], Nazca Ridge (17 km) [Bialas et al., 2000], Marquesas (14-18 km) [Caress et al., 1995], and Kerguelen (20-30 km) [Charvis et al., 1995], suggesting that these globally abundant structures are capable of altering the mode of subduction of moderately old <60 m.y. crust. Most of the flat slab segments around the world caused by single plateaus, (e.g., central Chile, Ecuador or Costa Rica) exhibit lateral widths from 300 to 500 km. Larger widths (600-1500 km) are observed for plateau pairs (i.e., SW Japan, Peru). The scale of these global flat slab segments matches well with the sizes predicted by the buoyancy calculations. Once oceanic lithosphere becomes much older (e.g., 80 m.y. old and 100 km thick [Cloos, 1993]) and denser, flat subduction becomes nearly impossible.

3.3. Impact of Flat Subduction: Interplate Coupling, Deformation and Thermal Structure

While it has been pointed out by previous workers that upper plate seismicity is more abundant above flat slab regions than over neighboring steep slab segments [Jordan et al., 1983; Smalley et al., 1993], no study has attempted to quantify this variation. We present a statistical analysis of the upper plate seismicity along the entire length of the subducting Nazca Plate, from 8°N to 44°S in Figure 8. This covers the two best documented flat slab regions in Peru and central Chile as well as two inferred shorter flat slab segments in Ecuador (Carnegie Ridge) and Colombia (Choco Block) (Figure 1). The seismic energy released by each earthquake is calculated and summed up in each 1° north-south box for a distance of 250-800 km from the trench. This spans from west of the volcanic arc (when present), across the central cordillera and in all cases, except the 800 km wide central Andes and Bolivian sub-andes (where the Brazilian Shield is underthrust to the west), all the way to the undeformed foreland. The histogram analysis of the seismicity demonstrates that the seismic energy released in the upper plate above flat slab segments is on average 3-5 times greater than in adjacent steep (>30° dipping) slab segments. In some extreme cases, there is more than an order of magnitude differ-

ence (i.e., central and southern Chile). Published [Jordan et al., 1983; Suarez et al., 1983; Gutscher et al., 1999b] and regional earthquake focal mechanisms (Figure 9) are predominantly compressional (thrust type) to transcurrent (strike-slip) with P axes typically aligned parallel to the plate motion (east-west) suggesting the subduction plate boundary stresses are transmitted far (several hundred km) into the heart of the upper plate.

We attribute this increased seismicity to an overall increase in viscous interplate coupling between the two lithospheres (Figure 9). Because the interplate interface is up to 400-500 km long for flat subduction (compared to 100-200 km for steep subduction), plate boundary forces are transmitted more effectively to the upper plate. The fact that the increase in seismic energy released (a factor of 3-5 times greater for flat slab segments) corresponds well to the increase in interplate contact area suggests a causal link between these quantities as proposed previously by other workers [Cross and Pilger, 1982]. While it is generally believed that the base of the lithosphere deforms plastically and therefore releases accumulated stress aseismically, numerical calculations show that stress can still be transmitted from the subducting plate to the crustal regions of the over-riding plate [Spencer, 1994]. Increased interplate coupling above flat slab regions has also been suggested to be responsible for thick-skinned deformation in the upper plate, resulting in large-scale block-type uplifts as in the Pampeanas Range [Jordan et al., 1983; Smalley et al., 1993] and in the Eastern Cordillera of Colombia (Figures 1 and 9). Many workers have suggested a similar origin for the eastern Rockies Laramide uplifts [Jordan et al., 1983; Bird, 1984, 1988; Dumitru et al., 1991].

Interplate coupling also appears to be an important factor governing strain partitioning in cases of oblique convergence as suggested by analog modeling and numerical modeling [Pinet and Cobbold, 1992; Pubellier and Cobbold, 1996; Chemenda et al., 2000], yet the mechanism for modifying this parameter remains unclear. We have shown that flat subduction increases interplate coupling and suggest that flat subduction will enhance strain partitioning at a position far inboard of the trench forearc region (Figure 10). Two prominent examples provide useful insights, the NW Andean margin and SW Japan. In both cases convergence is 20°-40° with respect to trench normal, and major dextral strike-slip motion occurs. GPS data suggest displacement of the north Andes block by 1-2 cm/a along the Dolores-Guyaquil megashear (Figure 1) [Kelllogg and Vega, 1995]. In Ecuador this dextral slip (see focal mechanisms in Figure 9) occurs 300-400 km from the trench, at the level of the adakitic volcanic arc and appears to be caused by increased coupling above the Carnegie Ridge flat slab segment [Gutscher et al., 1999b]. Similarly, beneath SW Japan flat subduction

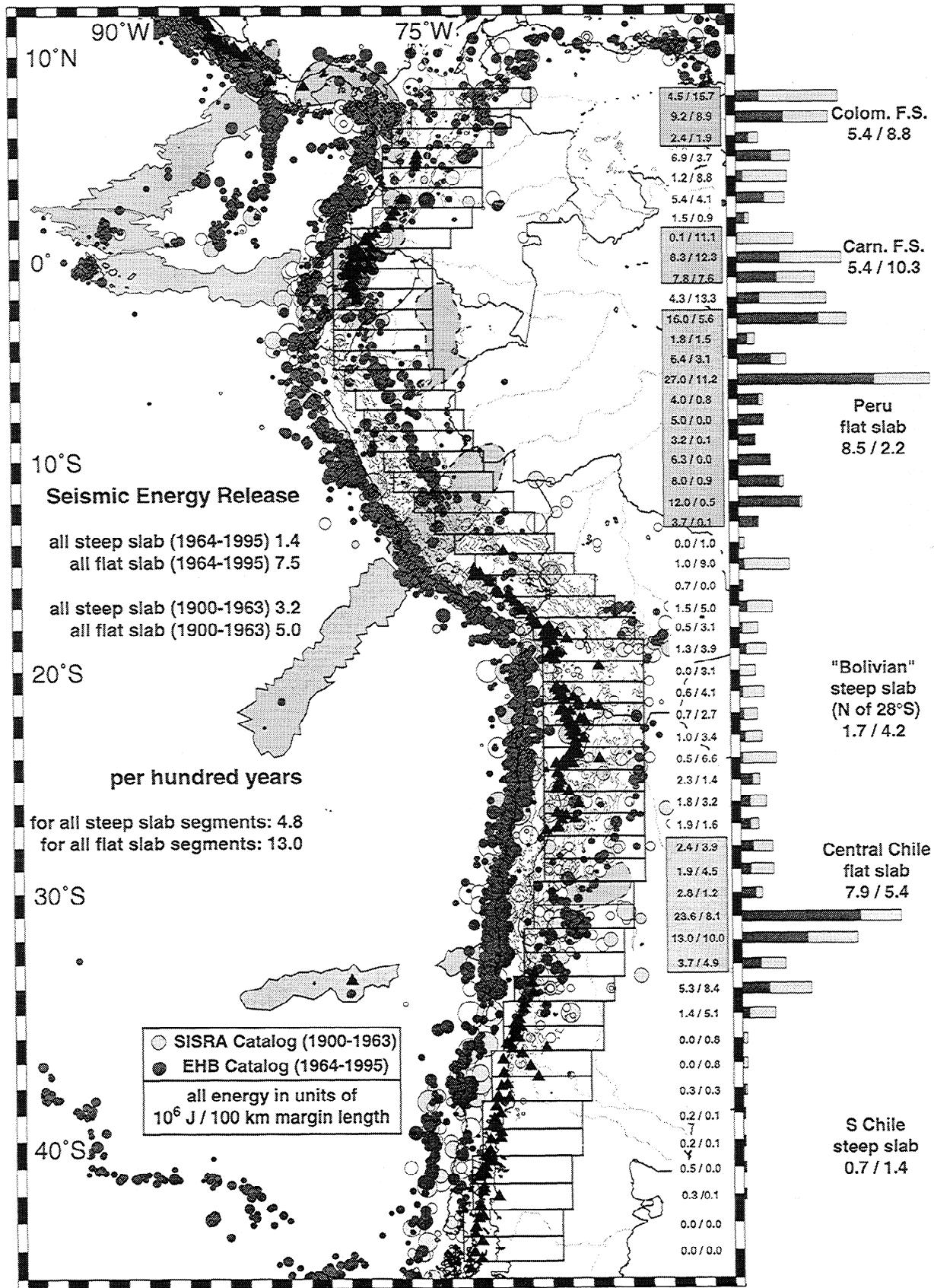


Figure 8. Shallow seismicity (<70 km) in South America, with histogram of seismic energy released in the upper plate 250-800 km from the trench from 8°N to 44°S (energy in 10^6 J). North-south width of sampling boxes is 1°. Gray shaded boxes at right indicate flat slab segments, with pairs of numbers indicating seismic energy released 1900-1963 (left) and 1964-1995 (right). Numbers at extreme right indicate averages per 100 km margin length for each major segment of the Andes.

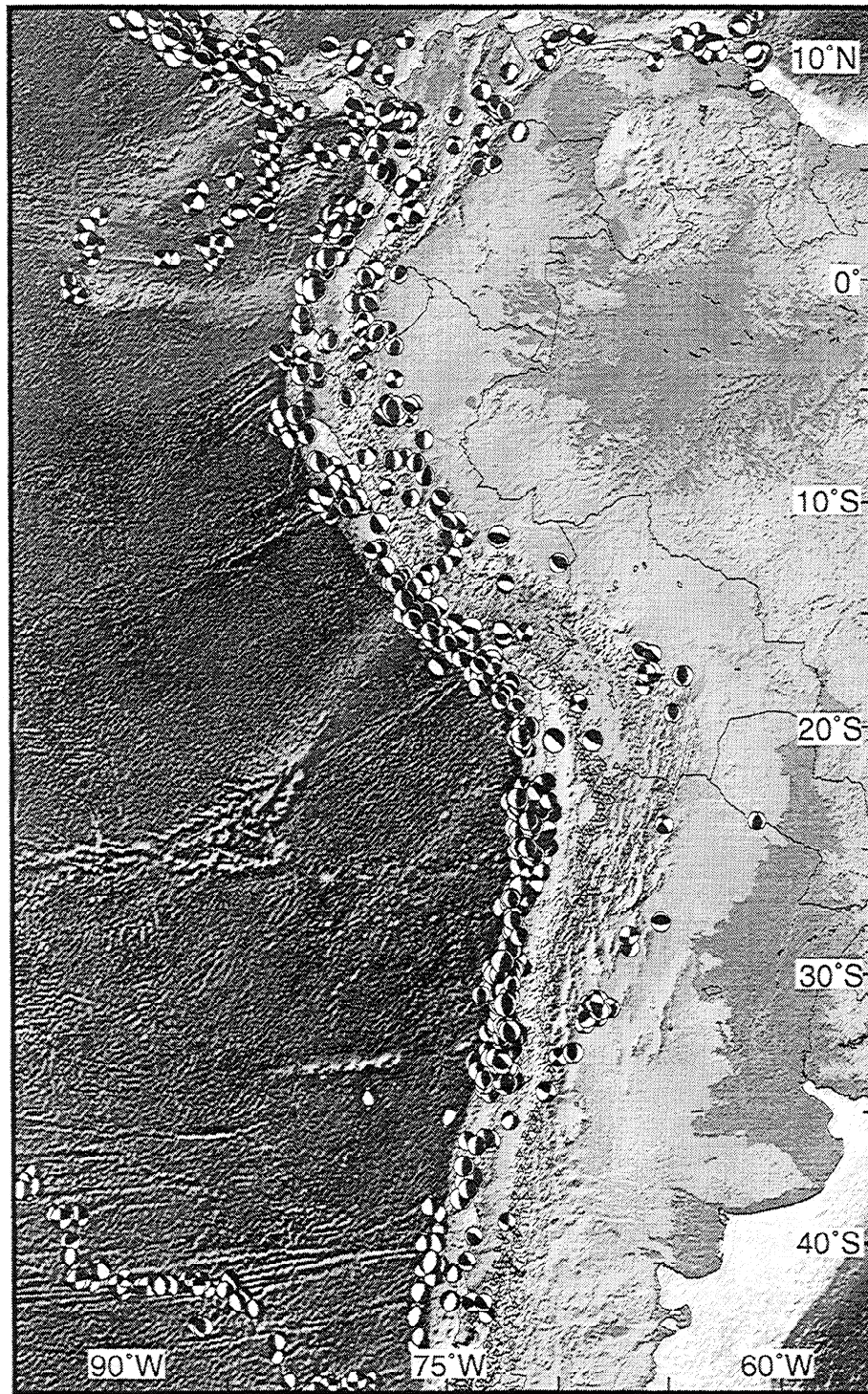


Figure 9. Relief and focal mechanisms in South America from the Harvard CMT catalog for shallow (<70 km) earthquakes (1976-1999). Shaded hill relief from digital topography and bathymetry database [Smith and Sandwell, 1997].

occurs along the Nankai Trough [Hirahara, 1981; Morris, 1995]. Dextral motion is observed by GPS along the Median Tectonic Line (MTL) [Le Pichon et al., 1998] and along a newly identified fault zone to the north of the MTL, the North Chugoku Shear Zone, which

has produced four $M7$ dextral strike-slip earthquakes in the past 130 years [Gutscher and Lallemand, 1999; Gutscher, 2000]. As in Ecuador, partitioning follows the adakitic volcanic arc, some 400 km from the Nankai trough.

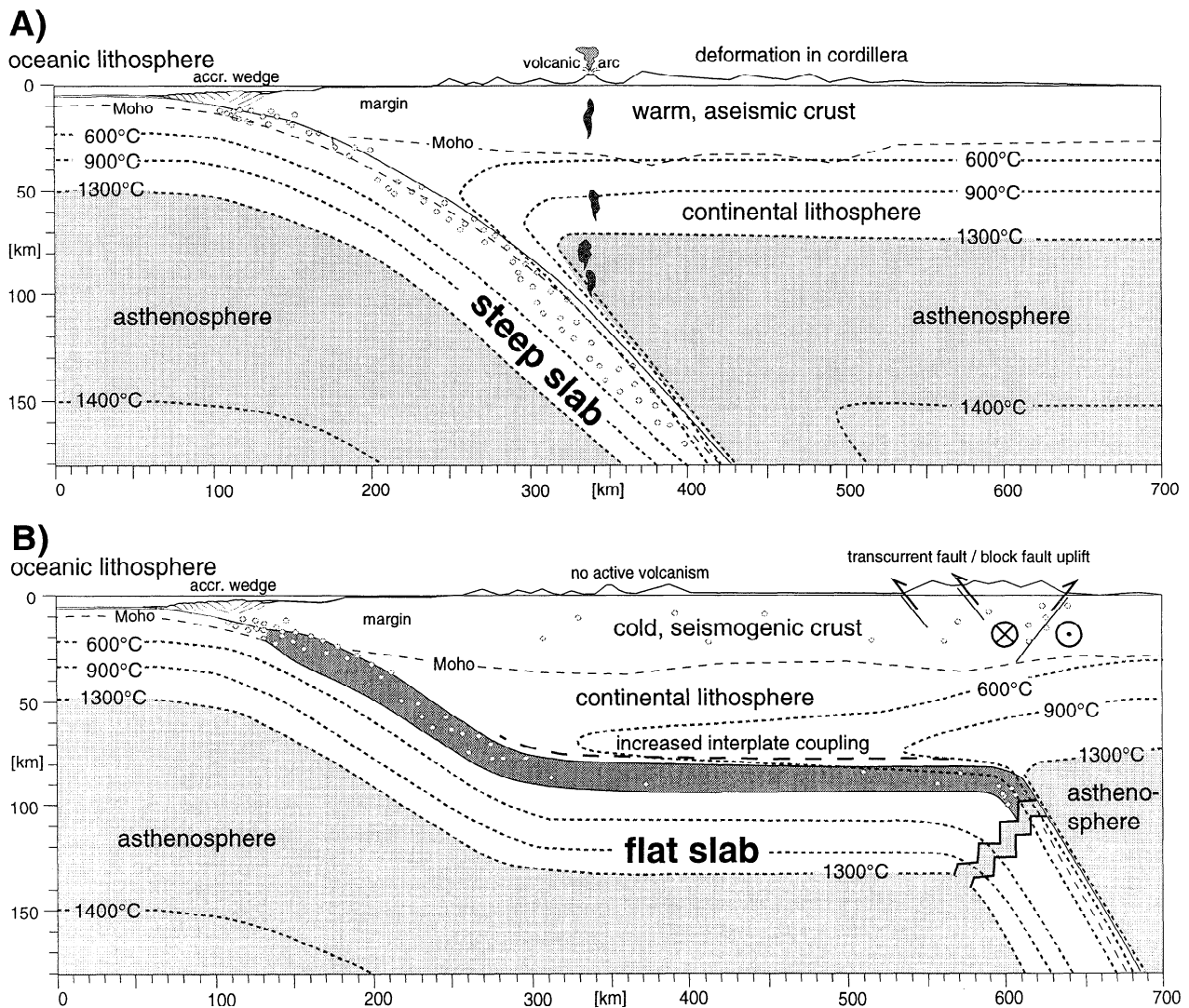


Figure 10. Effect of subduction style on thermal regime and deformation in the upper plate. Note the increased viscous interplate coupling for flat subduction and transfer of deformation inboard (to the backarc).

Last, we wish to emphasize the impact of flat subduction on the temperature and rheology of the margin since this directly controls the deformation processes in the upper plate and along the interface. Flat subduction completely alters the thermal structure of the margin, bringing cold oceanic lithosphere to a position beneath the upper lithosphere, where typically hot asthenosphere is present, at depths of 60-100 km and 200-500 km from the trench (Figure 10). The thermal effect is best illustrated by heat flow observations from Peru and Bolivia. High heat flow of 50-120 mW/m² is present above the steep slab in Bolivia owing to the underlying asthenosphere, whereas above the Peru flat slab, where the asthenosphere is absent, low "forearc" values of 30-70 mW/m² are observed up to 500 km from the trench [Henry and Pollack, 1988]. It is also the disappearance

of this asthenospheric wedge which is responsible for the cessation of calco-alkaline arc magmatism [McGeary *et al.*, 1985; Kay and Abbruzzi, 1996]. Thus, prolonged flat subduction cools both plates and greatly increases the strength of the upper plate [Vlaar, 1983; Spencer, 1994]. Finally, the impact of the cold thermal structure of flat subduction on the downdip limit of the seismogenic zone, commonly considered to be related to the 350° or 450°C isotherms [Oleskevich *et al.*, 1999], remains to be investigated and is potentially of tremendous importance for the assessment of seismic risk.

4. Conclusions

On the basis of the evidence presented here we conclude the following. (1) Flat subduction is caused pri-

marily by the buoyancy effect of anomalously thick (15–20 km) oceanic crust, i.e., commonly found in oceanic plateaus. However, a possible regional contribution from the absolute motion of the upper plate cannot be ruled out. (2) Flat subduction completely alters the thermal structure of the margin, bringing cold oceanic lithosphere to a position beneath the upper lithosphere, where typically hot asthenosphere is present. Prolonged flat subduction cools both plates and greatly increases the strength of the upper lithosphere. (3) The cooler thermal structure delays the basalt to eclogite transition by up to 8–10 m.y. allowing the subhorizontal slab to penetrate further inboard. Once the basalt to eclogite transition occurs, the average slab density increases (by up to 10%) and the underriding lithosphere collapses under its own weight, deflecting and sinking steeply down to the 670 km discontinuity (and beyond). At this point slab detachment can also occur as suggested by tomographic images beneath northern Peru. (4) Interplate coupling is highest above flat slab segments, as expressed by 3–5 times higher seismic energy release than above steep slab segments. This is attributed to viscous coupling across the increased area of interplate contact. (5) Increased interplate coupling together with the stronger rheology of a cooled upper lithosphere, allow deformation to be transferred several hundred km inland (to the backarc). This can take two forms: block fault uplift (Sierras Pampeanas, NW Argentina) or transcurrent faulting for oblique convergence (SW Japan and Ecuador).

Appendix: Identification of Flat Slab Segments as Supplement to Table 1

A1. Central Chile

Together with Peru this was one of the first segments to be identified as “low-angle subduction” [Barazangi and Isacks, 1976]. Subsequent work refined the slab geometry, identifying three inflection points, and thus redefining it as “flat,” which was attributed to the subduction of the Juan Fernandez Ridge and expressed at the volcanic arc by a change in geochemistry followed by a cessation of activity (volcanic gap) [Pilger, 1981; Cahill and Isacks, 1992; Kay and Abbruzzi, 1996].

A2. Peru

The Peru segment was first identified nearly 25 years ago as low-angle subduction [Barazangi and Isacks, 1976] based on teleseismic earthquake hypocenters. Local network data demonstrated the subduction angle is not constant and shallow, but rather moderately steep 30° down to 100 km and then practically horizontal for several hundred kilometers [Hasegawa and Sacks, 1981] and first established the concept of a “flat slab” geometry.

A3. Ecuador

This was proposed as a flat slab segment on the basis of scant teleseismic earthquake hypocenters [Gutscher *et al.*, 1999b]. A north-south oriented cross section suggests the slab lies some 20–30 km higher than in adjacent regions farther north or south. The correlation with modern adakites [Gutscher *et al.*, 2000] serves as indirect evidence but alone is not compelling. Tomographic data are inconclusive (see text), and thus the identification remains uncertain.

A4. Northwestern Colombia

Between 5.6° and 7°N, Panama Basin oceanic crust subducts eastward beneath western Colombia [Lonsdale and Klitgord, 1978; Pennington, 1981]. This was first suggested as a low angle/flat subduction caused by the Choco/Panama Block collision on the basis of the volcanic gap [McGeary *et al.*, 1985]. Tomographic data (see also Figure 5, section A) are the first to clearly identify this “flat slab” geometry [Engdahl *et al.*, 1995]. The subducted oceanic crust may be of Caribbean Oceanic Plateau affinity. Major portions of the Caribbean Plateau have been accreted to the margin of NW South America since the Cretaceous. Magnetic anomalies in the eastern Panama Basin are poorly constrained but were assigned Chrons 6B (22 Ma) at the trench [Hardy, 1991].

A5. Costa Rica

In Costa Rica, 14–20 m.y. old oceanic flanks the subducting Cocos Ridge [Protti *et al.*, 1994]. On the basis of local network hypocenter data a general decrease in slab dip from >60° in Nicaragua and NE Costa Rica to 30° in central Costa Rica is reported. In the segment facing the Cocos Ridge, hypocenters do not extend below 60 km (just as in SW Japan or Cascadia), yet these authors propose the slab geometry flattens, “continuing along an almost horizontal path like that found under Peru and southern Mexico” [Protti *et al.*, 1994, p. 282]. Here as well, there is a gap in Quaternary stratovolcanoes despite active subduction and the presence of recent adakites.

A6. Mexico

This margin was the third to be officially labeled as flat subduction [Suarez *et al.*, 1990]. The subhorizontal slab is unusually shallow, at a depth of 50 km. Interestingly, in Mexico the youngest (5–10 m.y. old) part of the slab (at 102°–105°W longitude) dips fairly steeply (>30°) and is well constrained by hypocenters and by the narrow trench arc gap. As lithospheric ages increase to the east, paradoxically, the slab dip decreases and becomes truly flat (at 99°–96°W longitude) [Singh

and Mortera, 1991]. Accordingly the trench arc gap increases along the east-west trending trans-Mexican volcanic belt. The Tehuantepec Ridge, while only a minor structure, has been proposed to be responsible for the local perturbation of the Mexico subduction and arc [McGeary *et al.*, 1985].

A7. Cascadia

The shallow dip angle along the Washington segment (10° - 12°) is best constrained by local network microseismicity hypocenters [Crosson and Owens, 1987]. The published east-west cross section (their Figure 2) is consistent with either a shallow angle or a flat slab geometry (three possible, but not well constrained inflection points). Indirect evidence for flat subduction is offered by the adakitic magmatism at Mount St. Helens [Defant and Drummond, 1993; Gutscher *et al.*, 2000] and by the along-strike segmentation of the Cascadia margin. Oregon has high heat flow, high volcanic extrusion rates, and almost no upper plate seismicity. Washington has low heat flow, low extrusion rates, and very high upper plate seismicity [Blackwell *et al.*, 1990; Flueh *et al.*, 1998], exactly the same pattern as observed in the Andes.

A8. Southern Alaska

This margin was identified as shallow-angle subduction based on hypocenters and on the eastward increase in the trench arc gap (in excess of 500 km) [Pennington, 1984]. TACT seismic refraction data [Brocher *et al.*, 1994], clearly show a steepening down to 30 km, then a shallowing of plate dip. Approximately 500 km from the trench the subducting plate steepens again (on the basis of hypocenter and tomographic data), and thus three inflection points are constrained here. The Yakutat Terrane, currently accreting to the Alaska margin has been suggested to provide the buoyancy necessary to modify the slab geometry [Brocher *et al.*, 1994].

References

- Abbott, D., R. Drury, and W.H.F. Smith, Flat to steep transition in subduction style, *Geology*, 22, 937-940, 1994.
- Barazangi, M., and B. Isacks, Spatial distribution of earthquakes and subduction of the Nazca Plate beneath South America, *Geology*, 4, 686-692, 1976.
- Bevis, M., The curvature of Wadati-Benioff zones and the torsional rigidity of subducting plates, *Nature*, 323, 52-53, 1986.
- Bialas, J., E.R. Flueh, and PAGANINI Scientific Team, FS SONNE Cruise Report SO144/1 and 2, PAGANINI (Panama Basin and Galapagos "Plume": New Investigations of Intraplate Magmatism), in *GEOMAR Report 94*, edited by J. Bialas, E. Flueh, and G. Bohrmann, 437 pp., GEOMAR Res. Cent., Univ. Kiel, Kiel, Germany, 1999.
- Bialas, J., N. Kukowski, and GEOPECO Scientific Team, FS SONNE Cruise Report SO146/1 and 2, GEOPECO (Geophysical Experiments at the Peruvian Continental Margin: Investigations of Tectonics, Mechanics, Gashydrates, and Fluid Transport), in *GEOMAR Report 96*, edited by J. Bialas, and N. Kukowski, 490 pp., GEOMAR Res. Cent., Univ. Kiel, Kiel, Germany, 2000.
- Bijwaard, H., W. Spakman, and E.R. Engdahl, Closing the gap between regional and global travel time tomography, *J. Geophys. Res.*, 103, 30,055-30,078, 1998.
- Bird, P., Laramide crustal thickening event in the Rocky Mountain foreland and Great Plains, *Tectonics*, 3, 741-758, 1984.
- Bird, P., Formation of the Rocky Mountains, western United States: A con-

A9. SW Japan

Some workers consider SW Japan to exhibit a shallow dip angle of 8° - 15° [Oleskevich *et al.*, 1999]. The precise geometry down to 60-70 km depth is only constrained by intraplate earthquake hypocenters since the last major interplate events occurred in 1944 and 1946 (the famous Tonankai and Nankaido earthquakes). Wide-angle data [Kodaira *et al.*, 2000] are insufficient to constrain slab geometry beyond 25 km. Tomographic data [Hirahara, 1981] show a higher velocity body (oceanic slab) lying subhorizontally to at least 300 km from the Nankai Trough. This corroborates earthquake phases interpreted as arriving from a flat lying unit at depths of 50-70 km [Nakanishi, 1980]. Recently, the geometry has been identified as flat and related to deformation in the upper plate [Gutscher and Lallemand, 1999; Gutscher, 2000].

A10. Western New Guinea/Irian Jaya

Plate convergence is poorly constrained along this margin (4-9 cm/a) which produced the largest interplate subduction earthquake ($M=8.2$ in 1996) in the 24 year CMT catalog [Okal, 1999]. Before this event it was debated whether active subduction occurs here! On the basis of hypocenter distribution and the total absence of a modern arc we classify the subduction as flat slab. Earlier work discusses western New Guinea as shallow angle and suggests the Euripik Ridge, a 2 km high oceanic plateau, is responsible for modifying the slab geometry [McGeary *et al.*, 1985]. Its southern extremity is currently entering the New Guinea Trench (138° - 142° E).

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- tinuum computer model, *Science*, 239, 1501-1507, 1988.
- Blackwell, D.D., J.L. Steele, S. Kelley, and M.A. Korosec, Heat flow in the state of Washington and thermal conditions in the Cascadia Range, *J. Geophys. Res.*, 95, 19495-19516, 1990.
- Boyd, T.M., J.A. Snoke, I.S. Sacks, and A. Rodriguez, High-resolution determination of the Benioff Zone geometry beneath Southern Peru, *Bull. Seism. Soc. Am.*, 74, 559-568, 1984.
- Brocher, T., G.S. Fuis, M.A. Fisher, G. Plafker, and M.J. Moses, Mapping the megathrust beneath the northern Gulf of Alaska using wide-angle seismic data, *J. Geophys. Res.*, 99, 11,663-11,685, 1994.
- Cahill, T., and B. Isacks, Seismicity and shape of the subducted Nazca Plate, *J. Geophys. Res.*, 97, 17,503-17,529, 1992.
- Cande, S.C., and W.F. Haxby, Eocene propagating rifts in the southwest Pacific and their conjugate features on the Nazca Plate, *J. Geophys. Res.*, 96, 12,061-12,084, 1991.
- Carress, D.W., M. McNutt, R.S. Detrick, and J.C. Mutter, Seismic imaging of hotspot related crustal underplating beneath the Marquesas Islands, *Nature*, 373, 600-603, 1995.
- Charvis, P., M. Recco, S. Operto, and D. BREFORT, Deep structure of the northern Kerguelen Plateau and hotspot-related activity, *Geophys. J. Int.*, 122, 899-924, 1995.
- Chemenda, A., S. Lallemand, and A. Bokun, Strain partitioning and interplate friction in oblique subduction zones: Constraints provided by physical modeling, *J. Geophys. Res.*, 105, 5567-5582, 2000.
- Cloos, M., Lithospheric buoyancy and collisional orogenesis: Subduction of oceanic plateaus, continental margins, island arcs, spreading ridges, and seamounts, *Geol. Soc. Am. Bull.*, 105, 715-737, 1993.
- Cross, T.A., and R.H. Pilger, Controls of subduction geometry, location of magmatic arcs, and tectonics of arc and back-arc regions, *Geol. Soc. Am. Bull.*, 93, 545-562, 1982.
- Crosson, R.S., and T.J. Owens, Slab geometry of the Cascadia subduction zone beneath Washington from earthquake hypocenters and teleseismic converted waves, *Geophys. Res. Lett.*, 14, 824-827, 1987.
- Davy, B., and R. Wood, Gravity and magnetic modeling of the Hikurangi Plateau, *Mar. Geol.*, 118, 139-151, 1994.
- Defant, M.J., and M.S. Drummond, Derivation of some modern arc magmas by melting of young subducted lithosphere, *Nature*, 347, 662-665, 1990.
- Defant, M.J., and M.S. Drummond, Mount St. Helens: Potential example of the partial melting of the subducted lithosphere in a volcanic arc, *Geology*, 21, 547-550, 1993.
- Defant, M.J., T.E. Jackson, M.S. Drummond, J.Z. de Boer, H. Bellon, M.D. Feigenson, R.C. Maury, and R.H. Stewart, The geochemistry of young volcanism throughout western Panama and SE Costa Rica: An overview, *J. Geol. Soc. London*, 149, 569-579, 1993.
- DeMets, C., R.G. Gordon, D.F. Angus, and C. Stein, Current plate motions, *Geophys. J. Int.*, 101, 425-478, 1990.
- Dumitru, T.A., P.B. Gans, D.A. Foster, and E.L. Miller, Refrigeration of the western Cordilleran lithosphere during Laramide shallow-angle subduction, *Geology*, 19, 1145-1148, 1991.
- Eberhart-Phillips, D., and M. Reyners, Continental subduction and three dimensional crustal structure: The northern South Island, New Zealand, *J. Geophys. Res.*, 102, 11,843-11,861, 1997.
- Engdahl, E.R., R.D. van der Hilst, and J. Berrocal, Imaging of subducted lithosphere beneath South America, *Geophys. Res. Lett.*, 22, 2317-2320, 1995.
- Engdahl, E.R., R.D. van der Hilst, and R. Buland, Global teleseismic earthquake relocation with improved travel times and procedures for depth relocation, *Bull. Seismol. Soc. Am.*, 88, 722-743, 1998.
- Feighner, M.A., and M.A. Richards, Lithospheric structure and compensation mechanisms of the Galapagos Archipelago, *J. Geophys. Res.*, 99, 6711-6729, 1994.
- Flueh, E.R., et al., New seismic images of the Cascadia subduction zone from cruise SO108 - ORWELL, *Tectonophysics*, 293, 69-84, 1998.
- Gardner, T.W., D. Verdonck, N.M. Pinter, R. Slingerland, K.P. Furlong, T.F. Bullard, and S.G. Wells, Quaternary uplift astride the aseismic Cocos Ridge, Pacific coast, Costa Rica, *Geol. Soc. Am. Bull.*, 104, 219-232, 1992.
- Gephart, J.W., Topography and subduction geometry in the central Andes: clues to the mechanics of a noncollisional orogen, *J. Geophys. Res.*, 99, 12,279-12,288, 1994.
- Gutscher, M.-A., An Andean model of interplate coupling and strain partitioning applied to the flat subduction of SW Japan (Nankai Trough), *Tectonophysics*, in press, 2000.
- Gutscher, M.-A., and S. Lallemand, Birth of a major strike-slip fault in SW Japan, *Terra Nova*, 11, 203-209, 1999.
- Gutscher, M.-A., J.-L. Olivet, D. Aslanian, R. Maury, and J.-P. Eissen, The 'lost Inca Plateau': Cause of flat subduction beneath Peru?, *Earth Planet. Sci. Lett.*, 171, 335-341, 1999a.
- Gutscher, M.-A., J. Malavieille, S. Lallemand, and J.-Y. Collot, Tectonic segmentation of the North Andean Margin: Impact of the Carnegie Ridge collision, *Earth Planet. Sci. Lett.*, 168, 255-270, 1999b.
- Gutscher, M.-A., E. Bourdon, J.-P. Eissen, and R. Maury, Can slab melting be caused by flat subduction?, *Geology*, 28, 535-538, 2000.
- Hall, M.L., and C.A. Wood, Volcanotectonic segmentation of the N. Andes, *Geology*, 13, 203-207, 1985.
- Hardy, N.C., Tectonic evolution of the easternmost Panama Basin: Some new data and inferences, *J. S. Am. Earth Sci.*, 4, 261-269, 1991.
- Hasegawa, A., and I.S. Sacks, Subduction of the Nazca Plate beneath Peru as determined from seismic observations, *J. Geophys. Res.*, 86, 4971-4980, 1981.
- Henry, S.G., and H.N. Pollack, Terrestrial heat flow above the Andean subduction zone in Bolivia and Peru, *J. Geophys. Res.*, 93, 15,153-15,162, 1988.
- Hey, R.N., Tectonic evolution of the Cocos-Nazca spreading center, *Geol. Soc. Am. Bull.*, 88, 1414-1420, 1977.
- Hirahara, K., Three-dimensional seismic structure beneath southwest Japan: The subducting Philippine Sea plate, *Tectonophysics*, 79, 1-44, 1981.
- Isacks, B., Uplift of the central Andean plateau and bending of the Bolivian orocline, *J. Geophys. Res.*, 93, 3211-3231, 1988.
- James, D.E., and J.A. Snoke, Structure and tectonics in the region of flat subduction beneath central Peru: Crust and uppermost mantle, *J. Geophys. Res.*, 99, 6899-6912, 1994.
- Jischke, M., On the dynamics of descending lithospheric plates and slip zones, *J. Geophys. Res.*, 80, 4809-4813, 1975.
- Jordan, T., B. Isacks, R.W. Allmendinger, J.A. Brewer, V.A. Ramos, and C.J. Ando, Andean tectonics related to geometry of subducted Nazca plate, *Geol. Soc. Am. Bull.*, 94, 341-361, 1983.
- Kay, S.M., and J.M. Abbruzzi, Magmatic evidence for Neogene lithospheric evolution of the central Andean "flat-slab" between 30°S and 32°S, *Tectonophysics*, 259, 15-28, 1996.
- Kellogg, J.N., and V. Vega, Tectonic development of Panama, Costa Rica, and the Colombian Andes: Constraints from Global Positioning System (GPS) geodetic studies and gravity, in *Geologic and Tectonic Development of the Caribbean Plate Boundary in Southern Central America*, edited by P. Mann, Spec. Pap. Geol. Soc. Am., 295, 75-90, 1995.
- Kodaira, S., N. Takahashi, J.-O. Park, K. Mochizuki, M. Shinohara, and S. Kimura, Western Nankai Trough seismogenic zone: Results from a wide-angle ocean bottom seismic survey, *J. Geophys. Res.*, 105, 5887-5905, 2000.
- Kolarsky, R.A., P. Mann, and W. Montero, Island arc response to shallow subduction of the Cocos Ridge, Costa Rica, in *Geologic and Tectonic Development of the Caribbean Plate Boundary in Southern Central America*, edited by P. Mann, Spec. Pap. Geol. Soc. Am., 295, 235-262, 1995.
- Le Pichon, X., S. Mazzotti, P. Henry, and M. Hashimoto, Deformation of the Japanese Islands and seismic coupling: an interpretation based on GSI permanent

- GPS observations, *Geophys. J. Int.*, *134*, 501-514, 1998.
- Lonsdale, P., and K.D. Klitgord, Structure and tectonic history of the eastern Panama Basin, *Geol. Soc. Am. Bull.*, *89*, 981-999, 1978.
- McCann, W.R., and R.E. Habermann, Morphological and geological effects of the subduction of bathymetric highs, in *Subduction Zones*, edited by L.J. Ruff and H. Kanamori, pp. 41-69, Birkhäuser Boston, Cambridge, Mass., 1989.
- McGeary, S., A. Nur, and Z. Ben-Avraham, Spatial gaps in arc volcanism: The effect of collision or subduction of oceanic plateaus, *Tectonophysics*, *119*, 195-221, 1985.
- Monzier, M., C. Robin, M.L. Hall, J. Cotten, P. Mothes, J.-P. Fissen, and P. Samaniego, Les adakites d'Equateur: modele préliminaire, *C. R. Acad. Sci., Ser. I*, *324*, 545-552, 1997.
- Morris, P.A., Slab melting as an explanation of Quaternary volcanism and aseismicity in southwest Japan, *Geology*, *23*, 395-398, 1995.
- Nakanishi, I., Precursors to ScS phases and dipping interface in the upper mantle beneath southwestern Japan, *Tectonophysics*, *69*, 1-35, 1980.
- Nur, A., and Z. Ben-Avraham, Volcanic gaps and the consumption of aseismic ridges in South America, in *Nazca Plate: Crustal Formation and Andean Convergence*, edited by L. Kulm et al., pp. 729-740, Geol. Soc. Am., Boulder, Colo., 1981.
- Okal, E.A., Historical seismicity and seismotectonic context of the Great 1979 Yapen and 1996 Biak, Irian Jaya earthquakes, *Pure Appl. Geophys.*, *154*, 633-675, 1999.
- Olbertz, D., M.J.R. Wortel, and U. Hansen, Trench migration and subduction zone geometry, *Geophys. Res. Lett.*, *24*, 221-224, 1997.
- Oleskevich, D.A., R.D. Hyndman, and K. Wang, The updip and downdip limits to great subduction earthquakes: Thermal and structural models of Cascadia, south Alaska, SW Japan, and Chile, *J. Geophys. Res.*, *104*, 14,965-14,991, 1999.
- Parsons, T., A.M. Trehu, J.H. Luetgert, K. Miller, F. Kilbride, R.E. Wells, M.A. Fisher, E. Flueh, U.S. ten Brink, and N.I. Christensen, A new view into the Cascadia subduction zone and volcanic arc: Implications for earthquake hazards along the Washington margin, *Geology*, *26*, 199-202, 1998.
- Peacock, S.M., T. Rushmer, and A. Thompson, Partial melting of subducting oceanic crust, *Earth Planct. Sci. Lett.*, *121*, 227-244, 1994.
- Pennington, W.D., Subduction of the eastern Panama Basin and seismotectonics of northwestern South America, *J. Geophys. Res.*, *86*, 10,753-10,770, 1981.
- Pennington, W.D., The effect of oceanic crustal structure on phase changes and subduction, *Tectonophysics*, *102*, 377-398, 1984.
- Pilger, R.H., Plate reconstructions, aseismic ridges, and low-angle subduction beneath the Andes, *Geol. Soc. Am. Bull.*, *92*, 448-456, 1981.
- Pilger, R.H., Cenozoic plate kinematics, subduction and magmatism: South American Andes, *J. Geol. Soc. London*, *141*, 793-802, 1984.
- Pinet, N., and P.R. Cobbold, Experimental insights into the partitioning of motion within zones of oblique subduction, *Tectonophysics*, *206*, 371-388, 1992.
- Protti, M., F. Guendel, and K. McNally, The geometry of the Wadati-Benioff zone under southern Central America and its tectonic significance: Results from a high-resolution local seismographic network, *Phys. Earth Planet. Inter.*, *84*, 271-287, 1994.
- Protti, M., F. Guendel, and K. McNally, Correlation between the age of the subducting Cocos plate and the geometry of the Wadati-Benioff zone under Nicaragua and Costa Rica, in *Geologic and Tectonic Development of the Caribbean Plate Boundary in Southern Central America*, edited by P. Mann, Spec. Pap. Geol. Soc. Am., 295, 309-326, 1995.
- Pubellier, M., and P. Cobbold, Analogue models for the transpressional docking of volcanic arcs in the Western Pacific, *Tectonophysics*, *253*, 33-52, 1996.
- Pubellier, M., G. Prouteau, R.C. Maury, and H. Bellon, Le changement de régime plio-quadernaire dans une zone d'échappement tectonique; controle par des intrusifs syntectoniques (Irian Jaya, Indonésie), *Proc. Réunion des Sciences de la Terre (RST Meeting)* Brest, France, 179-180, 1998.
- Sacks, I.S., The subduction of young lithosphere, *J. Geophys. Res.*, *88*, 3355-3366, 1983.
- Singh, S.K., and F. Mortera, Source time functions of large Mexican subduction earthquakes, morphology of the Benioff Zone, age of the plate and their tectonic implications, *J. Geophys. Res.*, *96*, 21487-21502, 1991.
- Smalley, R., and B. Isacks, A high resolution local network study of the Nazca Plate Wadati-Benioff Zone under Western Argentina, *J. Geophys. Res.*, *92*, 13903-13912, 1987.
- Smalley, R., J. Pujol, M. Regnier, J.-M. Chiu, J.-L. Chatelain, B.L. Isacks, M. Araujo, and N. Puebla, Basement seismicity beneath the Andean Precordillera thin skinned thrust belt and implications for crustal and lithospheric behavior, *Tectonics*, *12*, 63-76, 1993.
- Smith, W.H.F., and D.T. Sandwell, Bathymetric prediction from dense altimetry and sparse shipboard bathymetry, *J. Geophys. Res.*, *99*, 21803-21824, 1994.
- Smith, W.H.F., and D.T. Sandwell, Global seafloor topography from satellite altimetry and ship depth soundings, *Science*, *277*, 1956-1962, 1997.
- Spencer, J.E., A numerical assessment of slab strength during high- and low-angle subduction and implications for Laramide orogenesis, *J. Geophys. Res.*, *99*, 9227-9236, 1994.
- Suarez, G., P. Molnar, and B.C. Burchfiel, Seismicity, fault plane solutions, depth of faulting, and active tectonics of the Andes of Peru, Ecuador and S. Colombia, *J. Geophys. Res.*, *88*, 10403-10428, 1983.
- Suarez, G., T. Montfret, G. Wittlinger, and C. David, Geometry of subduction and depth of the seismogenic zone in the Guerrero gap, Mexico, *Nature*, *345*, 336-338, 1990.
- Talandier, J., and E. Okal, Crustal structure in the Society and Tuamotu Islands, French Polynesia, *Geophys. J. R. Astr. Soc.*, *88*, 499-528, 1987.
- Uyeda, S., and H. Kanamori, Back-arc opening and the mode of subduction, *J. Geophys. Res.*, *84*, 1049-1061, 1979.
- van der Hilst, R., and P. Mann, Tectonic implications of tomographic images of subducted lithosphere beneath northwestern South America, *Geology*, *22*, 451-454, 1994.
- van der Velden, A.J., and F.A. Cook, Proterozoic and Cenozoic subduction complexes: A comparison of geometric features, *Tectonics*, *18*, 575-581, 1999.
- Vlaar, N.J., Thermal anomalies and magmatism due to lithospheric doubling and shifting, *Earth Planet. Sci. Lett.*, *65*, 322-330, 1983.
- Vlaar, N.J., Precambrian geodynamical constraints, in *The deep Proterozoic crust in North Atlantic Provinces*, edited by A.C. Tobi and J.L.R. Tourel, pp. 3-20, Reidel Publ. Co., 1985.
- Vlaar, N.J., and M.J.R. Wortel, Lithospheric aging, instability and subduction, *Tectonophysics*, *32*, 331-351, 1976.
- von Huene, R., I. Pecher, and M. Gutscher, Development of the accretionary prism along Peru and material flux after subduction of Nazca Ridge, *Tectonics*, *15*, 19-33, 1996.
- von Huene, R., J. Corvalan, E.R. Flueh, K. Hinz, J. Korstgard, C.R. Ranero, W. Weinrebe and the Condor Scientists, Tectonic control of the subducting Juan Fernandez Ridge on the Andean margin near Valparaiso, Chile, *Tectonics*, *16*, 474-488, 1997.
- Wessel, P., and W.H.F. Smith, Free software helps map and display data, *Eos Trans. AGU*, *72* (41), 441, 1991.
- Wortel, M.J.R., Spatial and temporal variations in the Andean subduction zone, *J. Geol. Soc. London*, *141*, 783-791, 1984.
- Wortel, M.J.R., and N.J. Vlaar, Age dependent subduction of oceanic lithosphere beneath western South America, *Phys. Earth Planet. Inter.*, *17*, 201-208, 1978.

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