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Recent crustal foundering in the Northern Volcanic Zone of the Andean arc: Petrological insights from the roots of a modern subduction zone

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ABSTRACT

Periodic loss of the lower lithosphere into the convecting mantle due to gravitational instability is postulated to be a major mechanism for lithosphere recycling in orogenic zones, but unequivocal petrologic evidence of this process is elusive. The Granatifera Tuff, located in the Mercaderes–Rio Mayo area of the southern Colombian Andes, contains a wide variety of crustal and mantle xenoliths. Here we focus on the thermobarometry and Lu–Hf isotope systematics of crustal garnet clinopyroxenite xenoliths, the results of which offer the first evidence of recent, and likely active, crustal foundering in the Northern Volcanic Zone of the Andean arc. We find that most of these xenoliths equilibrated between 60–80 km depths, ~7–27 km below the seismically determined Moho in this region, and that at least one crustal garnet clinopyroxenite re-equilibrated at depths exceeding 95 km. A second garnet clinopyroxenite equilibrated at ~150 km depths, and is either foundered lithospheric material or the product of reaction between peridotite and a mobile component (either silicic melt or fluids) at >4 GPa. All of the investigated garnet clinopyroxenites are negatively buoyant relative to the upper mantle asthenosphere. The presence of minor amounts of secondary amphibole and orthopyroxene, coupled with the lack of major-element retrograde zonation in primary phases within these xenoliths, indicates that these rocks were rapidly transported to, and briefly resided at, shallow depths before eruption. Lu–Hf ages from two garnet clinopyroxenites and one garnet–clinopyroxene hornblendite are <5 Ma, and approximate the time at which these xenoliths were transported to shallow depths prior to eruption. A large-magnitude positive geoid anomaly and relatively low mean surface elevations indicate that the gravitationally unstable crustal root is still largely attached to the overriding crust in this part of the Northern Volcanic Zone. Thermobarometric calculations indicate that the lowermost crust in this region is a partial melt zone, and we argue that rheological weakening in the presence of melt has led to the foundering of relatively small parcels of gravitationally unstable crustal material, which the Mercaderes xenoliths document, without catastrophic removal of the crustal root.

1. Introduction

Lithospheric foundering occurs when the lowermost lithosphere develops a stable phase assemblage that is predominantly pyroxene and garnet, the bulk density of which is greater than that of the asthenospheric mantle. The resulting gravitational instability, combined with weak zones in the lower lithosphere, causes the dense lithospheric root to break away and sink into the underlying ductile asthenosphere (Bird, 1979; Houseman et al., 1981; Arndt and Goldstein, 1989; Kay and Kay, 1993). This process, also commonly referred to as delamination, is postulated to be an important mechanism for recycling lithospheric material back into the Earth's mantle largely due to its ability to explain two important observations: First, the average composition of the continental crust is andesitic and requires a large reservoir of ultramafic material at the base of the crust, which in general is not observed and is notably absent from magmatic arcs where continental crust is created (Kay and Kay, 1993; Rudnick, 1995). Second, the magnitude of structural shortening estimated from many conver-

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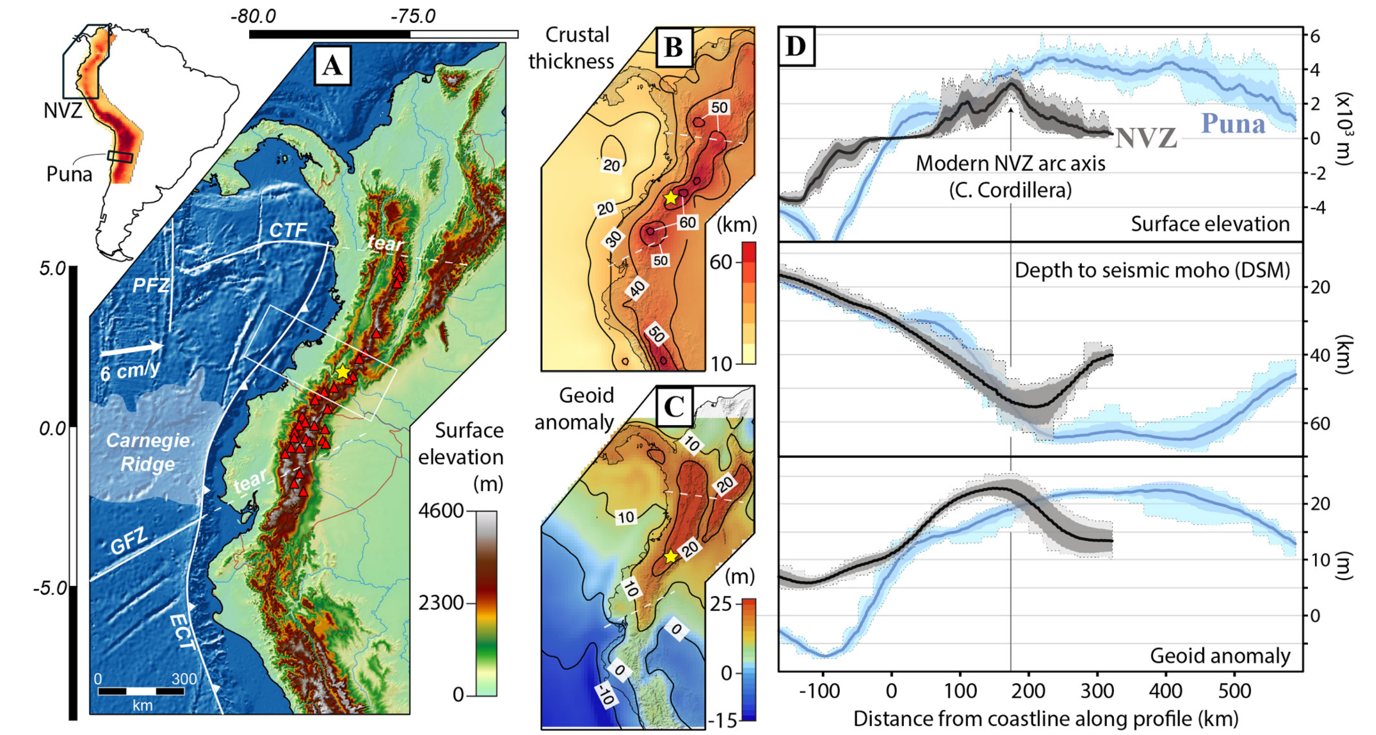

Fig. 1. Location of the Mercaderes xenolith field within the context of the Andes and the NVZ. **(A):** Digital elevation model of northwestern South America (data from GTOPO30) highlighting some important features of the subduction system. CTF – Coiba Fracture Zone; ECT – Ecuador–Colombia trench; GFZ – Grijalva Fracture Zone; PFZ – Panama Fault Zone; yellow star shows the location of the Mercaderes xenolith field; white box – area of calculated NVZ swath profiles in panel D. Inset: Outline of South America with simplified crustal thicknesses; black box labeled 'NVZ' shows bounds of the maps in panels A, B and C; black rectangle – area of calculated Puna swath profiles in panel C. **(B):** Seismic crustal thickness map (10 km contours), after Poveda et al. (2015); **(C):** Geoid anomaly map calculated from GRACE gravity data; **(D):** Comparative swath profiles showing topography, SDM and geoid anomalies in the Mercaderes arc segment and the Puna Plateau.

gent continental margins should produce an overthickened mantle lithosphere (DeCelles et al., 2009), which is also not commonly observed in the proportions predicted by mass balance calculations. Furthermore, foundering of a dense lithospheric root should modulate the buoyancy of the lithosphere and has been implicated in rapid surface uplift (Bird, 1979; Garzione et al., 2008; Bao et al., 2014; Erdman et al., 2016) and accompanying changes in magmatism, basin sedimentation, erosion, crustal deformation and rainfall distribution, making this process integral to the tempo of orogenic and climate-tectonic interactions (DeCelles et al., 2009; Hoorn et al., 2010; Lee et al., 2015). Despite these indications that foundering is a fundamental and common convergent margin process, direct geochemical evidence of lithospheric loss into the upper mantle is elusive. This limits our ability to clearly identify foundering events in the geologic record and directly investigate their timing, rate and magnitude.

Field studies aiming to document and further investigate lithospheric foundering itself have mainly relied on geophysical imaging of the upper mantle and the geochemistry of mafic volcanic rocks. Tomographic data from the central Andes, Sierra Nevada and Carpathians resolve large lithospheric blocks or drips in the process of foundering today (e.g. Beck and Zandt, 2002; Zandt et al., 2004; Fillerup et al., 2010). Basaltic melt is thought to be generated in the wake of foundering material by the concomitant adiabatic upwelling of asthenospheric mantle (Kay and Kay, 1993), or from partial melting of the foundering material itself (Elkins-Tanton, 2005; Ducea et al., 2013); therefore, elemental and isotopic variations in magma compositions, particularly small-volume mafic lavas, have been interpreted as fingerprints of foundering (e.g. Kay and Kay, 1993; Gao et al., 2004; Gutierrez-Alonso et al., 2011; Ducea et al., 2013; Murray et al., 2015). Xenoliths from orogenic zones are consistent with models of lithospheric loss (e.g. Ducea and Saleeby, 1996; Lee et al., 2006; Ulianov et al., 2006; Gordon et al., 2012; Erdman et al., 2016), but to date no reported xenoliths from an active continental margin provide unequivocal samples of crustal material that foundered to mantle depths.

The Granatifera Tuff, located in the Mercaderes–Rio Mayo area of the southern Colombian Andes (Fig. 1), contains a wide variety of crustal and mantle xenoliths (Weber, 1998; Weber et al., 2002; Rodriguez-Vargas et al., 2005). Here we use the thermobarometry and internal Lu–Hf isotope systematics of gabbroic cumulate, garnet–clinopyroxene hornblendite and garnet pyroxenite xenoliths from the Granatifera Tuff to investigate crustal foundering in the Northern Volcanic Zone (NVZ). At least one garnet-pyroxenite xenolith exhibits pressure–temperature (P–T) conditions and chemical compositions indicative of crustal material that recently transited the upper mantle, and we argue that progressive removal of a lower crustal root, catalyzed by partial melting at the base of the lithosphere, is likely to be actively occurring in the NVZ of the Andean arc.

2. The Northern Volcanic Zone

The NVZ of the Andean arc comprises the modern active-arc section located between central Ecuador and central Colombia, approximately from 1°S to 5°N (Fig. 1A), and is bounded by the Peruvian flat slab to the south and the Colombian flat slab to the north (Syracuse et al., 2016). The southern NVZ is a complex arc ca. 200 km in width, with active volcanism from the Western Cordillera to the Sub-Andean zone of the Ecuadorian massif (Fig. 1A). This may reflect that subduction in this region is 'incipiently flat' due to the collision of the Carnegie aseismic ridge (Ramos and Folguera, 2009). To the north, where thinner oceanic crust is being subducted, the so-called Cauca segment of the trench exhibits a steeper dipping angle (Syracuse et al., 2016) and is associated with a narrower and more linear arc in the Central