HAS DELAMINATION OF THE LOWER LITHOSPHERE OF THE CENTRAL ANDES OCCURRED?

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RESUMEN La cantidad del acortamiento cortical en los Andes centrales y la evidencia parA la delaminación (o subducción intracontinental) en otros cinturones de montañas indican que la delaminacion puede ser un proceso importante en el desarollo de los Andes. Las estimaciones del acortamiento definen la deformación de la litosfera inferior, y sugieren la cantidad de la corteza y del manto superior que peude ser involucrado en la delaminación. Se considera la evidencia termica, gravimetrica, estructural, y sismologica para la delaminación. Una comparison de los Andes con otros lugares donde la delaminación esta propuesta ayuda en definir el proceso en los Andes y en general.

KEY WORDS: delamination, convective instability, crustal shortening, central Andes, Bolivia

INTRODUCTION

Crustal shortening has played a key role in the formation of mountain belts around the world, ancient and modern, in a variety of tectonic settings. The corresponding shortening within the lower crust and mantle lithosphere has led to various hypotheses concerning the fate of those regions of the continental lithosphere, including subduction, delamination, or convective instability. The central Andes provide a unique opportunity, since they are young and actively forming, to examine the deformation of the entire continental lithosphere, and to assess spatial and temporal variations in the shortening of the lower lithosphere, and its possible loss to the asthenosphere.

This paper will use surface structural data from the Bolivian Andes to place constraints on the deformation of the lower lithosphere, consider some implications of the insights provided by these constraints, and summarize the evidence for and against the process of delamination in the Andes, both from the Andes and in comparison with other mountain belts. The term "delamination" is used in a general sense, to indicate a final geometry that results from loss of the lower continental lithosphere to the asthenosphere, but is not meant to differentiate between specific processes, e.g. the delamination of Bird (1978; Bird and Baumgardner, 1981) or the convective instability of England and Houseman (1988, 1989).

GEOLOGIC SETTING

The central Andes are the site of the earth's second largest plateau and some of the thickest crust on the earth, making them a unique site on the earth today. While these attributes invite comparison to the Himalaya and Tibet, the Andes have formed in response to subduction of oceanic lithosphere only. We currently understand the formation of the high elevations and thickened crust as primarily the result of crustal shortening, the product of deformation in fold and thrust belts extending across the Altiplano, Cordillera Oriental and Sub-Andes (Roeder, 1988; Isacks, 1988; Sempere et al., 1988; Sheffels, 1988; Hérail et al., 1990, Baby et al., 1992).

IMPLICATIONS OF SHORTENING ESTIMATES AND INITIAL GEOMETRIES FOR LITHOSPHERIC DEFORMATION

The amount of crustal shortening documented in the central Andes can be used to constrain the deformation of the lower lithosphere for various initial crustal and lithospheric thicknesses. A range of shortening estimates has been determined from balanced cross sections spanning the Bolivian Cordillera Oriental and Sub-andes at approximately 18°S (Sheffels, 1988), where shortening is plausibly a maximum in the central Andes. A lower bound of 210 kilometers is based on a set of restrictive assumptions for the cross section interpretations; relaxation of individual assumptions yields larger estimates of 325 and a maximum of 670 kilometers. Shortening estimates derived independently (Lyon-Caen et al., 1985; Isacks, 1988; Baby et al., 1992) lie in the range of 300-350 kilometers.

Lithospheric roots corresponding to the various estimates of shortening can be calculated, and demonstrate a sizable space problem. Initial thicknesses of 40 kilometers for the crust and 100 kilometers for the lithosphere (including the crust) and plane strain deformation are assumed initially. Initial crustal thickness is based on paleogeographic evidence and the tectonic history of the region. Substantial thickening of the mantle lithosphere results for each estimate of shortening, even the minimum case; the three estimates given above correspond to 23, 31, or 48 percent shortening. The geometry of the deformation is not addressed. Crustal material contributes to the thickened root if the cross sectional area resulting from a given estimate of shortening and initial crustal thickness exceeds the present-day crustal cross sectional area. The critical values of shortening are as follows: crustal subduction is required if the amount of shortening is greater than 315 kilometers, assuming the crust was initially 40 kilometers thick. If the crust was initially 45 kilometers thick, the necessary amount of shortening decreases to 215 kilometers; if initially 35 kilometers thick, crust will be subducted if shortening exceeds 445 kilometers. If the lithosphere is initially thinned beneath the future mountain belt, but is 140 kilometers thick elsewhere (Isacks, 1988), roots of the same size or larger are formed as when the lithosphere is initially uniformly 100 kilometers thick. A lower limit on initial thinning is determined: to produce a uniform layer of continental mantle 60 kilometers thick today, an average initial thickness of the entire lithosphere of 80 kilometers is required.

HAS DELAMINATION OCCURRED?

In other mountain belts, crustal subduction and loss of the thickened lithosphere are suggested by similar constant area arguments and by independent evidence for a thinned lithosphere. Indications that the asthenosphere has replaced the mantle lithosphere beneath substantially shortened mountain belts, have led to hypotheses of convective instability (Houseman et al., 1981; England and Houseman, 1989), or delamination (Bird, 1978, Bird and Baumgardner, 1981), as mechanisms to remove the thickened lithosphere due to gravitational instability. Theoretical considerations suggest that the instability can develop as quickly as 10 Ma after shortening commences (Houseman et al., 1981), and that a critical amount of shortening is required (England and Houseman, 1989). The involvement of the lower crust is dependent on the initial thicknesses assumed and on the behavior of the mantle lithosphere. Others have argued (Kincaid and Silver, 1993) or demonstrated (the Alps, Fleitout and Froidevaux, 1982) that the thickened lithosphere has not been lost beneath shortened mountain belts. In light of these diverse observations from other mountain belts and the constraints imposed by the surface structural data in the Andes, it is instructive to consider whether delamination has occurred in the central Andes.

Several lines of evidence are available to assess whether delamination has occurred in the central Andes, an argument that has been proposed for the region as a whole or with reference to specific regions (Froidevaux and Isacks, 1984; Sheffels, 1988, 1993; Isacks, 1988; Whitman et al., 1992; Kay and Kay, 1993). Heat flow data that indicate that the Cordillera Oriental and eastern Altiplano are unusually hot (Henry and Pollack, 1988) can be interpreted to indicate that asthenosphere has replaced lithosphere in those regions, although this interpretation is a non-unique one. Gravity data suggest that the lithosphere has elastic strength throughout the Sub-andes (Lyon-Caen et al., 1985), which can be interpreted as a lateral limit on the width of a region of delamination; where the lithosphere no longer behaves elastically, it has delaminated. The geoid anomaly, a high of 25 m (Froidevaux and Isacks, 1984), suggests a thermal component (Isacks, 1988) to the high elevations observed, which could be supplied by replacement of lithosphere by asthenosphere. Seismicity patterns are also suggestive: deep earthquakes (~650 kilometers) may be related to the subduction of the lower lithosphere, tensional earthquakes within the slab at intermediate depths may reflect bending of the slab resulting from deformation by the lithospheric root, and low levels of crustal seismicity may reflect a higher geotherm. Attenuation is described as high in the Altiplano region (James, 1971), although Whitman et al. (1992) restrict high attenuation regions to the active magmatic arc and the southern central Andes, arguing against delamination beneath the Bolivian Andes. The distribution and magnitude of normal faulting does not seem to be related to delamination in either of the ways that extensional processes in the Basin and Range (Sonder et al., 1987) or the Himalaya seem to be (England and Houseman, 1989). While the extension documented in the Andes could be related to delamination, such scenarios are not the simplest explanation. Some of the normal faulting, within the portion of the mountain belt containing the Altiplano, can be shown to be secondary faulting, accommodating tear faulting in thrust systems or steps in strike-slip faults; this interpretation may be the simplest, but additional data are needed. In any case, the absence of extension is not conclusive evidence that delamination has not occurred.

In summary, a definitive case for or against delamination can not be made. In addition to satisfying all of the available data, conclusions regarding delamination in the central Andes must integrate additional factors. For example, the "normal" effects of a subduction zone with an active magmatic arc on geotherms and convection must be considered. Also, the magnitude of shortening affecting the lithosphere suggests that three-dimensional deformation may be important: where shortening is a maximum, the deformation of the continental lithosphere may control the dip of the subducting oceanic slab, rather than vice versa; tectonic style is not determined by slab dip. Furthermore, along-strike flow may result from the convergence; the two-dimensional space problem may be resolved either by moving material down (delamination) or laterally out of the cross section, a possible explanation for the geometry of the Nazca slab. Note that the causal ordering follows from the surface constraints. Finally, comparison with other mountain belts is used to clarify the controls on the delamination process in continental lithosphere.

CONCLUSIONS

Well-constrained surface data from the Bolivian Andes allow the determination of bounds on amounts of lower crustal and upper mantle shortening, and therefore on amounts of subduction or delamination that may have occurred, for a range of initial thicknesses. Crustal subduction is not required for the most plausible estimates of shortening and initial crustal thickness. One implication of the magnitude of shortening is that the shortening may have driven the along-strike variation in the dip of the Nazca slab observed today. Although similar to the Himalaya, a mountain range produced by continental collision, the central Andes have formed in a non-collisional setting. Delamination is suggested by analogy with other mountain belts. Theoretical considerations suggest that sufficient time has passed since the onset of shortening for a convective instability to develop. While atttenuation data suggest that delamination has not occurred in this region, heat flow, gravity, and seismicity data are permissive evidence for delamination.

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