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Lithospheric structure of the Central Andes, constrained by ^{3}He and geological data.

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Abstract. We review recent isotopic[1,2] and geochemical and geochronological studies (Hoke and Lamb, unpublished data) of both Plio-Pleistocene volcanic rocks and geothermal regions in the Central Andes of northern Chile, Bolivia and north-western Argentina. These indicate a region of mantle melting, up to 400 km wide, characterised both by elevated mantle-derived ^{3}He signatures and also Pliocene-Pleistocene mafic monogenetic volcanism. Hilton et al. and Hoke et al. have shown that there is an enrichment of ^{3}He compared to ^{4}He, between 0.2 and 5.52 that of air and greater than that of crustally-derived radiogenic helium, in volcanic sulfataras and geothermal and mineral water springs extending from the Precordillera, across the active volcanic arc and Altiplano and Puna high plateau region to the western part of the Eastern Cordillera. In this region the crust is up to 75 km thick and the subducting slab at depths of 100 to 350 km[3]. Hoke et al. interpreted the elevated ^{3}He signature in the volcanic arc as a consequence of melting in the convecting mantle wedge between the subducted slab and the overlying lithosphere, where dehydration of the downgoing slab may hydrate and cause the overlying mantle wedge to melt if temperatures are greater than 1100°C. Hoke et al. argued that mantle melting in the wide region behind the arc, mapped by the elevated ^{3}He signatures, cannot be explained by the same mechanism as that invoked for mantle melting beneath the volcanic arc, and is a consequence of the thermal effects of convective removal of the lower thickening lithosphere. We suggest here that this is consistent with other geological data: (1) the timing of the onset of minor potassium-rich basaltic volcanism at ca 5 Ma; (2) normal faulting in the northernmost and highest part of the Altiplano in southern Peru and also in the Puna of north-western Argentina, which may be a consequence of surface uplift greater than that required by crustal thickening alone; (3) the history of crustal shortening in the Bolivian Andes. We speculate that widespread mafic volcanism in the Bolivian Altiplano at 22 to 25 Ma might also be a consequence of an earlier phase of convective removal of the lower part of the lithosphere.

1. Introduction

A special feature of the Central Andes is the existance of a high plateau region up to 250 km wide and 1200 km long, at an average elevation of ca. 4000 m. Though the plateau forms one of the highest parts of the Central Andes, where the crust is thickest [3,21] (up to 75 km), the total surface crustal shortening across this region does not appear to exceed a few tens of kilometres (oil company data) and the mechanism of both surface uplift and crustal thickening is not clear. In particular, the effects of processes in the mantle, as well as the possibility of substantial additions of new material to the base of the crust, have to be considered. Also, convective removal of the base of the thickened lithosphere may cause surface uplift[4,5] greater than that required by crustal thickening alone. This could lead to mantle melting if the lower 'cold' lithosphere is replaced with 'hot'mantle asthenosphere[6]. Mantle melting and melt segregation would be expected to release and transport mantle volatiles into the crust where they would be transported to the surface by geothermal and deeply-circulating groundwaters. It is in the light of these considerations that Hoke et al.[2] (see also Hilton et al.[1]) used helium isotopes as an unequivocal tracer of mantle volatiles in the Central Andes. Here, these studies are reviewed and integrated with other geological data.

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2. Geological setting of the Central Andes

The Central Andes form a high and wide mountainous region in the plate-boundary zone between the subducting Nazca plate and South American plate, and are the result of plate convergence since the Cretaceous. There is at present ca. 85 mm/yr of plate convergence at the latitude of the Central Andes [7] of which 65-75 mm/yr is accommodated near the interface with the down-going subducted slab [8]. The remaining convergence is absorbed at the surface by underthrusting of the Brazilian shield in the Subandean Zone. However, prior to ca. 5 Ma, significant surface deformation was active in the Altiplano and Eastern Cordillera[9].

The Altiplano acted as a major intramontane basin for much of Tertiary, accumulating up to 10 km of continental sedimentary and volcaniclastic sequences. However, sedimentation here was punctuated by two brief phases of folding and faulting. In places, Lower Tertiary fine to medium-grained red-bed sequences, up to several kilometres thick, are folded and overlain unconformably by Lower Miocene conglomeratic sequences, including a widespread 22-25 Ma mafic volcanic complex[9] with numerous laterally extensive pyroxenite sills. Subsequently, several kilometres of Early to Late Miocene medium to coarse-grained red-bed sediments, with abundant tuffaceous horizons, were deposited. However, sequences younger than ca. 5 Ma are only very gently deformed and rest with marked angular unconformity on these folded and faulted older sequences[9]. Since ca. 5 Ma, numerous mafic and shoshonitic volcanic centres have erupted in a wide region throughout the Altiplano and behind the volcanic arc (Hoke and Lamb, unpublished data).

The early phases of mafic volcanism and deformation in the Altiplano may be roughly coeval with granitoid emplacement and rapid cooling in the Cordillera Real between 22 and 27 Ma, on the western margin of the Eastern Cordillera. Significant regional surface crustal shortening in the Eastern Cordillera pre-dates the main phase of ignimbritic volcanism in the Los Frailes and satellite massifs[9] at ca. 7 Ma, and also the development of a regional peneplain in the Eastern Cordillera[9] since ca. 10 Ma. However, there may have been both crustal and possibly mantle deformation at depth beneath both the Altiplano and Eastern Cordillera since at least 5 Ma, when thin-skinned deformation in the Subandes has been most active.

3. Evidence for mantle melts beneath the Altiplano and western part of the Eastern Cordillera.

Recent helium isotope studies in the Central Andes[1,2] have documented $^3He/^4He$ ratios significantly above atmospheric values, not only in volcanic gases and geothermal and mineral water sites associated with the active volcanic arc, but also in a vast region extending up to 300 km behind the arc in the Altiplano and Puna high plateau regions and western part of the Eastern Cordillera. In the absence of significant crustal sources of ^3He, the most likely sources for this ^3He are mantle melts present at depth[2]. Hoke et al. suggested that this mantle helium signature maps an extensive area of active mantle melt generation and concomitant subsurface basalt addition to the Andean crust. This is also suggested by the presence of small young olivine-bearing basaltic andesite volcanic centres in the Altiplano (Fig.1), mainly concentrated in the area between the Coipasa and Uyuni salars and with ages less than ca. 5 Ma (Hoke and Lamb, unpublished data). However, the helium isotope results from geothermal areas and mineral springs show clearly that outgassing of mantle-derived helium is not only restricted to these regions of young basaltic volcanism, but occurs over a much wider area, extending right across the Altiplano and well into the Eastern Cordillera (Figs.1, 2).

Subduction-induced fluid fluxing and melting in the mantle wedge above the subducting slab[10] can explain the ^3He signature along the volcanic arc in the Central Andes. Here, the narrow region of active arc volcanism coincides with the anticipated melting zone at 100 - 120 km depth[3] where the hydrated mantle wedge above the subducting slab is expected to undergo the transition from amphibolite to eclogite facies metamorphism [10,19]. However, at greater depths the mantle and the subducting slab are considered too dry to trigger melt formation and segregation. In addition, even if small melts are present they would no longer be capable of percolating upwards by buoyancy[11]. Therefore, a different mechanism of melting is required to explain the presence of mantle melts at depth beneath both the Altiplano and western parts of the Eastern Cordillera.

4. Convective removal of the base of the lithosphere beneath the Cenral Andes, age and geochemical constraints.

The presence of mantle-derived helium beneath the Altiplano and western part of the eastern Cordillera and young (< 5.5 Ma) olivine-bearing basaltic volcanic cones scattered across the central Altiplano (Fig.1), suggest that the present phase of back-arc mantle melt generation beneath the Altiplano started at ca. 5 Ma and continues to the present day. The most plausible mechanism is a change in the thermal structure of the lithosphere which triggered mantle melt generation. In this respect, we believe it is significant that mafic volcanic activity in the Altiplano coincides with the cessation of surface crustal shortening here.

Changes in the lithospheric thermal structure could be brought about by gradual heating of the base of the lithosphere, as thermal re-equilibration takes place after a phase of lithospheric thickening. However, numerical models have shown that gradual heating by thermal diffusion of a thickened lithosphere would take place on a time scale of several tens to hundreds of million years[6], whereas most of the crustal thickening in the Central Andes appears to have occurred over the past 30 Ma [9]. Thus, the thermal diffusion model seems unlikely. However, convective removal of a relatively cold and dense thickened lithospheric root and its replacement with relatively hot and less dense upwelling asthenosphere, could result in mantle melting on a much more rapid time scale[6,12] and explain both active mantle melting in a 300 km wide zone behind the arc and normal faulting in parts of the Altiplano high plateau area during the Cenozoic

This model[12] is based on the thermal instability of a thickened layer created by the downward deflection of isotherms associated with a growing lithospheric root during lithospheric shortening. This would induce lateral temperature gradients in the mantle which could drive thermal convection and may lead to the self destruction of the lithospheric root. Local convection in the asthenospheric wedge between the subducted slab and overlying Andean lithosphere could also intereact with the overlying lithospheric root and promote convective removal, though this will depend critically on temporal and lateral variations in the geometry of the wedge, and the pattern of convection. Thus, removal or erosion of a lithospheric mantle root could occur gradually during lithospheric thickening rather than catastrophically after thickening, as has been suggested for the Tibetan plateau [5].

Detachment of the lithospheric root will lead to surface uplift in isostatic response to the replacement of the dense root with buoyant hot asthenosphere[13]. Thus, the rate of detachment should be clearly reflected in the surface uplift history. The latter is not constrained for the Central Andes, though fission track data suggest relative uplift of the Altiplano and an increase in the rate of surface denudation on the eastern margin of the Altiplano in the Cordillera Real during the Plio-Pleistocene[14], which might be a consequence of an increase in surface height. Also, the presence of normal faulting in southern Peru [15,16], as well as a possible reversal in the drainage pattern of rivers feeding Lake Titicaca, suggests that collapse of the Altiplano in southern Peru may be a consequence of a Plio-Pleistocene increase in surface height, greater than that required by crustal thickening alone [5]. This might have been caused by the detachment of a thickened lithospheric root. Normal faulting in the Puna region of northwestern Argentina may be a consequence of the same process. However, we have found no evidence for significant or active normal faulting in the Bolivian Altiplano, though strike-slip faulting has been detected.

Temperatures at the base of lithosphere beneath continental crust of normal thickness approach but apparently do not reach the dry solidus [17]. However, temperatures at the top of the convecting asthenosphere are probably sufficient to melt a volatile-rich mantle. McKenzie[18] suggested that the asthenosphere continually supplies small volumes of volatile-rich melts, rich in incompatible elements such as potassium, water and carbon. These melts rise up into the overlying mantle lithosphere and solidify in the region where the steady state geotherms intersect the solidus at ca. 900°C. If these small melt fractions solidify in the mechanical boundary layer, above the thermal boundary layer that forms the base of the lithosphere, they will not participate in convection and will form a metasomatic layer that will grow through time and that could be remelted by a slight increase in temperature. Thus, if this metasomatic layer was brought into contact with the convecting asthenosphere as a consequence of convective removal of the base of the lithosphere, a temperature increase sufficient to cause melting could be attained fairly rapidly by heat conduction from the adjacent 'hot' asthenosphere.The first melts should contain a strong mantle helium isotope signature, and would also be enriched in potassium. In this respect, we believe it is significant that the basaltic andesites, erupted over the last ca. 5 Ma in the central Altiplano, have high potassium contents typical of shoshonites (>2% K_2O), with $K_2O/Na_2O > 1$ and $K_2O+Na_2O \sim 7\%$ [Hoke and Lamb, unpublished data].

The previous discussion suggests the following possible scenario for the Central Andes. Crustal shortening in the Bolivian Altiplano, between 10 Ma and ca. 5 Ma, was related to convective removal of the basal part of the lithosphere in this region. This resulted in heating of the mantle metasomatic layer as the basal part of the lithosphere was replaced by 'hot' asthenosphere, triggering the generation of potassium rich mantle melts at ca. 5 Ma and the release of mantle volatiles, including helium, in a wide region. Isostatic adjustments resulted in surface uplift, which was locally sufficient to result in collapse and normal faulting.

We speculate that an earlier phase of widespread mafic volcanism in the central Bolivian Altiplano, between 22 and 25 Ma, which is coeval with rapid cooling of granitoid bodies in the Cordillera Real on the western margin of the Altiplano[9], may be related to an earlier phase of convective removal of the basal part of the lithosphere. We believe it is significant that the timing of this earlier phase of mafic volcanism shows a similar relationship to deformation as the present phase of mantle melting, occurring soon after a phase of crustal shortening in the Altiplano.

5. Present day lithospheric structure of the Central Andes and conclusions.

Our model for mantle melt generation in a wide region behind the volcanic arc has implications for the lithospheric structure in this part of the Andes.

In the Central Andes, earthquakes show that the Benioff zone dips at ca. 30° and is at a depth of ca. 120 km below the active arc [3,20]. Therefore, if arc volcanism is a consequence of melting in the asthenospheric mantle, as is suggested both by the helium isotopic studies and theoretical models of fluid flow in subduction zones [10,19], then the depth of the Benioff zone must also be greater than the depth to the lithosphere - asthenosphere boundary (1300°C isotherm). This implies that the base of the lithosphere beneath the arc is at a depth less than 120 km. As the observed ^3He signature is broadly constant right across the width of the Altiplano and into the Eastern Cordillera (Fig. 2), it is suggested here that the zone of thin lithosphere (<120km thick) also extends beneath the Altiplano and western part of the Eastern Cordillera as far as can be mapped with a significant mantle-derived contribution to the helium isotope signal (Fig.2).

Studies of gravity and topography in the Bolivian Andes show that the lithosphere here has marked flexural rigidity with an elastic thickness greater than 50 km[21]. This region of flexurally strong lithosphere coincides with underthrusting of the Brazilian shield in the Bolivian Subandean zone, and we would expect the 1300°C isotherm to be at a depth much greater 120 km.Thus, we interpret the transition to pure crustal helium isotope ratios in the Eastern Cordillera to mark the change to a thicker lithosphere (> 200 km, Fig.) and the western limit of underthrusting of the flexurally strong Brazilian shield beneath the Eastern Cordillera (Fig. 2).

Thus, our proposed lithospheric structure for the Bolivian Andes, with a wide zone of thinned lithosphere beneath the Altiplano and western part of the Eastern Cordillera, is similar to that previously proposed for the Bolivian Altiplano[23] and also Puna region of northwestern Argentina [24], but differs from the model of Whitman[25] to explain seismic data.

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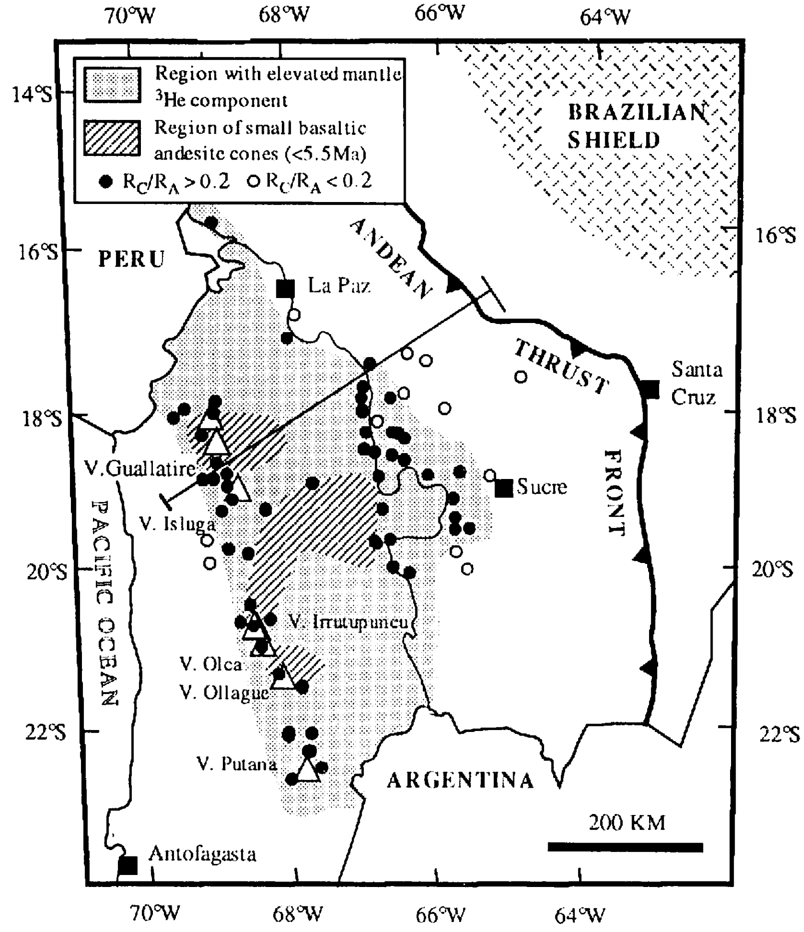
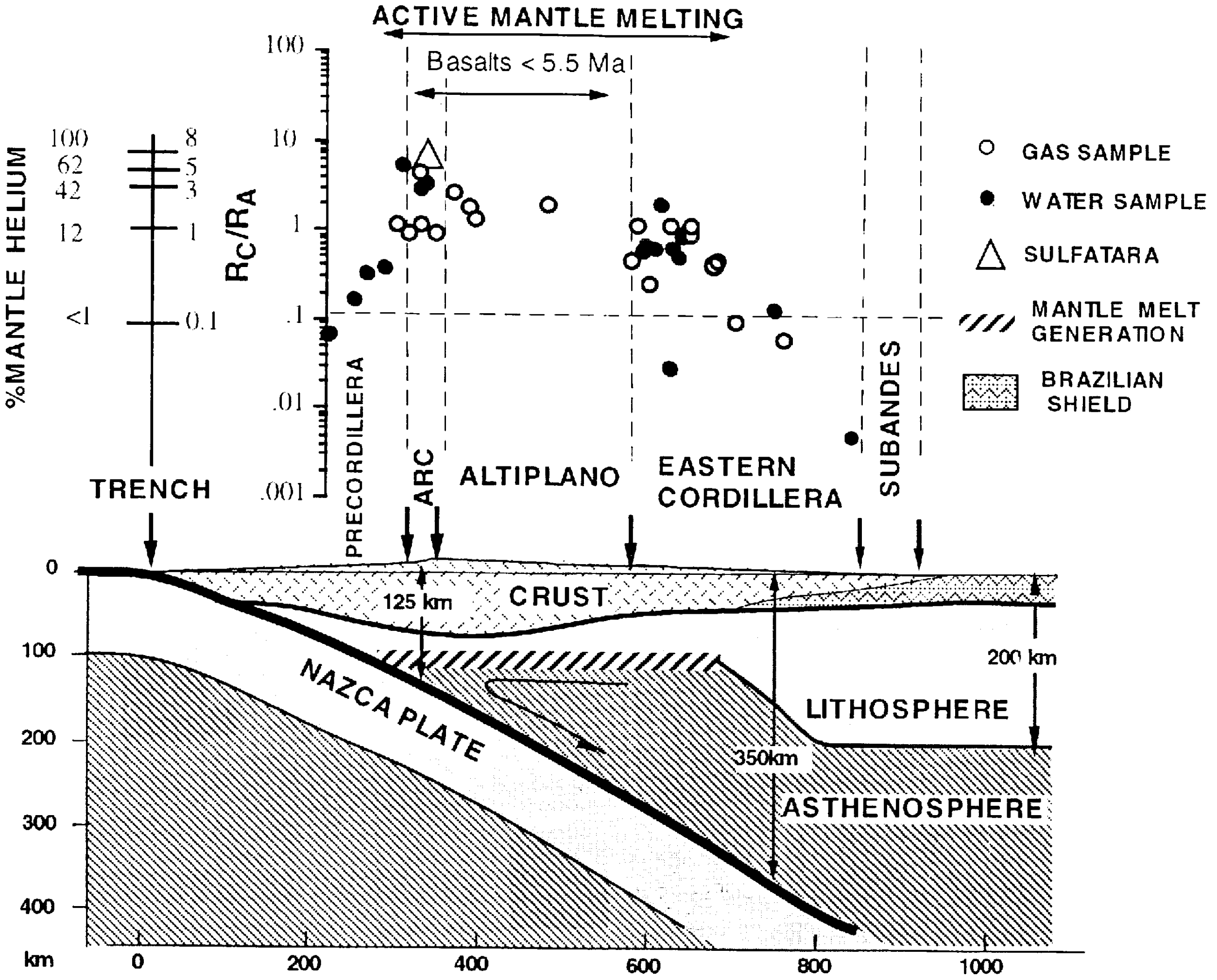

70°W
68°W
66°W
64°W
14°S
16°S
18°S
20°S
22°S
Region with elevated mantle ^{3}He component
Region of small basaltic andesite cones (<5.5Ma)
● $R_C/R_A > 0.2$ ○ $R_C/R_A < 0.2$
BRAZILIAN SHIELD
PERU
La Paz
ANDEAN THRUST FRONT
Santa Cruz
V.Guallatire
V. Isluga
Sucre
PACIFIC OCEAN
V. Irrutupuncu
V. Olca
V. Ollague
V. Putana
ARGENTINA
200 KM
Antofagasta


ACTIVE MANTLE MELTING
Basalts < 5.5 Ma
%MANTLE HELIUM
100
62
42
12
<1
8
5
3
1
0.1
R_C/R_A
100
10
1
.1
.01
.001
○ GAS SAMPLE
● WATER SAMPLE
△ SULFATARA
MANTLE MELT GENERATION
BRAZILIAN SHIELD
TRENCH
PRECORDILLERA
ARC
ALTIPLANO
EASTERN CORDILLERA
SUBANDES
CRUST
125 km
200 km
NAZCA PLATE
LITHOSPHERE
350km
ASTHENOSPHERE
0
100
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km
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