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A view into crustal evolution at mantle depths

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ABSTRACT

Crustal foundering is an important mechanism in the differentiation and recycling of continental crust. Nevertheless, little is known about the dynamics of the lower crust, the temporal scale of foundering and its role in the dynamics of active margins and orogens. This particularly applies to active settings where the lower crust is typically still buried and direct access is not possible. Crustal xenoliths derived from mantle depth in the Pamir provide a unique exception to this. The rocks are well-preserved and comprise a diverse set of lithologies, many of which re-equilibrated at high-pressure conditions before being erupted in their ultrapotassic host lavas. In this study, we explore the petrological and chronological record of eclogite and felsic granulite xenoliths. We utilized accessory minerals – zircon, monazite and rutile – for coupled in-situ trace-element analysis and U–(Th–)Pb chronology by laser-ablation (split-stream) inductively coupled plasma mass spectrometry. Each integrated analysis was done on single mineral zones and was performed in-situ in thin section to maintain textural context and the ability to interpret the data in this framework. Rutile thermo-chronology exclusively reflects eruption (11.17 ± 0.06 Ma), which demonstrates the reliability of the U–Pb rutile thermo-chronometer and its ability to date magmatic processes. Conversely, zircon and monazite reveal a series of discrete age clusters between 55–11 Ma, with the youngest being identical to the age of eruption. Matching age populations between samples, despite a lack of overlapping ages for different chronometers within samples, exhibit the effectiveness of our multi-mineral approach. The REE systematics and age data for zircon and monazite, and Ti-in-zircon data together track the history of the rocks at a million-year resolution. The data reveal that the rocks resided at 30–40 km depth along a stable continental geotherm at 720–750 °C until 24–20 Ma, and were subsequently melted, densified, and buried to 80–90 km depth – 20 km deeper than the present-day Moho – at 930 ± 35 °C. The material descended rapidly, accelerating from 0.9–1.7 $\mathrm{mm\,yr^{-1}}$ to 4.7–5.8 $\mathrm{mm\,yr^{-1}}$ within 10–12 Myr, and continued descending after reaching mantle depth at 14–13 Ma. The data reflect the foundering of differentiated deep-crustal fragments (2.9–3.5 $\mathrm{g\,cm^{-3}}$) into a metasomatized and less dense mantle wedge. Through our new approach in constraining the burial history of rocks, we provided the first time-resolved record of this crustal-recycling process. Foundering introduced vestiges of old evolved crust into the mantle wedge over a relatively short period (c. 10 Myr). The recycling process could explain the variability in the degree of crustal contamination of mantle-derived magmatic rocks in the Pamir and neighboring Tibet during the Cenozoic without requiring a change in plate dynamics or source region.

1. Introduction

Subduction, subduction erosion, and foundering at active margins profoundly impact the evolution of continents and influence global geochemical cycles (e.g., Kay and Kay, 1993; Rudnick and Fountain, 1995; 96; Jull and Kelemen, 2001). Despite their importance in the evolution of Earth's lithosphere, these processes are relatively poorly characterized, and their rates and relative importance, in particular those of foundering, are not well constrained. Crustal xenoliths derived from deep regions of active margins have provided promising insight into deep-crustal dynamics (e.g., Ducea and Saleeby, 1996) and may prove of key importance in revealing how the lower crust and mantle interact. Nevertheless, analyzing this material and recovering its petrological and chronological record is non-trivial; they are rare, typically mafic and consequently depleted in ideal geochronometers, and highly

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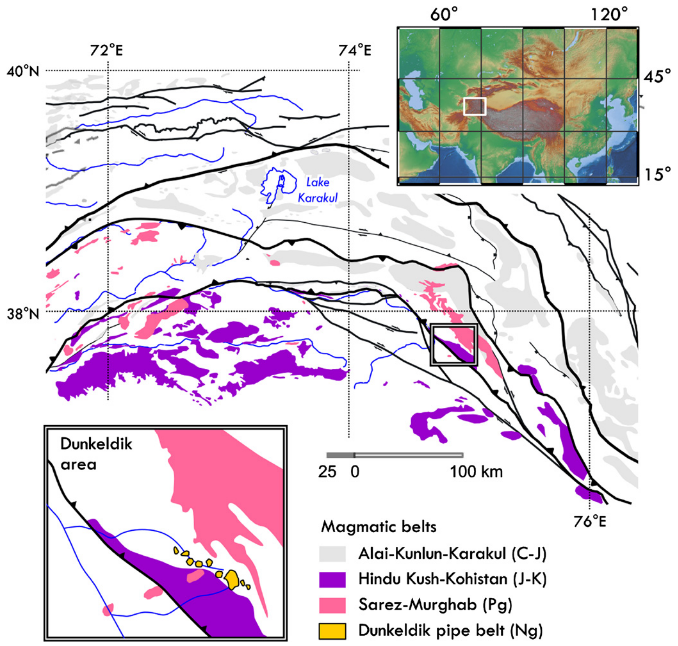

Fig. 1. Geological map of the Pamir with the Dunkeldik location in the inset. The map is based on that of Schmidt et al. (2011).

altered through melt interaction. An exception to this is provided by centimeter- to decimeter-sized, mafic to felsic crustal xenoliths in ultrapotassic pipes in Dunkeldik magmatic field, Southern Pamir (e.g., Dmitriev, 1976; Ducea et al., 2003). These rocks are unique in that they are very well preserved, large (decimeter-sized), and of a large compositional variety ranging from felsic granulites to eclogites and ultramafic rocks (e.g., Lutkov, 2003; Hacker et al., 2005; Gordon et al., 2012). The xenoliths were derived from the deep root of the Pamir-Tibet Orogen, thus permitting direct insight into the evolution of the deepest section of this active orogeny. To obtain a high-resolution record of the history of these rocks, we utilized combined multi-method geochronology (U–Pb zircon; U–Pb and ^{232}Th–^{208}Pb monazite), thermochronology (U–Pb rutile), petrology (REE), and thermometry (Ti-in-zircon; Zr-in-rutile). Each of these methods was done in-situ in thin sections enabling investigation of chronometric and thermometric data in relation to the petrological and textural context.

2. Geological setting and sample description

The xenoliths are from the Dunkeldik magmatic field in the East Pamir (Fig. 1), which comprises a series of Miocene ultrapotassic pipes. The magma in these pipes consists of trachyte, syenite, alkali-basalt and carbonatite, which erupted at 11.3 ± 0.2 Ma (Hacker et al., 2005). The xenoliths consist of felsic granulite, mafic granulite, eclogite and websterite. This association of rocks compositionally equilibrated at pressure (P) and temperature (T) conditions of 2.5–2.8 GPa and 1,000–1,100 °C (Hacker et al., 2005; Gordon et al., 2012), corresponding to depths of 75–90 km, 10–25 km below the present-day Moho depth (Mechie et al., 2012). Detrital zircon age data indicate that the rocks sample a deep section of the Early Cenozoic Hindu Kush–Pamir–Karakorum continental arc (Ducea et al., 2003; Schwab et al., 2004). Following equilibration on a 30 K/Ma pre-Neogene geotherm (Schmidt et al., 2011), the mid-crustal section of the same crustal column was exhumed in large domes during the Miocene (Stübner et al., 2013a, 2013b; Stearns et al., 2013). Seven lower-crustal xenoliths were chosen for this study – two eclogites (DK03, DK60), four felsic granulites (DK20, DK33, DK42, DK62), and one sample comprising felsic and mafic layers (DK19; thin section photos in Fig. 2). All

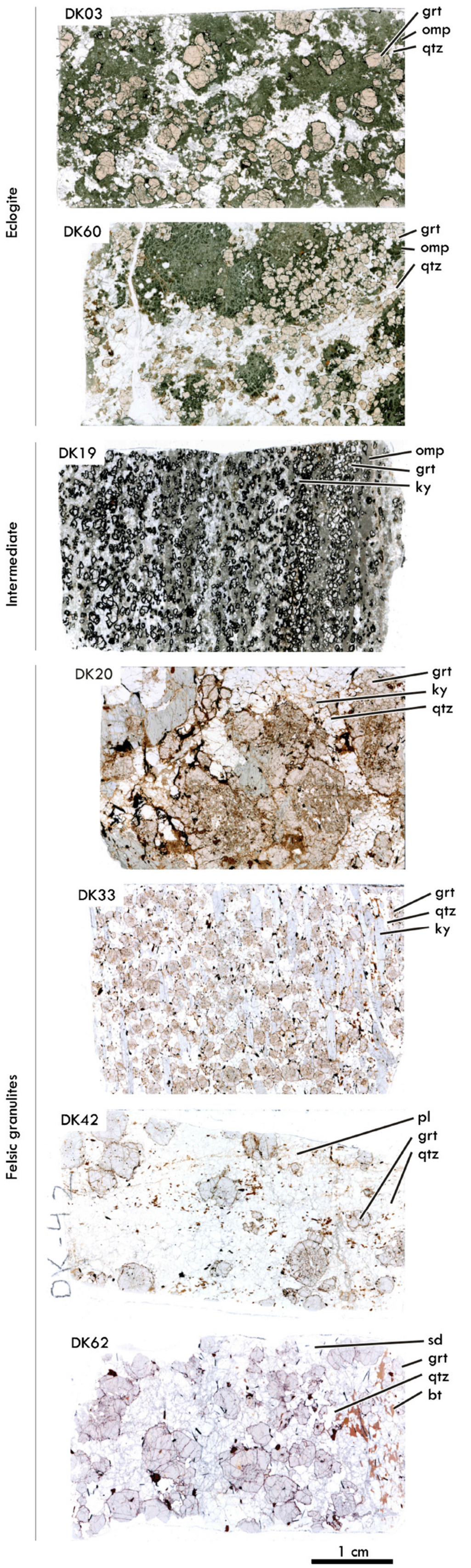

Fig. 2. Plane-polarized light photomicrographs of the samples analyzed here. All photomicrographs are of the thin sections subjected to in-situ analysis in this study.