



End member models for Andean Plateau uplift

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ABSTRACT

Diverse techniques have been applied over the past decade to quantify the uplift history of the central Andean Plateau (AP). In this study, opposing models for surface uplift are evaluated including: a rapid rise of ~2.5 km ~10–6 Ma and a slow and steady rise since ~40 Ma. These end member models are evaluated by synthesizing observations of the AP lithosphere and the history of deformation, sedimentation, exhumation, magmatism, uplift, and fluvial incision. Structural and geophysical studies estimate variable shortening magnitudes (~530–150 km) involving cover-to-basement rocks, an isostatically-compensated thick crust (~80–65 km), high heat flow, and zones of variable velocity and attenuation in the crust and mantle. These observations have invoked interpretations such as a hot/weak lithosphere, partial melt, crustal flow, and perhaps current, localized delamination, but do not provide strong support for massive delamination required by the rapid uplift model. Deformation and associated exhumation began ~60–40 Ma and generally migrated eastward with consistent long-term average shortening rates (~12–8 mm/yr) in Bolivia, favoring the slow uplift model. Volcanic and helium isotope evidence show an AP-wide zone of shallow mantle melting and thin lithosphere that has existed since ~25 Ma, which is inconsistent with the rapid rise model that suggests lithospheric thinning occurred 10–6 Ma. Paleoelevation data suggest a rapid ~2.5 km elevation gain 10 to 6 Ma, but are equally consistent within error with a linear rise since ≥25 Ma. Widespread fluvial incision (2.5–1 km) occurred along the western flank since ~11–8 Ma and may be associated with surface uplift as proposed by the rapid rise model. However, the paleoelevation and incision data can also be explained by regional climate change associated with plateau uplift. Implications of these results for reconstructions of AP evolution are that: (1) substantial deformation of a weak lithosphere is essential, (2) AP growth has taken significantly longer (≥40 Myr) and was more uniform along strike (~1500 km) than previously appreciated, and (3) the slow and steady uplift model is most consistent with available constraints. We conclude that the rapid uplift model may be an overestimate and that a more protracted Cenozoic uplift history is tenable.

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1. Introduction

The plateaus of Tibet and the central Andes are the largest tectonically active orogens. Despite this, the topographic, tectonic, and geodynamic evolution of orogenic plateaus remain imprecisely known and the focus of significant research. These plateaus are thought to influence local-to-far-field lithospheric deformation as well as global sediment flux, ocean chemistry, atmospheric circulation, precipitation, and climate change (Richter et al., 1992; Molnar et al., 1993; Masek et al., 1994; Lenters and Cook, 1995; Royden, 1996; Ruddiman et al., 1997; Sobel et al., 2003). In particular, numerous geologic observations have constrained the tectonomorphic evolution of the central Andean Plateau (see summaries in Isacks, 1988; Reutter et al., 1994; Allmendinger et al., 1997; Jordan et al., 1997; Kley et al., 1999; Gregory-Wodzicki, 2000; Kennan, 2000; Ramos et al., 2004; Barnes and Pelletier, 2006; Oncken et al., 2006b; Strecker et al., 2007; Kay and Coira, 2009), yet its history of uplift and consequently the associated geodynamic mechanisms of plateau development remain disputed (Garzione et al., 2006; Ghosh et al., 2006; Sempere et al., 2006; Garzione et al., 2007; Hartley et al., 2007; Hoke and Lamb, 2007; Ehlers and Poulsen, 2009).

A range of processes have been proposed for Andean Plateau (AP) growth (Fig. 1). These include: (1) magmatic addition (Thorpe et al., 1981; Kono et al., 1988), (2) distributed shortening (Isacks, 1988; Sheffels, 1995; Kley and Monaldi, 1998; McQuarrie, 2002b; Riller and Oncken, 2003; Gotberg et al., in press), (3) spatio-temporal variations in upper plate properties, plate interface, and subduction geometry (Jordan et al., 1983; Isacks, 1988; Gephart, 1994; Allmendinger and Gubbels, 1996; Kley et al., 1999; McQuarrie, 2002a; Lamb and Davis, 2003; Hoke and Lamb, 2007), (4) ablative subduction, crustal flow, and delamination (Kay et al., 1994; Lamb and Hoke, 1997; Pope and Willett, 1998; Husson and Sempere, 2003; Garzione et al., 2006; Schildgen et al., 2007), (5) cratonic under-thrusting (Lamb and Hoke, 1997), and (6) spatio-temporal erosion gradients (Masek et al., 1994; Horton, 1999; Montgomery et al., 2001; Barnes and Pelletier, 2006; Strecker et al., 2007; McQuarrie et al., 2008b; Strecker et al., 2009). Previous progress in AP studies has eliminated processes like magmatic addition as important (e.g. Sheffels, 1990; Francis and Hawkesworth, 1994; Giese et al., 1999) and stressed the significance of shortening, thermal weakening, extrusion, and lithospheric thinning for plateau formation (e.g. Allmendinger et al., 1997; McQuarrie, 2002b; Willett and Pope, 2004). Furthermore, numerical models can reproduce first-order Andean Plateau-like morphologies when accounting for temperature-dependent viscosity variations in a thickening crust (Willett et al., 1993; Wdowski and Bock, 1994b; Willett and Pope, 2004; Sobolev and Babeyko, 2005).

Despite these advances, the history of Andean Plateau surface uplift remains controversial. Resolving the uplift history is difficult because (1) inferring uplift from observations of shortening is difficult and rarely

quantified (Jordan et al., 1997) as well as potentially inaccurate if deformation and uplift are decoupled, and (2) uncertainties associated with direct observations of the elevation history using paleoaltimetry techniques are often substantial (e.g. $\pm \geq 1000$ m, Gregory-Wodzicki, 2000). Furthermore, numerical models of plateau formation are limited by inadequate knowledge of the kinematics, timing, and rates of AP deformation and uplift as well as variability in the kinematic and chronologic history along strike. Shortcomings in our present understanding of central Andes evolution are, in part, the result of both a tendency to apply local solutions to the entire plateau and a lack of integration of all available data into testing models of AP growth.

The goal of this study is to test two end member models of Andean Plateau uplift by integrating a range of geologic observations that constrain its Cenozoic history. The end member models for uplift considered are: (1) a *rapid and recent* rise whereby ~ 2.5 km of elevation ($> 1/2$ the current plateau height) was obtained during the late Miocene (~ 10 to 6 Ma) (Garzione et al., 2006) vs. (2) a *slow and steady* rise inferred to be commensurate with deformation (e.g. after Jordan et al., 1997) which began in the Paleocene–Eocene (~ 60 – 40 Ma) (e.g. McQuarrie et al., 2005). These models are evaluated by synthesizing the following constraints into a synoptic history: (1) the current structure of the lithosphere deduced from mapping, balanced cross sections, and geophysical studies, (2) the deformation history inferred from sedimentary basins, geochronology, and associated upper-crustal structures, (3) the deformation history estimated from rock exhumation, (4) the evolution of the mantle lithosphere and subduction geometry inferred from chronology and geochemistry of magmatism and helium emissions, (5) the uplift history constrained by marine sediments, paleobotany, biotaxa changes, paleoclimate proxies, erosion surfaces, and stable isotope paleoaltimetry, and (6) the history of fluvial incision into the plateau margins quantified from geomorphic, stratigraphic, and thermochronologic analyses. Within each section, we summarize the observations and highlight key consistencies, inconsistencies, interpretations and caveats. This study builds upon previous work by including: (a) reference to the large amount of literature published in the last decade, and (b) a wide variety of Earth Science disciplines that are not all integrated in previous reviews. The most important conclusions are that: (1) significant upper-plate deformation within a weak lithosphere is essential to AP growth, (2) AP development has taken significantly longer and was more uniform along strike than previously appreciated, and (3) the slow and steady end member uplift model is more consistent with available constraints.

2. Geologic setting

The central Andean (or Altiplano–Puna) Plateau (AP) is defined as the region > 3 km in elevation in the core of the Andes at ~ 14 – 28° S in western South America (Fig. 1) (Isacks, 1988; Allmendinger et al.,

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