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Geochronology and isotope geochemistry of Eocene dykes intruding the Ladakh Batholith

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ABSTRACT

In order to determine the extent and timing of dyke formation related to possible E–W extension along the southern margin of Eurasia during Early Cenozoic time, we examined *ca*. 30 mostly andesitic dykes intruding the Ladakh batholith from 10 to 50 km west of Leh (NW India). The dykes in the east of the area trend E–NE and those in the west trend N–NW. The difference in orientation is also evident in the petrography and isotopic signatures. The eastern dykes contain corroded quartz xenocrysts and show negative ε_0(Nd) and positive ε_0(Sr) values, whereas the western dykes do not contain quartz xenocrysts and exhibit positive ε_0(Nd) and near-zero ε_0(Sr) values. The variability in Sr–Nd isotopes (ε_0(Nd) = 3.6 to −9.6, ε_0(Sr) = 0.4 to 143) and the quartz xenocrysts can best be explained by (differing degrees of) crustal assimilation of the parent magma of the dykes. Separated minerals from five dykes were dated by $^{40}Ar–^{39}Ar$ incremental heating: amphibole ages range between 50 and 54 Ma, and one biotite separate dated both by Rb–Sr and $^{40}Ar–^{39}Ar$ gave an age of 45 Ma. One dated pseudotachylyte sample attests to brittle faulting at *ca.* 54 Ma. The combination of structural field evidence with petrographic, isotopic and geochronological analyses demonstrates that the dykes did not form from a single, progressively differentiating magma chamber, despite having formed in the same tectonic setting around the same time, and that processes such as crustal assimilation and magma mixing/mingling, also played a significant role in magma petrogenesis.

1. Introduction

The timing of the collision between the Indian and the Asian continents resulting in the largest mountain chain in the world and the mechanisms responsible for the uplift of the Tibetan plateau are controversial (Aitchison et al., 2007; Searle et al., 1987; Yin, 2006). In particular the high altitude and the forces sustaining the elevation of the plateau over a long period of time, as well as causes and timing of the present E–W extension, are subject of intense research and debate (*e.g.* Aitchison et al., 2009; Burchfiel et al, 1992; White et al., 2011; Williams et al., 2001, 2004). Evidence for E–W extension of the Tibetan plateau has been observed in the field (Armijo et al., 1986) as well as inferred from fault plane solutions (Molnar and Tapponier, 1978). A further indication of this regional extension is believed to be the volumetrically small, but geographically widespread post-collisional magmatism found across the Lhasa and the Qiangtang terrane (*e.g.* Turner et al., 1996; Williams et al., 2004), and in the Tethyan sedimentary series of southern Tibet (King et al., 2007).

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Of special interest is the occurrence of dykes, as they can provide both the strain direction and the timing of the magma generation. Ravikant and Guha (2002) reported a Miocene ultrapotassic dyke close to Leh and determined an age of 24.3 ± 2.2 Ma by a Rb–Sr two-point whole-rock–phlogopite isochron. The dyke intrudes a micrograniti dyke of an older, andesitic and doleritic swarm and does not exhibit a cross-cutting relationship with the dykes nor an igneous contact with the Ladakh batholith (Ravikant and Guha, 2002). It must therefore have the same attitude as the older dyke swarm, which is approximately ENE–WSW. Due to its age and ultrapotassic nature, the dyke was proposed to be linked to the Miocene dykes in S-Tibet (Ravikant, 2006). Although Ravikant and Guha (2002) give no further information about other ultrapotassic dykes, it can be assumed that more post-collisional dykes exist in close proximity, since the occurrence of post-collisional magmatism is unlikely to be restricted to one intrusion only.

Weinberg and Dunlap (2000) described the older, andesitic to rhyolitic dykes and named them `Phyang dykes', after Phyang, the village in the next side valley E of the dykes. These authors estimated that there were tens of dykes restricted to a few square kilometres, located between Phyang and Taru (village W of dyke swarm). Weinberg and

Dunlap (2000) estimated that there were tens of dykes in the Phyang/ Taru swarm and noted that they were restricted to a few square kilometres. They further reported that the dykes strike N 50°–70° E and dip between 70° SE and vertical. The dykes exhibit various compositions indicated by different phenocrysts such as embayed quartz phenocrysts, plagioclase, hornblende and biotite. A $^{40}Ar–^{39}Ar$ incremental heating age on one of the dykes yielded a crystallisation age from the 'plateau-like portion' of the age spectrum as 45.7 ± 0.8 Ma (2σ) (Weinberg and Dunlap, 2000).

These Eocene dykes are *ca.* 20 Ma older than the ultrapotassic dyke discovered at the same locality (Ravikant, 2006; Ravikant and Guha, 2002). Ravikant (2006) linked the ultrapotassic dyke to post-collisional intrusions in Tibet and thus suggested the same source and geochemical processes described by others (Williams et al., 2001, 2004). In contrast, Weinberg and Dunlap (2000) interpreted the Phyang dykes as the result of minor, late-magmatic activity associated with subduction and arc formation. Thus, these dykes may not be the result of the same processes responsible for the post-collisional, potassic and ultrapotassic magmatism in Tibet. In this study we examined dykes within the Ladakh batholith ranging approximately 10 to 50 km west of Leh (NW India), including those described above.

2. Geologic setting and fieldwork

2.1. The Ladakh batholith

The dykes intrude the Ladakh batholith, which is part of the calc-alkaline Trans-Himalayan batholith extending over 2500 km along the southern margin of the Eurasian continent. The western part of the Trans-Himalayan batholith, *i.e.* the Kohistan arc and the Ladakh batholith are believed to have been similar to the modern Aleutian arc with the western part being intra-oceanic (Kohistan arc) and the eastern part continental (Ladakh batholith and Gangdese plutonic belt) (Rolland et al., 2000, 2002). However, it is unclear where the transition from an intra-oceanic arc to a continental arc was located (Clift et al., 2002; Rolland et al., 2000, 2002). The Ladakh batholith is bounded by the Indus suture in the south, the Shyok suture zone in the north and the Karakoram fault in the east. However, the exact location of the Shyok suture in eastern Ladakh is uncertain due to restricted access to the area (Rolland and Pêcher, 2001; Rolland et al., 2000; Weinberg and Dunlap, 2001). The Indus suture marks the boundary between the Indian and the Eurasian continents with arc plutonic rocks located on the north side and deformed Zanskar shelf sediments south of the suture. In contrast, the Shyok suture zone is proposed to either have formed from an earlier collision of the Ladakh–Kohistan block with the Karakoram terrane (*e.g.* Weinberg and Dunlap, 2000) or to result from closure of a back-arc basin (Clift et al., 2002; Rolland et al., 2000, 2002). The Karakoram fault is a crustal-scale dextral strike-slip fault that separates and offsets the Ladakh batholith from its eastern continuation, the Gangdese batholith.

The general composition of the Ladakh batholith is described as complex sequences of gabbroic to granitic plutons (Schärer et al., 1984). According to Singh (1993), the batholith is predominantly composed of biotite- and hornblende-bearing granodiorite and less diorite–tonalite, quartz monzodiorite–granodiorite, biotite–hornblende granite, leucogranite, and pink porphyritic granite, which corresponds to a typical sequence of calc-alkaline rocks. The mafic members are estimated to comprise approximately 10–20 vol.%, intermediate rocks approximately 20–30 vol.% and granodiorites about 50 vol.% of the batholith (Schärer et al., 1984). Kumar, 2010 suggested a model of multistage mixing and mingling of coeval mafic and felsic magmas for the formation of the Ladakh batholith, based on detailed investigations of microgranular enclaves.

The southern margin of the Ladakh batholith is unconformably overlain by the Indus molasse (Fig. 1), which was deposited in an intramontane, narrow basin between the batholith and the Himalayas (Garzanti and van Haver, 1988) and mainly comprises conglomerates, shales and sandstones recording a fluvio-alluvial sedimentary environment. The material that accumulated in this intramontane basin mainly originated from the batholith in the north, but also from the suture zone and to a lesser degree from the Zanskar shelf carbonates in the south (St-Onge et al., 2010 and references therein).

Honegger et al. (1982), reported a zircon U–Pb age of 103 ± 3 Ma for the Kargil granodiorite of the Ladakh plutonic complex and this date was later confirmed by Schärer et al. (1984) who reported a zircon U–Pb age of 101 ± 2 Ma for the same granodiorite and 60.7 ± 0.4 Ma for a granite close to Leh. Over the last decade, more zircon U–Pb ages (especially SHRIMP ages) have been published and these range between 45 and 68 Ma (St-Onge et al., 2010; White et al., 2011 and references therein). White et al. (2011) concluded from the zircon U–Pb age distribution histograms that the magmatism responsible for forming the Ladakh batholith was not continuous but episodic with three distinct pulses of magmatic activity from 45–49 Ma, 56–60 Ma and 64–66 Ma. However, Ravikant et al. (2009) found only two main magmatic stages of granitic magmatism based on U–Pb zircon laser ablation analyses: from 83–103 Ma (Early Cretaceous) and 50–67 Ma (Early Cenozoic) with a magmatic gap between 67 and 83 Ma. Reports of inherited zircon grains found in the Ladakh batholith (Schärer et al., 1984; Weinberg and Dunlap, 2000; White et al., 2011) suggest that the Ladakh plutons assimilated pre-existing crustal components, although the estimated amount of crustal contribution varies from nearly absent (Singh et al., 2007), through restricted (Weinberg and Dunlap, 2000) to significant (Schärer et al., 1984). The Ladakh arc plutons generally have initial $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios near chondritic values (Allègre and Ben Othman, 1980; St-Onge et al., 2010; Weinberg and Dunlap, 2000 and references therein).

2.2. Field relations and sampling

Fieldwork in Ladakh was focused on finding the dykes close to Taru described by Ravikant and Guha (2002) and Weinberg and Dunlap (2000) as well as exploring whether additional dykes exist NW of this location. A path along the southern margin of the batholith on the northern side of the Indus valley (route walked shown in Fig. 2) yielded approximately 30 dykes over a distance of *ca.* 40 km. It could not be unambiguously determined if some dykes were individual or continuations of other dykes. 21 samples were collected from 33 documented sites listed in Supplementary Table A1. Two dykes from the Taru dyke swarm were sampled multiple times along strike. Most of the dykes occur in pairs or belong to a swarm. Only dykes M and N were single, *i.e.* no other dyke was found in the surrounding 10 km^2. The dykes intrude the batholith at high angles, often close to vertical.

The crust of the dykes is weathered to a dark brown to black colour contrasting with the bright brownish to orange coloured Ladakh batholith, which facilitates recognition of dykes from a distance. Many of the dykes (*e.g.* dykes 7, T, N, U and V) can be distinguished on Google Earth satellite images (coordinates are given in Supplementary Table A1). The photograph in Supplementary Fig. A1a shows dykes U and V, which are both about 5 m wide, intruding the Ladakh batholith just north of the village Hemis Shugpachan. The contacts of all dykes with the host rock are sharp and do not display macroscopic reaction rims or chilled margins. Approximately 2 km east of Yangthang (Fig. 2) a pseudotachylyte vein was observed. The fault vein of the pseudotachylyte is about 1.5 m thick and cuts the batholith vertically in N–S direction (see Supplementary Fig. A1b). In contrast to the sharp igneous contacts of the dykes, thin injection veins of glass spreading away from the pseudotachylyte penetrate the surrounding host rock as shown in Supplementary Fig. A1c. Furthermore, clasts of host rock embedded in a black coloured matrix can be recognised. Since pseudotachylytes have been proven valuable $^{40}Ar–^{39}Ar$ geochronometers (*e.g.* Müller et al., 2002), a sample (LiO1) was taken for $^{40}Ar–^{39}Ar$ dating.