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How do subduction processes contribute to forearc Andean uplift? Insights from numerical models

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ABSTRACT

We present numerical models to study how changes in the process of subduction may explain the observed Quaternary uplift of the Andean forearc region. Indeed, most segments of the South American Pacific coasts between 16 and 32° S have been uplifting since the Lower Pleistocene, following a period of stability of the forearc region. Models confirm that local uplift is expected to occur above ridges, this phenomenon being predominant in central Peru where the Nazca Ridge is subducting. We investigate the effects of slab pull, interplate friction and convergence velocity on the vertical displacements of the overriding plate. We propose that the global tendency to coastal uplift is accompanying the deceleration of the Nazca-South America convergence that occurred in the Pleistocene. In contrast, forearc subsidence may accompany increasing convergence velocities, as suggested by the subsidence history of the South America active margin.

It is well known since Darwin (1846) that segments of the Pacific coasts of South America are rapidly uplifting. Although obscured by rapid short-term vertical displacements resulting from the seismic cycle, long-term (at geological time-scales) coastal uplift is evidenced by well preserved paleoshores, some of them being perched several hundred meters above sea-level. Many of these paleoshores have been dated using different techniques (cosmogenic isotopes, U-Th, ESR and Amino-acid racemization on shells, Sr isotopes...). Available ages show that most of the preserved paleoshores are younger than 1 Myr and formed during highstand periods (e.g., Leonard and Wehmiller, 1992; Saillard et al., 2010). Since the global sea level did not reach elevations higher than 10 m above the present-day sea level during the last Myr, most of the present-day elevation of Pacific South American paleoshores results from tectonic uplift of the coastal area (e.g., Pédoja et al., 2011). Recently, Regard et al. (2010) noted that uplifted paleoshore remnants are preserved along the entire coastal segment of the Central Andes between 16 and 30° S, including along shore segments in northern Chile where the ocean is erosive and in which most of the coast corresponds to a several hundred meters-high cliff interrupting the Coastal Cordillera. Regard et al. (2010) concludes that South America, along a ~2000 km-long coastal segment corresponding to the Central Andes, has been uplifting since the Middle Pleistocene. Rodriguez et al. (2013) observe the same coastal evolution between 30 and 32° S. In fact, Fuenzalida et al. (1965) had already noted that Chilean Coasts North of 40° S have been uplifting during the Pleistocene. These authors note that this Quaternary renewal of coastal uplift contrasts with the stability and/or subsidence that prevailed before the Middle Pleistocene (Fuenzalida et al., 1965; Paskoff, 1978; Clift and Hartley, 2007; Rodriguez et al., 2013).

In this paper, we review the available information on present-day uplift at geological time scales (10^5 to 10^6 years), in order to constrain the causes that may explain it. Since the observed uplift is visible along ~3000 km of coasts between 40° S and 16° S, some causes responsible for the coastal vertical displacements must have a global origin resulting either from the dynamics of subduction, from the dynamics of plate convergence along the South American active margin, or from global changes that affect the interplate contact properties. We use a finite element model reproducing the subduction of the Nazca plate beneath South America, in order to see how geodynamical changes may control the vertical displacements of the overriding plate in the coastal area.

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1. Coastal uplift along the South American active margin

Long-term uplift is visible along large segments of the Pacific coasts of South America. Pédoja et al. (2011) review the evidence of coastal uplift since the last interglacial stage, 122 kyrs ago (Marine isotopic Stage 5e). They note that along most of the coasts of western South America, paleoshores dated from the last interglacial period are generally located between 15 and 50 m above the present-day sea level (Fig. 1). Since the maximum sea level during the last interglacial period was between 3 ± 1 m (Siddall et al., 2007) and 7.2 ± 1.3 m (Kopp et al., 2009) above the present-day sea level, it means that most of the coasts have been uplifting at rates generally larger than 0.1 mm/yr. Locally, the MIS-5e paleoshore has been observed at elevations higher than 60 m above sea level, the corresponding uplift rate being larger than 0.4 mm/yr. Such rapid uplift rates, however, are generally restricted to particular sites located above the subduction of buoyant aseismic ridges and/or in places where active faults are deforming the coastal area (Fig. 1).

The Carnegie and Nazca ridges are the two largest aseismic ridges being subducted beneath South America. The Carnegie Ridge is subducting beneath Ecuador since at least 1.4 Myrs, but the proposed age for the onset of subduction is disputed and ranges from 1 to 15 Myrs (see Michaud et al., 2009, for review). This ridge being roughly parallel with the convergence direction, its locus of subduction beneath the continent should have remained relatively stable during the Quaternary, although some authors suspect it has been migrating southward from the Colombian coasts (Gutscher et al., 1999). In contrast, the Nazca Ridge is oblique with respect to the convergence azimuth. Its subduction beneath Peru migrated 500 km to the South-East during the last 10 Myrs (Hampel, 2002). Particularly rapid uplift rates are observed in Ecuador above the subducting Carnegie Ridge (Pédoja et al., 2006), and in Peru above the Nazca Ridge (Hsu, 1992; Goy et al., 1992; Macharé and Ortlieb, 1992; Wipf et al., 2008; Saillard et al., 2011). South of the Nazca ridge axis, ridge subduction increases the coastal uplift velocity. Indeed, the consequence of the southward migration of the ridge is that more buoyant segments of the ridge are progressively being subducted beneath that part of the continent. The effect of the ridge on coastal uplift is noticeable, from Atico (16.2° S, 320 km SE of the ridge crest) to the ridge axis (Regard et al., 2010; Saillard et al., 2011). In contrast, north of the ridge axis, the Peruvian coast is subsiding because the ridge is progressively moving farther away to the south, explaining why Quaternary paleoshores are not visible onshore Central Peru. Paleocanyons filled by Quaternary deposits, for instance below the city of Lima (Le Roux et al., 2000), evidence subsidence in that part of the Pacific Coast.

Other ridges are being subducted beneath the continent (Iquique and Juan Fernandez Ridges, located at 21° and 33° S, respectively). The corresponding topographic anomalies, however, are much smaller and their effect on coastal uplift is not clear, despite the fact that the Juan Fernandez Ridge is suspected to be responsible for the appearance of a flat-slab segment beneath North-Central Chile (e.g., Yañez et al., 2001; Martinod et al., 2010).

In contrast, the very rapid uplift rate reported by Melnick et al. (2009) in the Arauco Peninsula (~37.5° S) does not correspond to any subducting ridge. Melnick et al. (2009) show this uplift may result from N–S continental shortening resulting from the Northward motion of the Chiloe forearc sliver. In fact, it has been noted that peninsulas generally correspond to particular places in which crustal deformations result in larger uplift velocities. Another example of rapidly uplifting peninsula is Mejillones (~23° S, Ortlieb et al., 1996; Gonzalez et al., 2003). Larger uplift rate of peninsulas result from roughly trench-parallel faults that accommodate the relative uplift of the western blocks and whose activity may result from basal accretion processes (e.g., Delouis et al., 1998; Gonzalez et al., 2003; Melnick et al., 2006). This tectonic activity seems to be related with the segmentation of subduction mega-earthquakes (Delouis et al., 1998; Melnick et al., 2009; Victor et al., 2011; Métois et al., 2012; Cortes-Aranda et al., 2015).

Despite the upper plate tectonics and the uplift rates at geological timescales ($>10^5$ years) share some common characteristics with mega-subduction earthquakes, the question of causal links between them remains open. The pattern of coseismic uplift during mega-earthquakes generally shows remarkable trench-distance dependence, with uplift close to the trench and subsidence inland of the earthquake rupture (Farias et al., 2010; Vigny et al., 2011). The analysis of worldwide MIS-5 shorelines also shows that long-term uplift depends on the distance to the trench (Henry et al., 2014). However, long-term uplift is observed both in zones where interseismic coupling is large (central Chile, northern Ecuador) or small (northern Peru) (Métois et al., 2012; Nocquet et al., 2014). Although rapidly uplifting peninsulas seem to correspond to zones of low interseismic coupling (Métois et al., 2012; Cortes-Aranda et al., 2015), coastal subsidence also occurs in central Peru, north of the Nazca ridge, where the interseismic coupling is particularly small (Nocquet et al., 2014). Then, there is no clear relationship between the interseismic behavior of the subduction channel and uplift of the coastal area.

Fig. 1 shows that coastal uplift is restricted neither to areas located above subducting ridges, nor subject to active crustal deformations. Regard et al. (2010) suggest that uplift has been generalized since the Middle Pleistocene along the coasts of Central Andes, between 15 and 30° S, which includes many areas where the oceanic floor does not present any noticeable topographic anomaly. Thus, although heterogeneities of the subducting plate may locally influence coastal uplift, other large-scale physical processes are uplifting the overriding plate at rates of ~0.1–0.3 mm/yr. Processes occurring along coastal segments larger than 1000 km are probably related with plate tectonics and the dynamics of subduction. In this paper, we use a finite element code to look at the effects on coastal uplift of changes in the parameters controlling the process of subduction.

2. Mechanical modeling

We use the finite element code Adeli to model the subduction of an oceanic plate beneath an advancing continent. This code belongs to the FLAC family of codes (Cundall, 1988; Poliakov and Podladchikov, 1992) and is based on the dynamic relaxation method. Adeli has been used in numerous geodynamical applications, for processes at crustal (e.g., Vanbrabant et al., 1999; Got et al., 2008) as well as at lithospheric scale (Lesne et al., 2000; Neves et al., 2008). The reader interested by the numerical method used in this code may consult Hassani et al. (1997) or Chéry et al. (2001) for details.

The modeling approach adopted here is close to that presented in Gibert et al. (2012): the model consists in two visco-elastic plates whose horizontal convergence velocity is imposed by lateral boundary conditions (Fig. 2). Parameters of the numerical models are given in Table 1. The overriding continental plate is 100 km-thick, including a 30 km-thick buoyant crust. The subducting oceanic plate is not homogeneous, in order to observe how changing the nature of the subducting plate triggers vertical displacements of the overriding plate. In the reference model, the oceanic lithosphere is 80 km-thick, with a 10 km-thick crust. The density of mantle lithosphere and oceanic crust is 3.3 g/cm^3 and 2.9 g/cm^3, respectively. That of the asthenosphere being 3.23 g/cm^3, the buoyancy of the subducting plate is negative, except when we model the subduction of a thick plateau beneath the continental plate.