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INVITED TALK

What caused Andean uplift?

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In a recent paper, Lamb and Davis (2003) proposed that climate change was indirectly responsible for the uplift of the Andes. They suggested that an increase in aridity during the Cenozoic associated with global climate cooling resulted in decreased erosion and reduction in sediment supply to the trench. This lack of sediment resulted in increased friction and enhanced shear stress along the plate interface and uplift and deformation of the South American Plate. However, this hypothesis is not supported by evidence for climate change from the Cenozoic sedimentary record in western South America, by studies of the plate interface itself and the deformation history of the Central Andes. It is proposed that uplift of the Andes is unrelated to sediment starvation at the trench, and rather results from a combination of limited erosion associated with a long-term arid climatic regime and changes in the direction and rate of relative plate convergence.

Climate Change

A substantial body of information is available (not reviewed here) on the late Mesozoic and Cenozoic geomorphological, sedimentological and tectonic history of the north Chilean forearc that allows constraints to be placed on the climatic history of the area. An early Cretaceous to late Eocene volcanic arc was located in the present day Central Depression. A 6000 m thick back-arc basin-fill was deposited east of the arc in the present day Precordillera. Sediments were deposited in alluvial fan, ephemeral fluvial, aeolian, ephemeral lacustrine, evaporite and playa environments under an arid/semiarid climate (Hartley et al. 1992). Intra-arc and forearc basins were developed in what is now the Central Depression and the Coastal Cordillera respectively.

Late Eocene to early Pliocene age sediments occur throughout northern Chile. Deposition took place in a similar forearc setting to the present day with sediments comprising alluvial fan, fluvial, sandflat, playa, evaporite, nitrate, lacustrine and marginal lacustrine deposits (e.g. Naranjo et al. 1994; Sáez et al. 1999; May et al. 2005). These sedimentary rocks were deposited in endorheic basins under a predominantly semiarid climate interspersed with periods of increased aridity (Hartley & Chong 2002).

The late Pliocene to present day succession is represented by localised evaporites restricted to topographic lows and development of a saline crust throughout the Peru-Chile desert (Chong 1988). This phase of deposition marked the onset of the present day hyperaridity in the Atacama at least south of 23°S and was established between 3 and 4 Ma (Hartley & Chong 2002). Recent work however, indicates that at least in the Coastal

Cordillera and western Central depression north of 23°S a hyperarid climate may have prevailed from the late Oligocene/early Miocene (Dunai et al. 2005; Evenstar et al. 2005). The Cretaceous and Cenozoic sedimentary record from northern Chile is dominated entirely by sediments deposited under an arid/semiarid climate. It appears therefore, that northern Chile has been subject to a continuously arid/semiarid climate for at least the last 100 Ma and possibly earlier. For much of the Cenozoic sedimentation took place in endorheic basins developed east of the Coastal Cordillera, consequently little or no sediment was supplied directly to the trench.

Palaeolatitude

An estimate of palaeolatitude derived from palaeomagnetic data provides indirect support for an unchanged climatic regime from the Cretaceous onwards (Hartley et al. 2005). Apparent polar wander (APW) paths and reference poles for the stable craton of South America from the Cretaceous to the present day (Beck, 1999; Somoza & Tomlinson 2002), indicate that since 80 Ma there has been no identifiable APW of South America relative to the present day spin axis. Palaeomagnetic data from northern Chile indicate that there has been no latitudinal translation of strata relative to the South American craton since the late Palaeozoic (Jesinkey *et al.* 1987; Somoza & Tomlinson 2002). Northern Chile has therefore remained at approximately the same latitude for the last 80 Ma. If as appears likely, the southern hemisphere desert belt has not moved significantly during the last 80 Ma (Hartley et al., 2005) then western central South America is likely to have been subject to an arid climate from at least the late Cretaceous onwards.

Evidence for high plate boundary shear stresses

The Central Andean convergent margin is commonly regarded as a high stress and high friction interplate end-member for subduction zones and is considered ideal for generating high rates of subduction erosion. High shear stresses are considered to have built up at the interface between the Nazca and South American plates due to sediment starvation of the Peru-Chile trench resulting from the arid onshore climate (e.g. Lamb and Davis 2003). However evidence from multibeam bathymetry and seismic records from the north Chilean margin indicate that this is not the case. von Heune and Ranero (2003) identified the presence of an interplate clastic layer that reduces friction and shear stress at the plate boundary. The interplate layer is derived from mass wasting of the slope and forms a frontal prism of remolded debris that elevates pore pressure to reduce interplate friction (von Heune and Ranero 2003). Interplate seismicity and taper analyses presented by these authors indicate that basal friction levels in the upper plate are similar to those in sediment-rich convergent margins. Consequently, there is no requirement for elevated shear stresses to be present at sediment starved convergent margins. Lamb & Davis (2003) suggested that there would be considerable material/compositional differences between the sediment incorporated into the subduction zone at sediment starved versus sediment rich margins and that this would affect the thermal properties of the subduction zone. However sediments at the two different margins are both likely to be largely unlithified, fine grained and water-rich and are unlikely to display any substantial differences that might account for variations in shear stress between sediment poor and sediment rich margins.

Deformation, Relative Plate Convergence and Andean Uplift

The detailed relationship between relative plate convergence and deformation in the Andes has yet to be resolved although a general relationship between plate convergence and Andean uplift is generally accepted. Work by Pardo-Casas and Molnar (1987) and Somoza (1998) allow constraints to be placed on the direction and rate of relative plate convergence during much of the Cenozoic. Between 68 and 49 Ma convergence was almost parallel to the South American margin (Pardo-Casas and Molnar, 1987). From 49 to 30 Ma convergence was oblique (between 45 and 35 degrees) and became largely orthogonal after 30 Ma when convergence rates doubled between 28 and 25 Ma (Somoza 1998).

The deformation associated with uplift of the Andes has been extensively documented and the spatial and temporal distribution of deformation is known to vary considerably. However some general comments can be made. There is a limited amount of evidence for Paleogene deformation in Bolivia, however it appears that the vast majority of deformation associated with uplift and volcanic and magmatic activity took place during the Miocene. Indeed the present arc was established in the early Miocene with little or no Oligocene volcanic activity recorded. From the albeit limited information available on uplift rates it is clear that at least 75% of Andean uplift is Miocene or younger in age (e.g. Gregory-Wodzicki 2000; Hartley 2003). It would appear therefore that there is a close correspondence between an increase in convergence rates and Andean uplift, although the detailed distribution of deformation and uplift varies between individual tectonically defined areas and the precise relationship has yet to be established.

Discussion and Conclusions

Lamb & Davis (2003) proposed that the dynamics of subduction and mountain building in the Andes are controlled by the processes of erosion and sediment deposition and are linked directly to climate. They suggested that increased Cenozoic aridity led to sediment starvation at the trench generating increased friction and enhanced shear stress at the plate interface, resulting in uplift and deformation of the South American Plate. The sedimentary record and palaeomagnetic data suggest that there is no evidence for a significant climate change in western South America at or around the mid/late Eocene (when initial Andean uplift is considered to have commenced) and that an arid climate prevailed both before and after this time period. This suggests that sediment fluxes to the trench are unlikely to have changed substantially during the Cenozoic. In addition the work of von Heune and Ranero (2003) indicate that even though the Peru-Chile trench is starved of sediment the lack of sediment does not result in increased interplate friction. In fact they found that basal friction levels in the upper plate off the coast of northern Chile are similar to those in sediment-rich convergent margins. Consequently, there is no requirement for elevated shear stresses to be present at sediment starved convergent margins.

It is concluded that there is no evidence to support the theory proposed by Lamb & Davis that Cenozoic climate change resulted in Andean uplift. Rather it is suggested that Andean uplift results from a combination of 1) the limited erosion associated with the arid climate that has prevailed across the region from the Late Jurassic, and 2) a change to more orthogonal convergence in the Eocene and doubling of convergence rates in the late Oligocene to early Miocene. In conclusion, the height of the Andes is strongly controlled by the prevailing climate, but only because uplift easily outpaces erosion.

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