The identification and significance of pure sediment-derived granites

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ABSTRACT

The characterization of the geochemical reservoirs of the Earth's continental crust, including the determination of representative upper and lower crustal compositions, underpins our understanding of crustal evolution. The classic I- and S-type granite classification has often been invoked to distinguish between melts derived from igneous protoliths and those derived from the melting of a sedimentary source. Recent geochemical studies suggest that most granites, even those cited as typical examples of 'S-type', show evidence for a mixture of mantle and upper crustal sources, thereby implying that granite formation is evidence for overall crustal growth. We have examined the source of leucogranite bodies in one of the world's youngest collisional orogens using novel zircon techniques that can resolve the presence of even minor mantle contributions. 232 zircons from 12 granites from the Bhutan Himalaya were analysed by *in-situ* techniques for O, Hf and U–Pb isotopic signatures. In combination with data from the granite host rocks, our data show that the Himalayan leucogranites were derived solely from metamorphosed crustal sediments, and do not record any mantle contribution. This finding is consistent with the time-lag between crustal thickening and widespread crustal melting, and the heat-producing capacities of the pelitic source rocks. We conclude that Himalayan leucogranites provide a more suitable type locality for 'S-type' granites than the Lachlan area in South-East Australia where the term was first defined. The Himalayan leucogranites therefore provide evidence that syn-orogenic melting during collisional events does not necessarily result in crustal growth. Importantly, crustal growth models should not always assume that crustal growth is achieved during collisional orogenesis.

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1. Introduction

Crustal melting and the formation of granitic magmas are key processes in crustal evolution, facilitating transfer of heat and volatile elements within the crust and contributing to mechanical weakening of the crust throughout episodes of mountain building. Granites are particularly associated with crustal melting at convergent plate margins where crustal rocks are thickened, heated and deformed. Whilst individual granite bodies may have multiple melt sources, it has become well-established that most granites can be classified as either 'I-type' (those with mainly igneous, including mantle, sources), or 'S-type' (those with mainly sedimentary sources) as first described formally in the Lachlan Fold Belt of south-east Australia (Chappell and White, 1974; McCulloch and Chappell, 1982). This simple classification, later ex-

tended to include further categories such as A-type (Loiselle and Wones, 1979), has arguably become the most widely used scheme for granite classification.

Since the initial study, further bulk-rock isotope results showed that the S-types granites from the Lachlan fold belt have significant mantle input and thus are not 'pure' crustal melts (Gray, 1984; Collins, 1996; Healy et al., 2004). Nevertheless, Lachlan granites classified as 'S-type' continue to be taken as a paragon of sediment-sourced magmas (Teng et al., 2004; Bea et al., 2007; Savage et al., 2012). A misunderstanding of the nature of 'S-type' granites may lead to misleading conclusions in interpreting the role of granite petrogenesis or geochemical behaviour during crustal melting. For example, based on the assumption that the Lachlan 'S-type' granites represent the crustal end-member of granitic rocks, minor differences in the bulk-rock Si isotope composition of 'I-type' and 'S-type' granites led researchers to conclude that Si isotopes are not sensitive to sedimentary input (Savage et al., 2012). A further study documenting the similarity between

bulk-rock Li isotopic compositions of Lachlan S-type granites and their associated sedimentary rocks suggested that Li-isotope fractionation during crustal melting was negligible (Teng et al., 2004). Neither conclusion is necessarily valid if the S-type samples analysed are in fact mixtures of both mantle and crustal melt sources.

Despite suggestions from field evidence, there is yet there is no conclusive chemical evidence that coherent granite bodies, as opposed to the leucosome component in migmatites (Inger and Harris, 1993), may be derived entirely from melting sediments. The recognition of such bodies will provide representative compositions of pure crustal melts for future geochemical studies. The establishment of the total volume of pure crustal melts of different ages are critical for calculating the global magmatic budget, as these magmas have not contributed to net crustal growth.

The chemical recognition of pure crustal melts also carries implications for the thermal and tectonic evolution of orogenic belts. Two processes can control magma generation during orogenesis. During collision, hot mantle material may firstly become directly entrained in the lower crust, which will ultimately cause advective heating and crustal melting. These melts will incorporate a mantle chemical signature. This process is more likely during slow collisions with some element of lateral extension. In contrast, rapid collisions result in melting when a thick pile of radiogenic pelitic to semi-pelitic sedimentary rocks is tectonically buried deep enough to allow them to melt extensively without an external heat source. The distribution and timing of melting depends on the heat production of the sediments (abundances of radioactive elements U, Th and K), the distribution and thickness of fertile lithologies, and to some extent, the geometry of the collision (Patiño-Douce et al., 1990).

The origin of the High Himalayan leucogranites is therefore intrinsically associated with the geodynamic and thermal evolution of the India–Asia collision. Although collision and crustal thickening is widely held to have occurred at 50–55 Ma (Najman et al., 2010) and may have begun as early as 59 ± 1 Ma (Hu et al., 2015), an alternative view for major collision at ∼34 Ma has also been proposed (Aitchison et al., 2007). Given that the High Himalayan leucogranite bodies formed at ∼20 Ma, the competing models allow timespans varying from >30 million yrs (for early Eocene collision) and ∼14 million yrs (for collision on the Eocene–Oligocene boundary). For widespread melting to occur in the mid crust, temperatures must reach values of at least ∼700 °C (the temperature of the muscovite dehydration reaction; Harris et al., 1995). Thermal models for orogenic evolution require a time period of at least 20 to 30 million yrs between collision and melting for all realistic values of heat production and sedimentary thicknesses and assuming no advective heat source (Medvedev and Beaumont, 2006). Acceleration of heating could only occur if additional heat sources were available, such as from rising melts from the lower crust or mantle, or from shear heating along discrete thrusts. In the Himalaya, there is little to no field or chemical evidence for such extra heat sources (Harris and Massey, 1994). Hence in the Himalaya, the 'young' collision model requires a widespread mantle melt component to provide advective heating to accelerate the rate of Miocene magmatism. The absence of any recognized intermediate or mafic intrusions across the High Himalaya therefore suggests an early collision, unless a mantle component can be identified in the leucogranite melts themselves.

Traditionally, granite geochemical studies have been based on bulk-rock data that provide averaged information of all component mineral phases and therefore fail to resolve contributions from discrete individual sources. Furthermore, bulk-rock samples may not reflect the original composition of the crystallised melt for a variety of reasons, ranging from incomplete separation of magma from restitic or peritectic phases (due to the high viscosity of granite magmas and to the small density contrast between such melts and

silicate phases), or to the modification of the crystallised granite by post-magmatic processes such as hydrothermal activity and weathering.

Advances in *in-situ* micro-analysis techniques for the determination of e.g. U–Pb, Lu–Hf and O isotopic compositions in accessory minerals have revolutionized approaches to assessing the evolution of the continental crust, and granite petrogenesis (Kemp et al., 2006, 2007; Appleby et al., 2010; Roberts and Spencer, 2014). Zircon is a common accessory mineral in granitic rocks and retains geochemical information about the evolution of its host melt. For typical peraluminous melt, <100 ppm zirconium is needed to saturate the melt and crystallise zircon (Hanchar and Watson, 2003). Therefore Zr saturation is likely reached early in the magmatic evolution of such granites, the time at which it is most likely to retain the record of its source.

The three isotope systems combine to inform both timing and melt source. U–Pb is a well-documented geochronometer that records the timing of zircon crystallisation, while the Lu–Hf and O systems together combine to record the geochemical characteristics of the source. Lu–Hf is a radiogenic isotope system that records the average age of mantle extraction of the melt source. In general, samples with more negative εHf values were extracted from the mantle further back in time (a deviation in $^{176}Hf/^{177}Hf$ from the chondritic uniform reservoir (CHUR) value in parts per ten thousand). The behaviour of oxygen isotopes in rocks and minerals provides a stable-isotope proxy for the extent of sedimentary recycling in the sample source. Oxygen isotopes are fractionated during low-temperature processes such as subaerial weathering. Magmas that incorporate this supracrustal material will inherit a heavier $\delta^{18}O$ signature (or greater $^{18}O/^{16}O$ value) with respect to the Vienna Standard Mean Ocean Water (VSMOW; in parts per thousand).

Hf–O measurements of zircon from granitic rocks from the Lachlan type area have suggested that 'S-type' granitic and volcanic rocks cannot be derived from a single protolith and instead incorporate between 20 and 75% of material from a mantle source (Kemp et al., 2006, 2007). A more recent Hf–O isotopic study of zircons in 'S-type' granites from the Caledonian orogeny report a range of zircon compositions including those with typical 'mantle-like' O isotope signatures (Appleby et al., 2010). Thus on the basis of published zircon Hf–O studies it appears that many granites, including those traditionally classified as 'S-type', are derived from mixed evolved and juvenile sources, generally interpreted as crustal and mantle-sources respectively.

We have analysed the chemical composition of zircons from 12 peraluminous Oligocene to Miocene (33–11 Ma) leucogranites exposed in the eastern Himalayan orogen in Bhutan (Fig. 1). The granites represent a range of mineralogical types, with seven two-mica (1G03, 3A03, 4D01, 1247, 1251, CWB16 and CWB23), three tourmaline (1G02, 3A04, 1215) and two garnet leucogranites (1D01, 3A02) studied. These leucogranites intrude amphibolite-facies metasediments of primarily Neoproterozoic source age, the Greater Himalayan Sequence (GHS) (Ahmad et al., 2000; Gehrels et al., 2011). Structurally below the GHS is the Lesser Himalayan Sequence (LHS), a primarily Paleoproterozoic-sourced stack of metasediments (Ahmad et al., 2000; Gehrels et al., 2011). Both sequences comprise a mix of orthogneiss, carbonate and quartzite compositions with a minor pelite component. The pelitic assemblages are significantly more fusible and therefore provide appropriate source materials for anatectic melts where temperatures are relatively low (<750 °C, Patiño Douce and Johnston, 1991). Bulk-rock isotope geochemical data from similar High Himalayan leucogranites exposed elsewhere in the Himalaya suggest that they formed by partial melting of the GHS pelitic lithologies into which they now intrude (Le Fort et al., 1987; Harris et al., 1995). The granites are therefore appropriate for testing the hypothesis that