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Thermo-mechanical controls of flat subduction: Insights from numerical modeling

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ABSTRACT

Numerical experiments are used to investigate the thermo-mechanical controls for inducing flat subduction and why flat subduction is rare relative to normal/steep subduction. Our modeling results demonstrate that flat subduction is an end-member of a steady state subduction geometry and is characterized by a curved slab with a nearly-horizontal slab section. Intermediate cases between normal/steep and flat subduction appear to be transient in origin and evolve toward one of the stable end-members. Physical parameters inducing flat subduction can be classified into four categories: buoyancy of the subducting oceanic lithosphere (e.g., slab age, oceanic crustal thickness), viscous coupling between the overriding and downgoing plates (e.g., initial subduction angle), external kinematic conditions, and rheological properties of the subduction zone. On the basis of parameter sensitivity tests and the main characteristics of present-day flat subduction zones, positive buoyancy from either the young slab or the thickened oceanic crust is considered as the primary controlling parameter. Our results show that the possibility of flat subduction is directly proportional to oceanic crustal thickness and inversely proportional to the slab age. Furthermore, oceanic crust must be thicker than 8 km to induce flat subduction, when the slab is older than 30 Ma with an initial subduction angle of ≥20° and without absolute trenchward motion of the overriding plate. The lower the initial subduction angle or the thicker the overriding continental lithosphere, the more likelihood for flat subduction. The initial subduction angle is more influential for the development of flat subduction than the overriding lithospheric thickness, and a thick overriding lithosphere induces flat subduction only under the condition of an initial subduction angle of ≤25°, with a slab age of ≥30 Ma and without absolute trenchward motion of the overriding plate. However, when the initial subduction angle is increased to >25°, no flat subduction is predicted. All the parameters are evaluated within the constraints of a mechanical framework in which the slab geometry is regarded as a result of a balance between the gravitational and hydrodynamic torques. Any factor that can sufficiently reduce gravitational torque or increase hydrodynamic torque will exert a strong effect on flat subduction development. Our results are consistent with the observations of modern flat subduction zones on Earth.

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1. Introduction

At convergent plate margins, variations in the dip of the downgoing slab of oceanic lithosphere in its upper 125 km enable the division of subduction zones into low-angle (or flat) subduction (<30°), intermediate-angle subduction (between 30°–60°) and high-angle subduction (>60°) (e.g., Rodriguez-Gonzalez and Negredo, 2012). As shown in Fig. 1, flat subduction, which is characterized by a distinct flat-slab underlying the overriding lithosphere, occurs only in ~10% of the world's convergent margins, e.g., Central Chile (Kay and Abbruzzi, 1996), Peru (Petford and Atherton, 1996), Ecuador (Beate et al., 2001), Costa Rica (Grafe et al., 2002; Gardner et al., 2013), SW Mexico (Suarez et al., 1990; Skinner and Clayton, 2011), Cascadia (Defant and Drummond, 1993), SE Alaska (Fuis et al., 2008) and Nankai Trough (Morris, 1995). Geological features ascribed to flat subduction include compressive deformation and crustal-thickening in the overriding continental lithosphere and a broad across-strike zone of arc magmatism with a magmatic gap and mineralization pulses (Gutscher et al., 2000a; Kay and Mpodozis, 2001; Sigloch et al., 2008). Flat subduction has been invoked to explain the geological characteristics in a number

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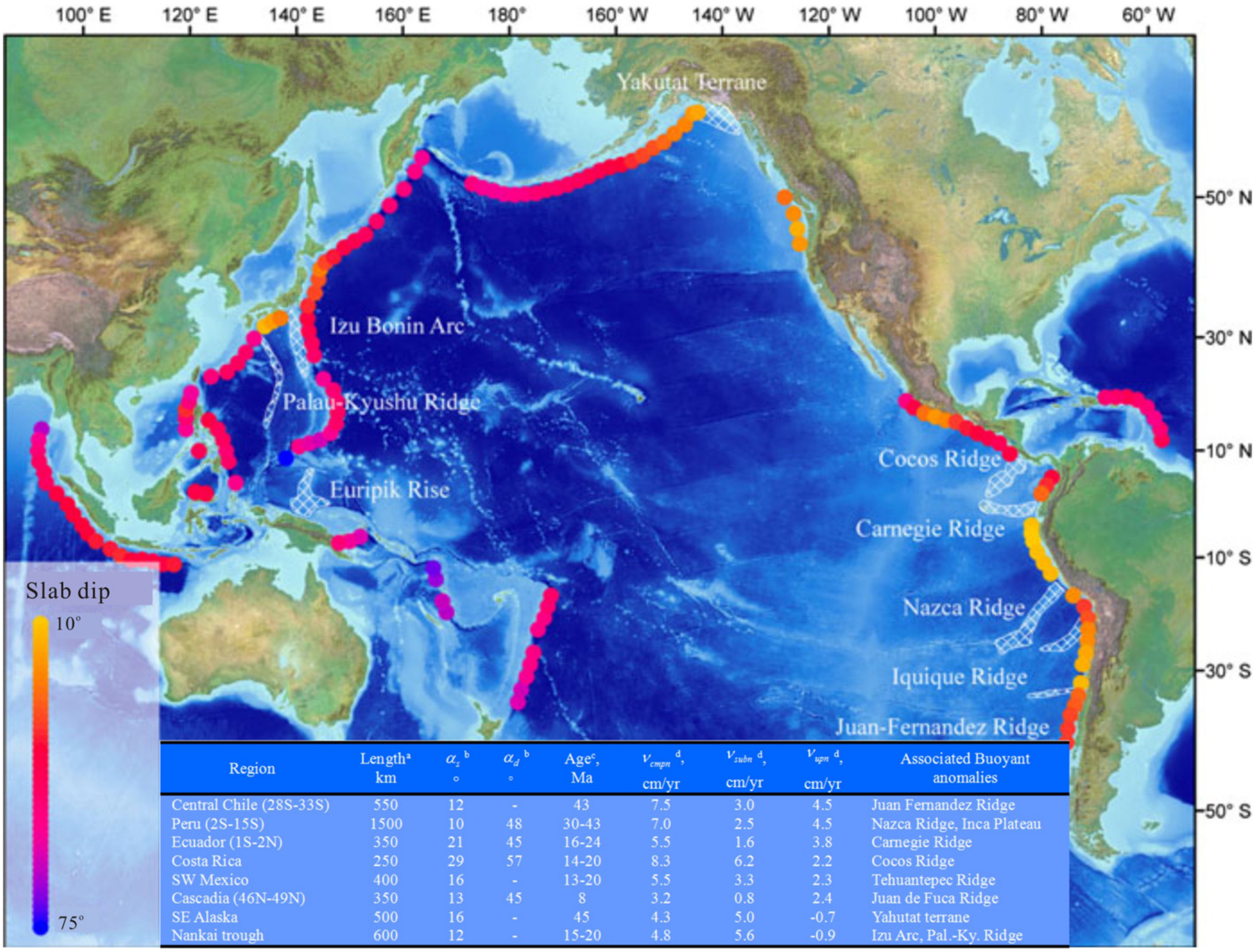

Region	Length[a] km	α_s [b] °	α_d [b] °	Age[c], Ma	v_{cmpn} [d], cm/yr	v_{subn} [d], cm/yr	v_{upn} [d], cm/yr	Associated Buoyant anomalies
Central Chile (28S-33S)	550	12	-	43	7.5	3.0	4.5	Juan Fernandez Ridge
Peru (2S-15S)	1500	10	48	30-43	7.0	2.5	4.5	Nazca Ridge, Inca Plateau
Ecuador (1S-2N)	350	21	45	16-24	5.5	1.6	3.8	Carnegie Ridge
Costa Rica	250	29	57	14-20	8.3	6.2	2.2	Cocos Ridge
SW Mexico	400	16	-	13-20	5.5	3.3	2.3	Tehuantepec Ridge
Cascadia (46N-49N)	350	13	45	8	3.2	0.8	2.4	Juan de Fuca Ridge
SE Alaska	500	16	-	45	4.3	5.0	-0.7	Yahutat terrane
Nankai trough	600	12	-	15-20	4.8	5.6	-0.9	Izu Arc, Pal.-Ky. Ridge

Fig. 1. Map of Pacific seafloor showing the dip of shallow portion (<125 km depth) of subducting slab (modified from Lallemand et al., 2005; Skinner and Clayton, 2011) and spreading ridges that are associated with flat subduction zones (white crosshatched pattern). The inserted table shows the chief geodynamic settings of the preset-day flat subduction (Gutscher et al., 2000a; Gutscher et al., 2000b; Lallemand et al., 2005). [a]Cumulative length = 5000 km, which represents around 10% of all subduction zone. [b]α_s is defined as the mean shallow dip between 0 and 125 km; α_d the mean deep dip from depths greater than 125 km. [c]This age refers to the age of subducting oceanic lithosphere around the trench before sinking into the subduction zone. [d]v_{cmpn}, v_{subn}, and v_{upn} are the normal component of the velocities: v_{cmp}, v_{sub}, and v_{up} referring to the relative convergence velocity, the absolute velocity of the subducting plate, and the absolute velocity of the overriding continental plate, respectively. The positive value means trenchward motion.

of ancient orogens, such as the end Mesozoic to early Paleogene orogenesis in western North America (e.g., Snyder et al., 1976; English et al., 2003) and the Mesozoic evolution of South China (e.g., Li and Li, 2007).

The causes of flat subduction remain debated, and a variety of explanations has been proposed, which can be grouped into the following six categories. (1) The most popular viewpoint is the buoyant nature of the downgoing oceanic slab due to either its overall young age or the thickened nature of the oceanic crust (Pilger, 1981; Brocher et al., 1994; Kay and Abbruzzi, 1996; Gutscher et al., 2000b; van Hunen et al., 2002b, 2004; Anderson et al., 2007; Espurt et al., 2008; Fuis et al., 2008; Sak et al., 2009; Skinner and Clayton, 2011). Both the young slab and the thickened oceanic crust can effectively reduce the average density of the oceanic slab, inhibiting the slab sinking steeply and promoting the development of low-angle subduction. (2) Thermal structure of the overriding continental lithosphere strongly correlates with the slab geometry (e.g., Rodriguez-Gonzalez and Negredo, 2012). A colder overriding continental plate could induce a shallow slab to develop flat subduction, as a result of the increased viscosity of the mantle wedge and increased suction forces acting on the slab. (3) Trenchward motion of the overriding continental plate with respect to the downgoing slab exerts a significant influence on the slab dip angle (Uyeda and Kanamori, 1979; Jarrard, 1986; Lallemand et al., 2005). Vlaar (1983) proposed a "lithospheric doubling" scenario to relate the combined effects of active trenchward motion of the overriding continent and a relatively young oceanic lithosphere with the development of flat subduction. (4) The slab dip angle might be influenced by rheological properties of the slab and surrounding mantle (van Hunen et al., 2001; van Hunen et al., 2002a, 2002b, 2004; Bellahsen et al., 2005; Billen and Hirth, 2005, 2007; Manea and Gurnis, 2007). After the formation of flat subduction, a weak slab is favorable to resubduction from flat to steep subduction, whereas a highly strong slab will resist bending and descending (van Hunen et al., 2002b). A strong upper mantle might enhance flat subduction through increasing plate suction forces (van Hunen et al., 2004). (5) The interaction of the slab with large-scale mantle flow can greatly influence the slab dip angle (Ricard et al., 1991; Doglioni et al., 1999; Boutelier and Cruden, 2008). Physical modeling shows that overpressure on the slab lower surface induced by imposed mantle flow promotes shallow subduction, but underpressure tends to induce steep subduction (Boutelier and Cruden, 2008). (6) Hydrodynamic forces (slab suction forces) are additionally proposed to account for flat subduction (Stevenson and Turner, 1977; Tovish et al., 1978). The low slab dip angle is attributed to strong slab suction. Other factors, which are believed to influence subduction pattern, include latent heat effects of the major mantle phase

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