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Can slab melting be caused by flat subduction?

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ABSTRACT

Slab melting has been suggested as a likely source of adakitic arc magmas (i.e., andesitic and dacitic magmas strongly depleted in Y and heavy rare earth elements). Existing numerical and petrologic models, however, restrict partial melting to very young (≤5 Ma) oceanic crust (typically at 60–80 km depth). Paradoxically, most of the known Pliocene-Quaternary adakite occurrences are related to subduction of 10–45 Ma lithosphere, which should not be able to melt under normal subduction-zone thermal gradients. We propose an unusual mode of subduction known as flat subduction, occurring in ~10% of the world's convergent margins, that can produce the temperature and pressure conditions necessary for fusion of moderately old oceanic crust. Of the 10 known flat subduction regions worldwide, eight are linked to present or recent (<6 Ma) occurrences of adakitic magmas. Observations from Chile, Ecuador, and Costa Rica suggest a three-stage evolution: (1) steep subduction produces a narrow calc-alkaline arc, typically ~300 km from the trench, above the asthenospheric wedge; (2) once flat subduction begins, the lower plate travels several hundred kilometers at nearly the same depth, thus remaining in a pressure-temperature window allowing slab melting over this broad distance; and (3) once flat subduction continues for several million years, the asthenospheric wedge disappears, and a volcanic gap results, as in modern-day central Chile or Peru. The proposed hypothesis, which reconciles thermal models with geochemical observations, has broad implications for the study of arc magmatism and for the thermal evolution of convergent margins.

Keywords: flat subduction, thermal structure, slab melting, adakites.

INTRODUCTION

Petrologic models suggest that formation of trondhjemite-tonalite-dacite (TTD) by partial melting of the subducted slab was widespread during Archean time, and these rocks represent a major component of Precambrian gneiss terranes (Martin, 1986; Drummond and Defant, 1990). However, given the cooler mantle temperatures during the Phanerozoic, these processes should be uncommon today (Martin, 1986). Recent models of magma genesis emphasize the role of fluids released via dehydration reactions from the subducting plate, thereby causing melting in the overlying mantle wedge (Schmidt and Poli, 1998). In the past decade, numerous occurrences of Cenozoic adakites (andesitic and dacitic magmas characterized by strong depletion in heavy rare earth elements and high Sr/Y ratios) have been documented and discussed as possible examples of slab melting (Fig. 1) (Defant and Drummond, 1990; Morris, 1995). These include Mount St. Helens (Defant and Drummond, 1993) and the recent major eruption of Mount Pinatubo (Prouteau et al., 1999).

Numerical and petrological studies of pressure-temperature-time (*P-T-t*) paths in subduction zones suggest that this process can only occur for subduction of very young (≤5 Ma) lithosphere (Peacock et al., 1994) (Fig. 2A, solid lines). Paradoxically, of the ~20 known occurrences of adakites worldwide, only 5 occur near Pliocene-Quaternary spreading center–trench triple junctions, where very young oceanic lithosphere is being or was recently subducted. The remaining occurrences involve subduction of moderately old (10–45 Ma) lithosphere, which is not expected to melt under normal subduction-zone pressure and temperature conditions. We present a new geodynamic model to explain the formation of adakitic magmas for these cases, related to an unusual subduction geometry known as flat subduction (Fig. 3) (Sacks, 1983; Pennington, 1984; Cahill and Isacks, 1992; Abbott et al., 1994; Gutscher et al., 1999a, 2000). Of the 10 known flat slab regions worldwide (Fig. 1), 8 are linked to present or recent (<6 Ma) occurrences of adakitic magmas (Table 1).

GEODYNAMIC MODEL

Comparative observations from several well-constrained flat slab regions along the Andean and Central American margin suggest a three-stage evolution illustrating how a reduction of slab dip can lead to episodes of slab melting. In the normal situation, a narrow calc-alkaline arc (volcanic line) develops above a steeply dipping slab, commonly between the 100 and 150 km isodepth contours to the subducted plate (Fig. 3A). When the dip of the downgoing plate flattens, in response to a change in buoyancy (i.e., subduction of overthickened oceanic crust), the arc typically widens, extending much farther (≥400 km) from the trench (Fig. 3B and 3C). During this transitional stage, lasting several million years, adakitic melts are generated across a wide volcanic arc. This corresponds to modern Ecuador (arc 250–400 km from trench) (Monzier et al., 1997; Gutscher et al., 1999b; Bourdon et al., 1999) and to central Chile at 10–5 Ma (arc 250–800 km from trench) (Kay and Abbruzzi, 1996). Due to the unique set of

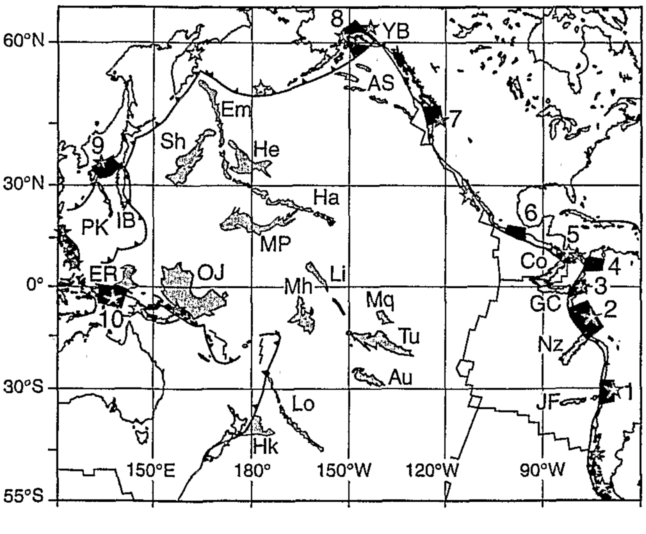

Figure 1. Global distribution of flat slab regions (labels correspond to Table 1) and adakitic magmas (stars). Filled stars are modern occurrences, unfilled stars are 1–6 Ma old occurrences. Principal oceanic plateaus, hotspot tracks, and subducting arcs are shaded gray: Hk—Hikurangi Plateau, Lo—Louisville Ridge, Au—Austral Plateau, Tu—Tuamotu Plateau, Mq—Marquesas Plateau, Mh—Manihiki Plateau, Li—Line Islands, OJ—Ontong Java Plateau, ER—Euripik Rise, PK—Palau-Kyushu Ridge, IB—Izu-Bonin Arc, Sh—Shatsky Rise, MP—Mid-Pacific Mountains, He—Hess Rise, Ha—Hawaiian Chain, Em—Emperor Chain, YB—Yakutat Block, AS—Alaska Seamounts, Co—Cocos Ridge, GC—Galápagos-Carnegie Ridge, Nz—Nazca Ridge, JF—Juan-Fernandez Ridge.

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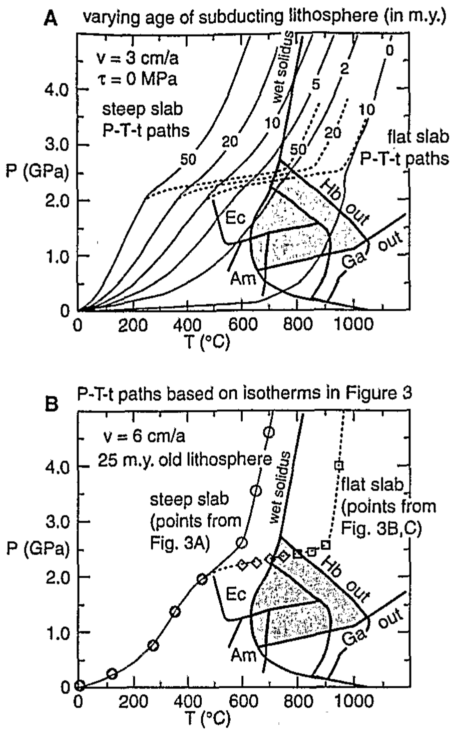

Figure 2. Pressure-temperature (*P-T*) metamorphic reaction diagram showing expected *P-T-t* (*t* = time) paths for varying conditions. Ec—eclogite, Am—amphibolite, Ga—garnet, Hb—hornblende. A: *P-T-t* paths for normal 27° subduction dip (solid lines), with varying lithospheric ages, and subduction velocity of 3 cm/yr, with no shear heating, according to finite difference models (Peacock et al., 1994, Fig. 8B). *P-T-t* paths for flat subduction (dashed) are calculated using analytical solution for slab thermal structure (Davies, 1999) beneath 70 km depth. These paths are much flatter and intersect slab melting field (shaded) at 700 °C and 2.5 GPa for 10–50 Ma subducted lithosphere. B: *P-T-t* paths for steep (circles) and flat (diamonds and squares) subduction based on isotherms in Figure 3 sampled every 50 km along slab surface.

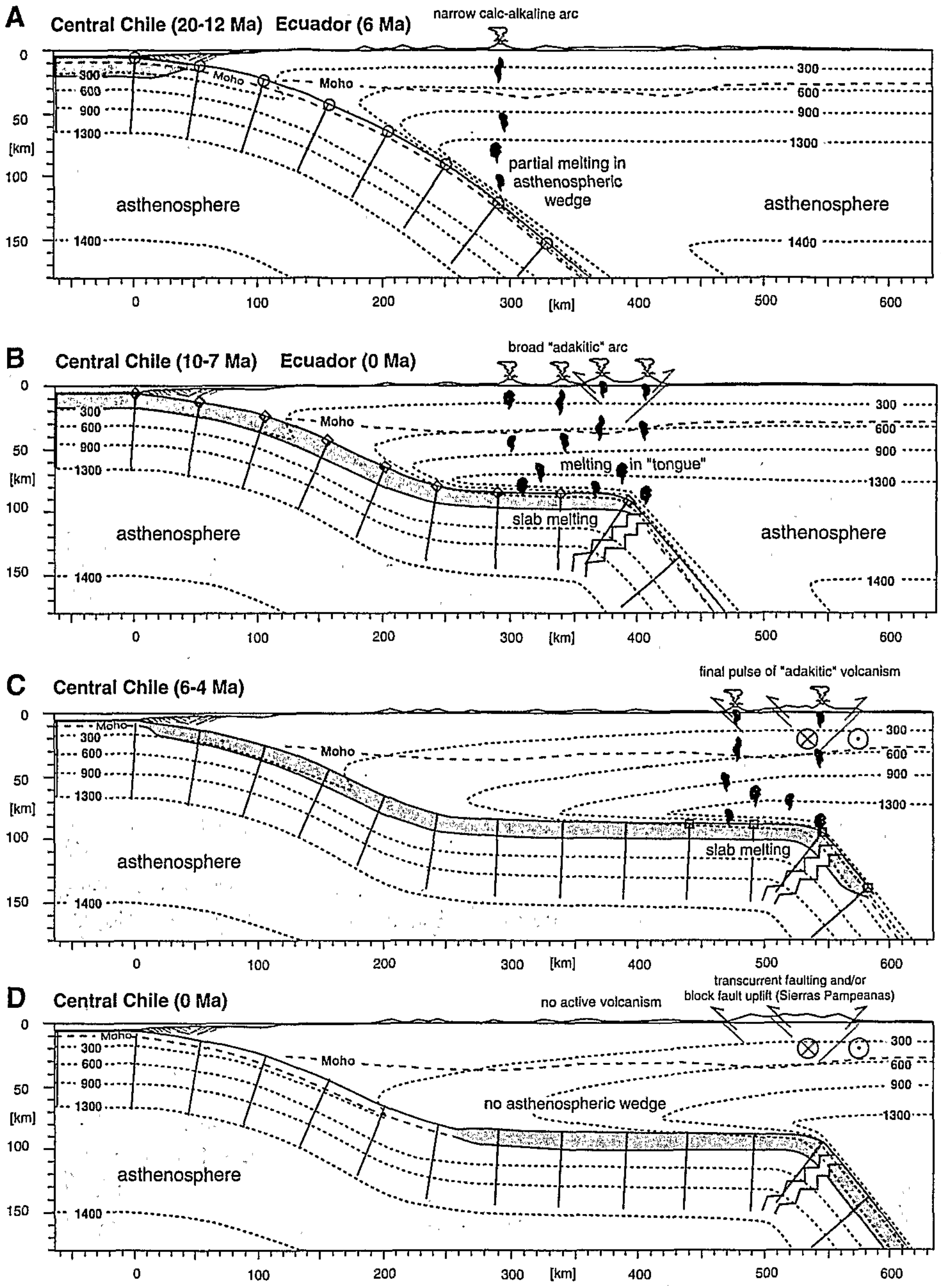

Figure 3. Three-stage evolution showing transition from steep to flat subduction style due to subduction of buoyant, overthickened oceanic crust (e.g., oceanic plateau), with impact on magmatic arc. Thermal structure is constructed based on adaptation of published numerical models (Peacock et al., 1994; Peacock, 1996) and analytical solution (Davies, 1999) (see text). A: Steep or normal subduction (≥30° dip), with narrow calc-alkaline arc, ~300 km from trench produced by slab dehydration and partial melting in overlying asthenospheric wedge. B: Early stage magmatic flat subduction; oceanic slab crosses 700 °C geotherm at ~80 km depth (300–400 km from trench) allowing broad adakitic arc to develop. Partial melting continues in narrow intervening tongue of asthenospheric material. C: Late stage magmatic flat subduction; intervening asthenospheric tongue cools and retreats. Partial melting can only occur at great distance (~450–600 km) from trench, and final pulse of magmatism occurs, as in Sierras Pampeanas, Pocho eruption 4.7 Ma (Kay and Abbruzzi, 1996). D: Prolonged (amagmatic) flat subduction; oceanic slab is cooler than 600 °C, asthenospheric wedge has disappeared, and thus no partial melting can occur, and volcanism ceases.

isotherms and *P-T-t* paths involved in flat subduction, slab melting can occur (Fig. 2). Prolonged flat subduction will sufficiently cool both lithospheres such that the downgoing oceanic crust dehydrates before the necessary temperatures for partial melting are attained and thus the final stage, a volcanic gap, is achieved (Fig. 3D). This complete evolution has been documented for central Chile between 20 Ma and the present (Kay and Abbruzzi, 1996). Ecuador is known to have had a narrow calc-alkaline arc at 5 Ma (Barberi et al., 1988) and has evolved to stage 2 today due to flattening of the slab in response to subduction of Carnegie Ridge (Pennington, 1981; Gutscher et al., 1999b).

The Costa Rican margin also exhibits a similar magmatic evolution (Defant et al., 1992). Before 6 Ma, magmatism was calc-alkaline in nature and the subduction angle presumably steep. Around 5 Ma uplift began in the Talamanca Cordillera, suggesting that the arrival of Cocos Ridge began modifying the style of subduction to the current flat slab configuration (Protti et al., 1994). Since 5 Ma, adakitic magmatism developed, interpreted as originating from slab melting (Defant et al., 1992). Today, the Talamanca segment of Costa Rica appears to have advanced to the final stage, a volcanic gap, because no Quaternary stratovolcanoes are present along this 100 km segment.

TABLE 1. FLAT SLAB REGIONS WORLDWIDE

#	Region*	Length† (km)	Associated plateau(s) or blocks	Age§ (Ma)	Volcanism	
					Quaternary arc	Age of adakites (Ma)
1	Chile (28°S-33°S)	550	Juan Fernandez Ridge	43	No	4–7
2	Peru (2°S-15°S)	1500	Nazca Ridge, Inca Plateau	30–43	No	3–6
3	Ecuador (1°S-2°N)	350	Carnegie Ridge	16–24	Yes	0–3
4	Columbia (6°N-9°N)	350	Choco block	20	No	(none known)
5	Costa Rica	250	Cocos Ridge	14–20	No#	1–3
6	Mexico	400	Tehuantepec Ridge	13–20	Yes	(none known)
7	Cascadia (46°N-49°N)	350	(none known)	8	Yes	0
8	Southern Alaska	500	Yakutat terrane	45	No	0**
9	Southwestern Japan	600	Izu Bonin Arc, Pal.-Ky. Ridge	15–20	Yes	0
10	New Guinea (135°E-140°E)	550	Euripik Ridge	~20	No	2–4?††

*Sources: (1) Kay and Abbruzzi, 1996, (2) Petford and Atherton, 1996, (3) Monzier et al., 1997, (4) Pennington, 1981, (5) Defant et al., 1992, (6) Suarez et al., 1990, (7) Defant and Drummond, 1993, (8) Preece, 1991, (9) Morris, 1995, (10) Pubellier et al., 1998. See also compilations (Pennington, 1984; McGeary et al., 1985; Abbott et al., 1994; Gutscher et al., 2000).

†Cumulative length = 5400 km, which represents ~10% of all subduction zones.

§Age of subducted lithosphere at trench.

#In Costa Rica there is a 100 km gap (Talamanca segment) with an absence of stratovolcanoes.

**In eastern Alaska there is a 500-km-wide volcanic gap. The adjacent volcanoes Hayes and Wrangell show adakitic signatures.

††While Sr/Y ratios for 4.4–2.6 Ma intrusions plot in the adakitic field, new isotope data suggest strong contamination by Australian continental crust (Housh and McMahon, 2000).

THERMAL EVOLUTION AND PETROLOGICAL CONSTRAINTS

Although prolonged flat subduction generally produces a cooler thermal structure (i.e., both upper and lower lithospheres are cooler) (Fig. 3D), (Sacks, 1983; Vlaar, 1983; Henry and Pollack, 1988; Dumitru et al., 1991), during the initiation of flat subduction the leading edge of the undersliding slab can be anomalously heated. An analytic solution for the thermal structure of a cold slab subducting through hot asthenosphere demonstrates temperature to be a function of the downdip length, the slab thickness, and the rate of subduction, but independent of the subduction dip, thus allowing application to a slab with variable dip down its length (Davies, 1999). In other words, a slab moving a fixed distance through hot asthenosphere will gain heat at the same rate whether it descends vertically, at 60°, at 30°, or even if it moves horizontally (as in Fig. 3B and 3C). This allows published steep-slab isotherms (Peacock et al., 1994; Peacock, 1996) to be recalculated for a flat slab geometry for pressures >2 GPa (~70 km depth) (Fig. 2A). Due to the unusual path traveled, first downward to 70 km depth, and then subhorizontally for several hundred kilometers, the *P-T-t* paths differ greatly from steep subduction paths and cross over the wet solidus into the slab melting field.

To date, all published numerical models of subduction-zone thermal structure feature a constant (Davies and Stevenson, 1992; Furukawa, 1993; Peacock et al., 1994; Peacock, 1996; Stein and Stein, 1996) or constantly increasing (Oleskevich et al., 1999; Peacock and Wang, 1999) slab dip, and are typically run until thermal equilibrium is reached. No numerical study has yet attempted to rigorously model a reduction in slab dip (flat subduction), including its transient thermal structure. Past attempts, either static (Vlaar, 1983) or one dimensional (Spencer, 1994), have proven unsatisfactory. In order to illustrate a plausible sequence for the thermal evolution resulting from a change in subduction style from steep to flat, a thermal model was constructed using an adaptation of published numerical and analytical solutions. The steep slab thermal structure is based on both finite difference models (Peacock et al., 1994; Peacock, 1996) and the analytical solution (Davies, 1999) and shows good agreement with earlier (Davies and Stevenson, 1992; Stein and Stein, 1996) and recently published finite-element calculations (Oleskevich et al., 1999; Peacock and Wang, 1999) for slabs with comparable subduction parameters (age, velocity, dip angle). The flat slab thermal structure below 70 km is calculated using the analytical solution as described here (Davies, 1999). The subduction parameters and geometry applied here are based loosely on typical Andean values (25 Ma lithosphere with a 60 km thermal thickness, velocity = 6 cm/yr, and a 300 km subhorizontal slab at 80 km depth). It assumes no shear heating, no heat of fusion, and no advective heat transport to the arc. This set of isotherms is sampled every 50 km along the downdip direction in order to illustrate the *P-T-t* paths predicted by this evolutionary model, shown in Figure 2B, by the use of symbols (circles, diamonds, and squares), each corresponding to a position in *P-T* space (Fig. 2B). Because the leading edge of the undersliding slab spends ~5 m.y. at a nearly constant depth of 70–80 km (pressures of 2–2.5 GPa), it has sufficient time to heat to 700–800 °C, leading to the fluid-present partial melting of the oceanic crust (Drummond and Defant, 1990; Peacock et al., 1994; Prouteau et al., 1999).

DISCUSSION

Alternate models have been proposed for producing adakitic-like magmas in a convergent margin setting; melting of the edges of oceanic crust in the context of a slab window (Johnston and Thorkelson, 1997), direct melting of the base of an overthickened orogenic continental crust (Atherton and Petford, 1993; Petford and Atherton, 1996; Kay and Abbruzzi, 1996), and melting of the base of an accreted arc or ophiolite complex, as invoked for Ecuador (Arculus et al., 1999).

The slab window model in general applies to trench–spreading center triple junctions, and thus could succeed in explaining the Chile triple junction and possibly the Panama occurrence (assuming that a spreading center segment was recently subducted). However, it is insufficient to explain the numerous cases where moderately old oceanic crust is subducting (e.g., Peru, central Chile, Japan, Alaska) and where no evidence of lithospheric tears exists.

Melting at the base of an overthickened orogenic crust (garnet eclogite) has been suggested for Chile (Kay and Abbruzzi, 1996), Peru (Petford and Atherton, 1996), and Ecuador (Monzier et al., 1997) based on isotopic imprints and trace element features indicative of crustal components. However, in Ecuador the crustal imprint is known to be weak (<15%) (Barragan et al., 1998; Bourdon et al., 1999). Furthermore, it is very difficult to distinguish whether these characteristics reflect melting of the base of the crust, or slab melting followed by crustal contamination during ascent through the Andean crust (e.g., the MASH model, Hildreth and Moorbath, 1988). Because these two processes often cannot be distinguished geochemically, the reasons commonly given for dismissing the slab-melting model are thermal considerations, i.e., that crust older than 20 Ma cannot melt (Petford and Atherton, 1996; Kay and Abbruzzi, 1996).

The first argument against melting of the base of a crust thickened by underplating of mafic material is that, while this explanation may work for parts of South America, it does not explain Cascadia, southern Alaska, or southwestern Japan, where continental crustal thicknesses do not exceed 40 km (Oleskevich et al., 1999). Moreover, the relatively high Mg, Cr, and Ni contents of Andean adakites and related rocks are best explained by interaction with mantle peridotite (Sen and Dunn, 1995).

The strongest argument against crustal melting (either of continental or accreted oceanic materials) is temporal. All well-studied adakitic provinces are known from radiometric dating to have been active for only a brief time span of 2–3 m.y. or less (e.g., Panama and Costa Rica, Defant et al., 1992). Adakitic magmatism in central Chile ceased at 4.7 Ma (Kay and Abbruzzi, 1996), yet subduction beneath the thickened crust continues today. The same is true for Ecuador, where subduction has been occurring and arc magmas have been ascending through the accreted ophiolitic crust for at least 20 m.y. Why is there no older (10–20 Ma) adakitic magmatism and why does its onset correspond to the change in subduction dip?

It is important to note that our flat subduction slab melting model includes this temporal evolution. It is only during the early stages of flat subduction that the upper part and leading edge of the slab can melt. Prolonged flat subduction will cool both lithospheres and impede partial melting. It has been repeatedly suggested that only the subduction of hot, very young lithosphere will allow slab melting to occur (Defant and Drummond, 1993; Peacock et al., 1994). The emphasis here is not on the initial temperature of the slab, but on its buoyancy and thus on the time spent at a relatively shallow (~80 km) depth, allowing the slab to heat. Therefore, oceanic crust as old as 50 Ma can melt if it is given sufficient time to warm. Young crust (5–10 Ma) subducts steeply at lat 42°S in Chile, yet no adakites are observed between lat 42° and 44°S.

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COVER

Optical photomicrograph, under cross-polarized light, of high-pressure metamorphosed pelite from the Tso Morari dome (eastern Ladakh, northwest Himalaya): This rock shows eclogitic foliation composed of stable Si phengite, kyanite, and quartz. Because the Tso Morari unit belongs to the Indian margin, the high-pressure, low-temperature assemblage implies the subduction of the Indian margin down to a depth of 70 km. During the decompression, the eclogitic foliation is overprinted by recumbent folds and deformation leads to mineral re-crystallization in the hinge of the folds. Magnification ×25. See "Dating the Indian continental subduction and collisional thickening in the northwest Himalaya: Multichronology of the Tso Morari eclogites," by Julia de Sigoyer et al., p. 487.

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