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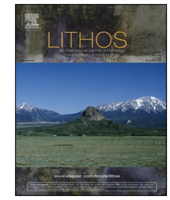

Primitive high-Mg andesites from the Western Alps, Italy: Products of interaction of sediment diapir derived melts with mantle-wedge peridotite in a continental collision zone

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Ar—Ar amphibole age
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A B S T R A C T

Primitive (high-Cr, Ni), high-Mg andesites (HMA) at convergent plate margins are considered primary, mantle-derived melts, and are not part of the classical tholeiitic or so-called calc-alkaline igneous differentiation series. Their genesis is often considered the product of melting of lower crustal sequences or the subducting slab, though their genesis is far from being understood. Alternatively, they may represent differentiated rocks from boninitic precursors. Here we present isotope and geochemical data for a rare suite of high-Mg andesites that were preserved as decimetre-sized boulders in molasse-type sedimentary rocks of the Oligocene-Miocene Gonfolite Lombarda (Como Formation; Italy), as part of the post-orogenic alpine sedimentary succession. The HMA have moderate to high MgO (1.9–6.4 wt%), high Al_2O_3 (16.3–18.8 wt%), along with high Cr (30–306 ppm) and Ni (13–92 ppm), and moderate Yb (1.2–2.5 ppm) and Y (12–26 ppm) abundances, matching those of primitive HMA. These HMA are LILE- and LREE-enriched and most samples have negligible negative Eu anomalies. Primitive mantle-normalized compositions show depletions in Nb, Ta, P, Ti and Y. Most samples have unradiogenic Nd (εNd: −6.2 to −7.8) and radiogenic $^{87}Sr/^{86}Sr$ isotope compositions (0.708 to 0.710), elevated $\delta^{18}O$ values (+7.6 ‰ to +9.5 ‰) and radiogenic Pb isotope compositions, with a pronounced variation in $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ at rather constant $^{206}Pb/^{204}Pb$. Initial εHf isotope values range from −0.4 to −2.3, some of which deviate from the Hf—Nd crust-mantle isotope array. One sample is unevolved ($^{87}Sr/^{86}Sr$: 0.708; εNd: −3.3, εHf: +1.8, $\delta^{18}O$: 8.5 ‰) whereas another sample is strongly evolved ($^{87}Sr/^{86}Sr$: 0.720; εNd: −9.3, εHf: −5.8, $\delta^{18}O$: 9.3 ‰); the latter probably representing a crustal melt. The remaining samples have intermediate compositions ($^{87}Sr/^{86}Sr$: 0.709–0.713; εNd: −6.2 to −8.5, εHf: −0.4 to −4.3, $\delta^{18}O$: 7.6–10.6 ‰) that either result from limited AFC processes or represent source heterogeneities. The sum of these features cannot be the result of a simple slab or mantle wedge melting process. To account for the observed geochemical signatures of the high-Mg andesites, a three-stage model is suggested that invokes melting of slab-derived sediment diapirs, followed by melt-rock-reaction in the mantle wedge and subsequent crustal assimilation-fractional crystallization (AFC). The diapirs that rise into the mantle wedge are composed of subducted wet, Alpine sediments. Hydrous dacitic (siliceous) partial melts derived from them react with the ambient mantle wedge and cause the formation of boninitic melts with elevated MgO, Ni and Cr; the archetype features of primitive high-Mg andesites. Subsequent interaction with the overlying arc crust is evidenced by crustal xenoliths, which may account for some isotope features of the rock suite. We consider this scenario most plausible because it is relatively simple, and explain most if not all geochemical features, based on modelling and experimental evidence.

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Age and petrogenesis of Ni-Cu-(PGE) sulfide-bearing gabbroic intrusions in the Lausitz Block, northern Bohemian Massif (Germany/Czech Republic)

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ABSTRACT

The Lausitz Block, located in the northernmost part of the Bohemian Massif, hosts a large number of dike- to stock-shaped gabbroic intrusions that mainly comprise brown hornblende-poor (Group I; i.e. olivine gabbronorite, olivine gabbro, gabbro and diorite) and subordinately brown hornblende-rich lithologies (Group II; i.e. olivine-hornblende gabbro and hornblende gabbro). Several of these intrusions host small-scaled magmatic Ni-Cu-(PGE) sulfide accumulations. The intrusions are part of interconnected mafic–(ultramafic) plumbing systems that intruded Cadomian granodiorites of Lausitz Block in the Middle to Late Devonian during the early stages of the Variscan Orogeny. The previously inferred Devonian age of the intrusions is refined by biotite Ar-Ar dating that yield ages between 389.1 ± 3.9 Ma and 372.2 ± 3.7 Ma (2σ). Group I and Group II lithologies differ in their mineralogical and geochemical composition. Compared to the Group I lithologies those of Group II are characterized by higher modal contents of primary brown hornblende, Fe-Ti oxides and apatite, by Ti- and Al-enriched clinopyroxene and by lower contents of SiO_2 and increased contents of TiO_2, P_2O_5, LILE, HFSE and LREE. The differences suggest at least two different magmatic series where Group I rocks are linked to tholeiitic basaltic magmas with low to moderate Ti and volatile contents, whereas Group II rocks are derived from Ti- and volatile-enriched alkaline basaltic magmas. The magmas experienced clinopyroxene fractionation during their crustal ascent and storage, but were only minor affected by crustal contamination (< 5%) according to Sr-Nd-Pb isotope systematics. The tholeiitic and alkaline basaltic magmatism could be explained by a tectonic environment between a subduction and intraplate setting. Group II rocks have an intraplate chemical signature and their parental magmas are clearly originated from a deeper-seated mantle source with melting of garnet peridotite, likely associated with an asthenospheric upwelling. By contrast, precursor magmas of Group I rocks are originated from partial melting of a less-enriched source, presumably spinel peridotite, from a subduction-related environment. Trace elements systematics suggest that both groups at least partly resulted from an interaction (mixing) of the alkaline and tholeiitic magmas. Partial melting estimates for both groups vary between 5 and 20%. The proposed tectonic setting could have been related to a subduction slab retreat within the framework of the Variscan orogeny, which led to an upwelling of the asthenospheric mantle. Cu/Zr ratios <1 of gabbroic rocks from several intrusions suggest a previous segregation of magmatic sulfides in other sections of the magmatic plumbing system and give rise for a vertical and lateral Ni-Cu exploration potential.

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ORIGINAL PAPER

High-K andesites as witnesses of a continental arc system in the Western Alps, Italy: constraints from HFSE and Hf–Nd–Sr–Pb–O isotope systematics

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Abstract

Geochemical and isotopic data are presented for ~ 32 Ma-old high-K andesites and dacites from the Alpine Chain. The samples consist of plagioclase, amphibole, titanomagnetite and rare biotite and quartz. Geochemical and isotope data indicate that slab-derived fluids, sediment melts and presumably AFC processes involving continental crust played a key role in the petrogenesis of the high-K rocks. A contribution of fluids is suggested based on the overall enrichment of large-ion lithophile elements and related high Ba/La, Ba/Zr, Ba/Th, Ba/Nb and Pb/Nd, sometimes distinctively higher than average continental crust. Positively correlated Ba/Nb–Th/Nb relationships, low Ce/Pb, low Nb/U and a negative correlation of Pb isotopes with Ce/Pb and Nb/U and positive Δ 7/4 and Δ 8/4 values similar to GLOSS imply the additional involvement of a sediment-derived melt. Negatively correlated Nb/Ta–Zr/Hf ratios at overall low Nb/Ta (13–7.5) are best explained by parental magma differentiation involving amphibole and biotite in a continental arc system. The samples have moderately unradiogenic Nd (εNd: – 2.0 to – 6.7) and radiogenic $^{87}Sr/^{86}Sr$ isotope compositions (0.7085–0.7113), moderately radiogenic Pb isotope compositions ($^{206}Pb/^{204}Pb$: 18.50–18.72; $^{207}Pb/^{204}Pb$: 15.59–15.65; $^{208}Pb/^{204}Pb$: 38.30–38.67), and elevated $\delta^{18}O$ values (+ 6.5 to + 9.1 ‰). Epsilon Hf isotope values range from + 2.5 to – 4.0. Negative εHf(*t*) and εNd(*t*) values and $^{206}Pb/^{204}Pb$ ratios are correlated with elevated K_2O abundances that indicate enrichment in K_2O is related to AFC processes. The offset of εHf at a given εNd points to involvement of aged garnet-bearing crustal lithologies. The latter feature is qualitatively consistent with modification of unexposed primary basaltic andesites by AFC processes involving deep crustal material. In conclusion, in an Alpine context, inferred unexposed primitive high-K basaltic to andesitic melts are generated in the mantle wedge through fluid infiltration from the descending slab where fluids may have caused also partial melting of sedimentary rocks that mixed with evolving andesite–dacite compositions towards shallow-level intrusive and extrusive rocks. High-K and related trace element and isotope features thus result from a combination of already elevated values with participation of fluids and melts and probably AFC processes.

Keywords High-K andesites · Trace elements · Nb–Ta–Zr–Hf systematics · Nd–Sr–Pb–Hf–O isotopes · Alpine chain

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ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER

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Key Points:

- Indian-affinity Tethyan Himalaya Series occur in central Myanmar, ~450 km south of the Himalayan rocks in the Eastern Himalayan Syntaxis
- A low temperature-high pressure subduction-early collision system was active at ~65 Ma, peaked at ~45 Ma, and ended at ~30 Ma
- The Sagaing transform fault reactivated the Indus-Yarlung suture, and imbricated the Indian rocks and the Burma microplate from ~30 Ma on

Supporting Information:

Supporting Information may be found in the online version of this article.

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Data curation: Myo Min, Lothar Ratschbacher, Leander Franz, Bradley R. Hacker, Eva Enkelmann
Formal analysis: Lothar Ratschbacher, Leander Franz, Bradley R. Hacker, Eva Enkelmann, Eko Yoan Toreno, Marion Tichomirowa, Jörg A. Pfänder
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India (Tethyan Himalaya Series) in Central Myanmar: Implications for the Evolution of the Eastern Himalayan Syntaxis and the Sagaing Transform-Fault System

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Abstract In the Katha Range of central Myanmar, lithologic tracers and pressure-temperature-deformation-time data identify Cambro-Ordovician, Indian-affinity Tethyan Himalaya Series, located ~700 km from their easternmost outcrop in S-Tibet, and ~450 km from Himalayan rocks in the Eastern Himalayan Syntaxis. Metamorphism began at ~65 Ma, peaked at ~45 Ma (~510°C, 0.93 GPa), and exhumation/cooling (~25°C/Myr) occurred until ~30 Ma in a subduction-early collision tectonic setting. When the Burma microplate—part of the intra-Tethyan Incertus arc—accreted to SE-Asia, its eastern boundary, the southern continuation of the Indus-Yarlung suture (IYS), was reactivated as the Sagaing fault (SF), which propagated northward into Indian rocks. In the Katha rocks, this strike-slip stage is marked by ~4°C/Myr exhumation/cooling. Restoring the SF system defines a continental collision-oceanic subduction transition junction, where the IYS bifurcates into the SF at the eastern edge of the Burma microplate and the Jurassic ophiolite-Jadeite belts that include the Incertus-arc suture.

Plain Language Summary Central Myanmar hosts rocks typical for the northernmost continental crust of the Indian continent—the Tethyan Himalaya Series. These rocks are now located ~700 km from their easternmost outcrop in S-Tibet and ~450 km from Himalayan rocks in the Eastern Himalayan Syntaxis (EHS)—the northeastern edge of India. They record a high pressure-low temperature oceanic subduction-continental collision tectonic setting from ~65 to 30 Ma, formed at the northern front of India. They moved around the EHS and were involved in the northward growth of the Sagaing transform-fault (SF) system. The SF system imbricated the Indian-affinity rocks, and the Burma microplate—part of the intra-Tethyan Incertus-arc system.

1. Introduction

Indenter corners in collisional orogens—syntaxes—feature 3-D deformation with crustal thickening, lateral material flow, and transitions from continental to oceanic subduction. In the Cenozoic India-Asia collision zone, the underthrusting Indian craton has induced shortening in the Himalaya and Tibet, and lateral material flow out of the collision zone (e.g., Zhang et al., 2004; Zubovich et al., 2010). Pronounced lateral flow and clockwise vertical-axis rotations occur at and south of the Eastern Himalayan Syntaxis (EHS) where the Himalayan continental subduction transitions into the highly-oblique Burma oceanic subduction zone and the Sagaing transform-fault (SF) system (Figure 1a). Paleomagnetic studies in the Burma microplate, and the Asian-affinity Tengchong (Lhasa) and Baoshan (Qiangtang-Sibumasu) blocks indicate 40–90° clockwise, vertical-axis rotations in Myanmar and Yunnan since the Paleocene, changing the original ~W-strike of these blocks in Tibet to a ~N-strike south of the EHS (e.g., Kornfeld et al., 2014; Li et al., 2020, 2018; Westerweel et al., 2019).

Northward-widening cratonic India extends northeastward into the EHS region, and is rimmed in the east by the oceanic lithosphere of the Bay of Bengal. The current transition from continental collision to oceanic subduction must occur in the Indo-Burman Ranges (IBR), part of the Jurassic-Recent subduction-accretionary wedge that bounds the Indian plate in the east, because the footwall of the northern IBR is made up of the Indian continental crust of the Shillong Plateau (Figure 1a). The past position of this transition is unclear due to the intervening

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Geochemistry and petrogenesis of alkaline rear-arc magmatism in NW Iran

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ABSTRACT

High Na- to K- alkaline magmatism is common in the rear-arc region of the Cenozoic Urumieh-Dokhtar Magmatic Belt of Iran, but their geochemical signatures, as well as their formation mechanisms, have been poorly studied thus far. In the Kleybar area of NW Iran, Middle Eocene magmatic activity comprises silica-undersaturated to -saturated gabbros, monzogabbros, monzosyenites to nepheline-monzosyenites, and nepheline syenite as well as tephritic to trachy-basaltic and trachy-andesitic dikes. New $^{40}Ar—^{39}Ar$ results show a restricted age range (39.2–43.6 Ma) for the intrusive rocks (43.16 ± 0.43 and 43.34 ± 0.43 Ma for gabbros, 43.56 ± 0.44 for monzogabbros, 39.22 ± 0.48 and 42.09 ± 0.42 Ma for nepheline syenites, 42.17 ± 0.42 Ma for nepheline-monzosyenites), whereas a cross-cutting trachy-andesitic dike yielded an $^{40}Ar—^{39}Ar$ age of 41.78 ± 0.42 Ma. The Kleybar rocks are enriched in alkalis (K_2O and Na_2O) with variable K_2O/Na_2O ratios (0.14 to 2.93), light rare earth elements and large ion lithophile elements such as Th, Rb, K, U and Pb. High field strength elements such as Nb—Ta are depleted in these rocks.

The isotopic compositions of the different rock types are quite variable: gabbros and monzogabbros have $^{87}Sr/^{86}Sr_{(t)}$ = 0.70419–0.70436, εNd(t) = +3.1 to +3.8 and εHf(t) = + 7.8 to +10.1; nepheline monzosyenites and nepheline syenites have $^{87}Sr/^{86}Sr_{(t)}$ = 0.70359–0.70566 (except a nepheline syenite with a ratio of 0.74833 and very high Rb/Sr), εNd(t) = +1.5 to +4.2 and εHf(t) = +4.6 to +8.8; and trachy-basaltic to trachy-andesitic to tephritic dikes have $^{87}Sr/^{86}Sr_{(t)}$ = 0.70437–0.70469, εNd(t) = +2.8 to +4.2 and εHf(t) = +8.3 to +10. In the thorogenic-Pb isotope diagram, the Kleyber igneous rocks define an array above the Northern Hemisphere Reference Line (NHRL), with Δ8/4 (deviation from the NHRL) of ~40–60. These samples also plot above the NHRL in uranogenic Pb space (Δ7/4–5-10). The positive Δ8/4 Pb and Δ7/4 Pb may reflect the involvement of subducted terrigenous sediments in their mantle source during the subduction of the Neotethyan oceanic lithosphere. Two nepheline syenite samples have significantly higher thorogenic and uranogenic Pb isotopic compositions, that may reflect assimilation of surrounding clay-rich sedimentary rocks.

Modelling of trace elements compositions using less fractionated Kleybar trachybasalt and fine-grained monzogabbro samples indicate that a 96:4 mixture of the depleted mantle and subducting (trench)-sediment melts with 6% aggregated fractional melting closely matches the trace-element abundances of the Kleybar trachybasalt and monzogabbro. Together with previous studies on high-K volcanic rocks from NW Iran, our results indicate that Neotethyan slab retreat and related extension of the Iranian continental lithosphere in the rear-arc region of the Urumieh-Dokhtar Magmatic Belt generated alkali-rich magmatic rocks throughout the NW Iran rear-arc during Middle-Late Eocene.

1. Introduction

Magmatic rocks of continental arcs are geochemically diverse over a range of temporal and spatial scales. Interpreting the origin of this diversity is important for understanding how arc source regions and magma plumbing systems evolve. Numerous studies demonstrate that continental rear-arc magmatism, which is generally more silica-undersaturated and alkalic, differs from volcanic front arcs, which largely consist of calc-alkaline and tholeiitic rocks (Jacques et al., 2014). These chemical differences reflect different melting regimes and

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Exceptionally High Emplacement Rate of the Afar Mantle Plume Head

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Key Points:

- 1-km-thick picritic basalts at the Waja section were emplaced at the onset of chron C12n (∼31 Ma) above the Afar mantle plume head
- The Waja section was extruded in <260 kyr according to Ar-Ar dating and at least 20 kyr using a secular variation geochronometer
- Extrusion rates above the Afar plume head were >10 km^3/yr, compared to 0.3–1.2 km^3/yr for the entire Ethiopia-Yemen Traps

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

We investigated a 1-km-thick sequence of lava flows that erupted over the Afar plume axis in order to better understand the emplacement history of the ∼30 Ma Ethiopia-Yemen Traps. Geochemical analyses reveal high-titanium concentrations (TiO_2 3.9 ± 0.5 wt%) in basalts close to picritic compositions. Indistinguishable $^{40}Ar/^{39}Ar$ ages throughout the section define a weighted-mean of 31.18 ± 0.28 Ma (95% confidence). This date, together with solely normal polarity magnetization directions in 68 geomagnetically independent horizons, constrain the eruption to within chron C12n, with a maximum duration of a few hundreds of kyr for the entire 1-km-thick section. The rate of geomagnetic secular variation used as a chronometer refines the duration to only a few tens of kyr, leading to a local extrusion rate of 4–13 km^3/yr for the Afar plume head, which greatly exceeds the average rate of 0.3–1.2 km^3/yr for the entire Ethiopia-Yemen Traps.

Plain Language Summary

The Ethiopia-Yemen Traps are the expression of an important geodynamic process where a mantle plume pierced the lithosphere, resulting in the massive outpouring of a few million km^3 of basaltic lava over a geologically brief (1–3 Myr) interval. Here, we provide constraints on the extrusion rate of lava flows from the 1-km-thick Waja section, which originated from the Afar mantle plume head. Radioisotopic and magnetostratigraphic results indicate that the outpouring of the lava spanned only a few hundreds of kyr. Moreover, incessant eruption provides a continuous record of changes in the ancient magnetic field direction, called secular variation, which can also be used as a chronometer. A limited amount of secular variation at Waja refines the maximum duration to only a few tens of kyr. The corresponding extrusion rate of 4–13 km^3/yr greatly exceeds the average rate of 0.3–1.2 km^3/yr for the entire Ethiopia-Yemen Traps. Consistent with geodynamic models predicting that plume head eruptions are the most intense, our results suggest that 20% of the trap basalts were emplaced within ∼0.02–0.2 Myr, whereas the remaining 80% were erupted over ca. 1.5 Myr.

1. Introduction

Traps and oceanic plateaus are types of Large Igneous Provinces (LIPs) characterized by the massive outpouring of a few million km^3 of basaltic lava over a 1–3-Myr interval (Mahoney & Coffin, 1997). These geodynamic events, ascribable to the impingement of mantle plumes on the lithosphere, are thought to have notable consequences on the biosphere due to the sudden release of CO_2 and SO_2 into the atmosphere or hydrosphere (Courtillot & Renne, 2003). Most of the 12 major LIPS are linked to mass extinctions or anoxia events, such as two most important extinction events at the Cretaceous-Paleogene and Permo-Triassic boundaries associated with the Deccan and Siberian traps, respectively.

The Ethiopia-Yemen Traps (EYT) stem from the arrival of the Afar mantle plume around 30 Ma and represent among the youngest and best-preserved LIP (Hofmann et al., 1997; Rochette et al., 1998). Initially covering an area of 4–8 × 10^5 km^2 for an estimated volume of 0.6–1.2 × 10^6 km^3 (Natali et al., 2016; Rochette et al., 1998), this pile of several hundred lava flows is 2–5 times less voluminous than the Deccan and Siberian Traps but is singular in several respects. Geographically, the EYT are located at the junction of two oceanic rifts (Red Sea, Gulf of Aden) and the East-African continental rift, with the consequence that the original edifice has been dissected into several parts. Geochemically, the EYT are zoned with high-Ti (HT) picritic basalts (HT2, TiO_2 3–7 wt%) above the inferred location of the plume head, followed by progressively lower Ti (LT) tholeiitic basalts (HT1, TiO_2 2–4 wt% and then LT, TiO_2 1–3 wt%) toward the periphery (Beccaluva et al., 2009; Pik et al., 1998).

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Microtectonic control of $^{40}Ar/^{39}Ar$ white mica age distributions in metamorphic rocks (Erzgebirge, N-Bohemian Massif): Constraints from combined step heating and multiple single grain total fusion experiments

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Abstract

Felsic rocks of the Erzgebirge in the Central European Variscides experienced ultra-high pressure metamorphism at ~340 Ma, followed by nearly isothermal decompression during channel like rapid exhumation within ~10 Ma. Despite the general time frame of exhumation and emplacement within mid-crustal levels is known, available geochronological data do not provide a detailed timescale of individual stages of the entire process. Addressing this problem we combined white mica $^{40}Ar/^{39}Ar$ ages obtained from multi-grain step heating and multiple single grain total fusion experiments with mineral chemical, structural and tectono-metamorphic constraints. Gneisses of the channel center are characterized by E-W elongated white mica exclusively aligned in the continuous foliation. The rocks of the channel contact zone and in the hanging and footwall contain NW-SE stretched white mica parallel to the foliation, but also components of ductile to brittle-ductile shear bands truncating the main foliation. Well defined weighted plateau ages of all samples range between 340.0 ± 1.1 Ma and 327.9 ± 1.3 Ma, confirming previously published data, but represent presumably mixed ages due to multi-phase deformation. Single grain age distributions, in contrast, exhibit two statistically significant age peaks at 338.6 ± 0.2 Ma and at 332.8 ± 0.3 Ma. Rocks without shear bands exclusively contain white mica belonging to the older age fraction, whereas rocks with shear bands show a broad age scatter including both age fractions. We interpret these age distributions as being independent of closure temperature, but reflecting different dynamic recrystallization events. The older age fraction reflects the formation of the main foliation during west-directed emplacement of the ultra-high pressure rocks in mid-crustal levels at ~339 Ma, whereas the shear band related neo- or recrystallization is responsible for the younger age fraction dating the final transport in the upper crust at ~333 Ma.

Keywords: Microstructures; Multiple single grain $^{40}Ar/^{39}Ar$ experiments; Statistics; Pressure-temperature-deformation-time relationship; Exhumation

1. INTRODUCTION

Ultra-high pressure (UHP) continental rocks exposed as tectonic slices in medium pressure (MP) metamorphic units are common in orogenic belts (Massonne, 1999; Carswell et al., 2003; Janák et al., 2015; Stepanov et al., 2016; Liao et al., 2017; Fassmer et al., 2020) and can be explained by

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ARTICLE

Li-Co–Ni-Mn-(REE) veins of the Western Erzgebirge, Germany—a potential source of battery raw materials

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Abstract

Situated in the western Erzgebirge metallogenetic province (Vogtland, Germany), the Eichigt prospect is associated with several quartz-Mn-Fe-oxyhydroxide veins that are exposed at surface. Bulk-rock geochemical assays of vein material yield high concentrations of Li (0.6–4.1 kg/t), Co (0.6–14.7 kg/t), and Ni (0.2–2.8 kg/t), as well as significant quantities of Mn, Cu, and light rare earth elements, a very unusual metal tenor closely resembling the mixture of raw materials needed for Li-ion battery production. This study reports on the results of a first detailed investigation of this rather unique polymetallic mineralization style, including detailed petrographic and mineralogical studies complemented by bulk rock geochemistry, electron microprobe analyses, and laser ablation inductively coupled mass spectrometry. The mineralized material comprises an oxide assemblage of goethite hematite, hollandite, and lithiophorite that together cement angular fragments of vein quartz. Lithiophorite is the predominant host of Li (3.6–11.1 kg/t), Co (2.5–54.5 kg/t), and Ni (0.2–8.9 kg/t); Cu is contained in similar amounts in hollandite and lithiophorite whereas light rare earth elements (LREE) are mainly hosted in microcrystalline rhabdophane and florencite, which are finely intergrown with the Mn-Fe-oxyhydroxides. $^{40}Ar/^{39}Ar$ ages (~40–34 Ma) of coronadite group minerals coincide with tectonic activity related to the Cenozoic Eger Graben rifting. A low-temperature hydrothermal overprint of pre-existing base metal sulfide-quartz mineralization on fault structures that were reactivated during continental rifting is proposed as the most likely origin of the polymetallic oxyhydroxide mineralization at Eichigt. However, tectonically enhanced deep-reaching fracture-controlled supergene weathering cannot be completely ruled out as the origin of the mineralization.

Keywords Lithiophorite · Coronadite group · Hollandite · Cryptomelane · 40Ar/39Ar geochronology · Trace elements · Lithium · Manganese · Cobalt · Exploration · Raw materials

Introduction

Lithium, nickel, manganese, and cobalt are essential raw materials for the production of rechargeable Li-ion batteries, a critical component in the transition to electromobility and energy storage in a renewable energy system (UNCATAD, 2020). While these raw materials are produced from a variety of ore deposit types, none is currently known to contain all four in concentrations sufficient for economic extraction (Verplanck and Hitzman, 2016).

In search of unexplored and unconventional Li resources, Lithium Australia NL recently acquired an exploration license in the Eichigt area, Germany (Gruber (2018); Fig. 1A). Within the license area, several NW–SE trending vein structures can be traced at surface (Fig. 1B and Fig. 2A). In surface exposure, the vein material consists of

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Research Article

$^{40}Ar/^{39}Ar$ ages and bulk-rock chemistry of the lower submarine units of the central and western Aleutian Arc

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ABSTRACT

In order to further constrain the timing of the Aleutian Arc initiation as well as its early evolution, an extensive $^{40}Ar/^{39}Ar$ dating and geochemical (major and selected trace elements) campaign (40 samples) of the lower units of the Aleutian ridge has been carried out on samples dredged from deep fore-arc canyons and rear-arc tectonic structures. The new dataset slightly increases the minimum inception age for the Aleutian system, with the two oldest samples dated at 46.1 ± 3.3 Ma and 47.80 ± 0.57 Ma. Both mid Eocene ages were obtained on tholeiitic mafic volcanic rocks from the western section of the arc. The new data also support the occurrence of three distinct periods of enhanced magmatic activity (magmatic pulses) during the pre-Quaternary evolution of the arc (at 38–27, 16–11 and 6–0 Ma), as previously suggested based on a more limited and dominantly subaerial dataset. Moreover, the data refine the duration of the first pulse of activity, which ended 2 Ma later than previous estimates. The first and last pulses may be associated with rotations of the subducting plates while the second pulse might result from regional tectonic changes. The significant overlap between the age distribution of the submarine and subaerial samples suggests that much of the earlier parts of the arc may have been uplifted and subaerially exposed. The expected crustal growth associated with the pulses is unlikely to have significantly impacted magmatic residence times, since no variation in the degree of differentiation of the rocks can be observed during or after the pulses. On the other hand, the type of magmas erupted may have changed during the arc evolution. Prior to the first pulse, activity appears to have been dominantly tholeiitic. On the other hand, the first pulse was characterized by coeval tholeiitic, transitional and calc-alkaline magmas, with calc-alkaline activity increasing after the first ~3 Ma. Subsequently, a dominantly calc-alkaline period occurred from 29 to 8 Ma, followed by a progressive return of coeval tholeiitic, transitional and calc-alkaline activity. These temporal changes in magma types correspond to likely variations in arc crustal thickness beneath the active front, and could therefore be a response to physical changes of the overriding plate.

1. Introduction

Since the 1960's the Aleutian Arc (Fig. 1) has been a key and extensively studied locality to understand subduction zone processes, the evolution, composition and structure of arc crusts and the link between arc and continental crust (e.g., Coats, 1962; Kay and Kay, 1994; Kelemen et al., 2003). Nevertheless, many aspects regarding its formation remain unknown or uncertain. In particular, the age at which the Aleutian Arc crust started to develop, the evolution of its accumulation rate through time (in pulses vs. steady state) and the related impact on its magma compositions remain conjectural.

The oldest age measured so far in the Aleutians, which is also the accepted minimum inception age for the subduction system, is an $^{40}Ar/^{39}Ar$ age of 46.31 ± 0.91 Ma (2 sigma-error here and in the rest of the manuscript; Fig. 2a) obtained on a metavolcanic rock from the submarine Murray canyon (at 3018 m depth; Jicha et al., 2006). Three

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Tectonics

RESEARCH ARTICLE
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Key Points:

- Activity along the shear zone exhuming Cer metamorphic core complex in the internal Dinarides was dated by $^{40}Ar/^{39}Ar$ geochronology to ~17 Ma
- Exhumation was facilitated by extensional reactivation of Late Cretaceous-Paleogene nappe contacts resulting from Adria-Europe collision
- Extensional reactivation of the thrusts is interpreted as a far-field effect of Oligo-Miocene Carpathian slab rollback

Supporting Information:

Supporting Information may be found in the online version of this article.

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Torn Between Two Plates: Exhumation of the Cer Massif (Internal Dinarides) as a Far-Field Effect of Carpathian Slab Rollback Inferred From $^{40}Ar/^{39}Ar$ Dating and Cross Section Balancing

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Abstract Extension across the southern Pannonian Basin and the internal Dinarides is characterized by Oligo-Miocene metamorphic core complexes (MCCs) exhumed along mylonitic low-angle extensional shear zones. Cer MCC at the transition between Dinarides and Pannonian Basin occupies a structural position within the distal-most Adriatic thrust sheet and originates from two different tectonic processes: Late Cretaceous-Paleogene nappe-stacking during a continent-continent collision with Adria in a lower plate position, and exhumation related to Miocene extension driven by the Carpathian slab-rollback. Structural data and a balanced cross section across the Cer massif show linking of the exhuming shear zone to a breakaway fault, which reactivated the early Late Cretaceous most internal nappe contact. Paleozoic greenschist-to amphibolite-grade lithologies surround a polyphase intrusion composed of I- and S-type granites and were exhumed along a shear zone characterized by top-N transport. Thermobarometric analyses indicate an intrusion depth of 7–8 km of the Oligocene I-type granite; cooling below ~500°C occurred at 25.4 ± 0.6 Ma (1σ) yielded by $^{40}Ar/^{39}Ar$ dating of hornblende. Biotite and white mica from this intrusion as well as from the mylonitic shear zone yield $^{40}Ar/^{39}Ar$ cooling ages of 17–18 Ma independent of the used techniques (in situ laser ablation, single-grain total fusion, single-grain step heating, and multi-grain step heating). White mica from the S-type granite yield an $^{40}Ar/^{39}Ar$ cooling age of 16.7 ± 0.1 Ma (1σ). Associated dikes intruding the shear zone were also affected by N-S extension resulting in the exhumation of the MCC, which was triggered by the opening of the Pannonian back-arc basin in response to the Carpathian slab-rollback.

Plain Language Summary Horizontal stretching of continental plates induces thinning of the crustal upper part, melting of rocks, the sinking of the land surface, and formation of large basins. One of the world's best-studied basins formed by such a process is the Central European Pannonian Basin. This basin is surrounded by the mountain belts of the Alps, Carpathians, and Dinarides. We have studied rocks between the Pannonian Basin and the southerly adjacent Dinaride Mountains, where rocks deposited in the basin are found right next to rocks that were initially about 7–8 km deep in the crust. These rocks are separated by a shear zone, along which they were brought to the surface. We have dated the activity of the shear zone by measuring concentrations of radioactive isotopes and their decay products contained in deformed minerals. The shear zone was active at a time when the Pannonian Basin started to open due to tectonic processes further NE underneath the Carpathian mountain chain. We also found evidence that the shear zone, which brought metamorphic rocks upwards was formerly one that brought rocks downwards into the crust during an earlier phase of mountain building, predating basin formation.

1. Introduction

Back-arc extension due to slab-rollback (Uyeda & Kanamori, 1979) is often observed in the hinterland of convergent plate boundaries and promotes the formation of large rift basins (Malinverno & Ryan, 1986). One of the largest continental back-arc basins in the circum-Mediterranean region is the Pannonian Basin (Figure 1), which formed in Late Oligocene to Late Miocene times in response to slab-retreat underneath the Carpathian orogen (e.g., Horvath & Berckhemer, 1982; Horváth et al., 2006; Royden, 1988; Royden

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Original Article

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Protracted late Neoproterozic – early Palaeozoic deformation and cooling history of Sør Rondane, East Antarctica, from $^{40}Ar/^{39}Ar$ and U–Pb geochronology

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Abstract

$^{40}Ar/^{39}Ar$ and U–Pb data from five structural domains constrain the late Neoproterozoic – early Palaeozoic tectonothermal history of the eastern part of the East African–Antarctic Orogen in Sør Rondane. A total of 27 new Ar/Ar ages span 570–474 Ma, roughly corresponding to the age range of three generations of syn- to post-tectonic granitoids. The ages are distinct for the five structural domains. The oldest cooling ages come from the weakly deformed southern part of the SW Terrane of Sør Rondane (SW Terrane S), a sliver of a Tonian island arc, which escaped much of the late Neoproterozoic accretionary deformation. This terrane was intruded by the oldest and largest granitoid complex at *c.* 640–620 Ma. The oldest Ar/Ar amphibole and biotite ages of 570–524 Ma are from the Main Shear Zone, along the northern margin of the SW Terrane S sliver. It hosts granites of age *c.* 584–570 Ma strung out along the shear zone. Two younger granitoid phases are recorded in the adjacent four terranes to the west, north and east of the SW Terrane S, and correlate with the younger group of Ar/Ar biotite ages spanning 513–474 Ma. We interpret the magmatic and cooling history of duration > 150 Ma to reflect repeated phases of accretion, magmatism and reactivation, that is, collage-style tectonism, partly pre-dating the incorporation of Sør Rondane into Gondwana. The study area first accreted to the cryptic Valkyrie Craton in Tonian times, was then 'sandwiched' between the Kalahari and Indo-Antarctica cratons, and experienced extensional tectonics and elevated heat flux due to lithospheric delamination, which resulted in slow cooling during the Pan-African Orogeny.

1. Introduction

Sør Rondane in Dronning Maud Land (DML) is located in a key region of East Antarctica and is crucial for understanding the final amalgamation of Gondwana. Two models aim to explain the final collision. Jacobs & Thomas (2004) proposed a Himalayan-style continental collision that resulted in the formation of the late Neoproterozoic – early Palaeozoic East African–Antarctic Orogen (EAAO) (Fig. 1a, c). In the EAAO, remnants of the Mozambique Ocean, that is, the Tonian Oceanic Arc Super Terrane (TOAST; Jacobs *et al.* 2015), are sandwiched between the Kalahari craton (Namaqua–Natal Belt, Proto-Kalahari, Maud Belt, Nampula Complex) and Indo-Antarctica (Indian cratons, Napier Craton, Lützow–Holm Belt, Rayner Belt, Madagascar, Sri Lanka, Ruker Craton). The eastern margin of the Kalahari craton and the western boundary of the TOAST are delineated by the Forster Magnetic Anomaly (Riedel *et al.* 2013; Jacobs *et al.* 2015, 2020), whereas the eastern boundary of the TOAST is transitional in character and is located east of the Yamato Mountains with its continuation found in Sri Lanka and Madagaskar (Boger *et al.* 2015; Ruppel *et al.*, 2018). An alternative model interprets the Sør Rondane region as part of the E–W-trending Kuunga Orogen (e.g. Meert, 2003), in which large parts of DML, including Sør Rondane, constitute a mega-nappe rooting in northern Mozambique (e.g. Meert, 2003; Grantham *et al.* 2013) (Fig. 1b).

Sør Rondane comprises extensive rock exposures at 1000–3300 m elevation that follow a continental margin-parallel escarpment *c.* 200 km inland of the coastline (Fig. 2). Previous geological studies by Belgian (e.g. Picciotto *et al.* 1964; Van Autenboer *et al.* 1964; Van Autenboer, 1969) and Japanese (e.g. Shiraishi *et al.* 2008; Grantham *et al.* 2013; Higashino *et al.* 2013; Osanai *et al.* 2013) expeditions focused on orogenic processes related to the final

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THEMED ISSUE: Reporting and Interpretation of Geochronologic Data

Interpreting and reporting $^{40}Ar/^{39}Ar$ geochronologic data

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Crust-mantle interaction during syn-collisional magmatism – Evidence from the Oamikaub diorite and Neikhoes metagabbro (Damara orogen, Namibia)

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ABSTRACT

The early-syntectonic 563.7 ± 6.1 Ma old Oamikaub diorite (Damara orogen, Namibia) consists of metaluminous, magnesian, calc-alkalic to calcic diorites, granodiorites and granites. Associated gabbro-diorites and gabbros belong to the Neikhoes metagabbro. Linear major and trace element variations imply that the rock suite evolved through fractional crystallization processes involving amphibole, biotite, Fe-Ti oxides, zircon and apatite. Initial Sr ($^{87}Sr/^{86}Sr$: 0.7058–0.7123) and Nd (ε Nd: −2.1 to −18.8) isotopic compositions are highly variable and negatively correlated indicating that assimilation of crustal components occurred. Unradiogenic initial $^{206}Pb/^{204}Pb$ (16.23–17.23) and $^{207}Pb/^{204}Pb$ ratios (15.50–15.57) suggest derivation from or interaction with ancient crust with low U/Pb. Two gabbro-diorites have MgO, Ni and Cr abundances that are compatible with derivation of these rocks from upper mantle lithologies. Their initial ε Nd values (−2.1 and – 7.4) and $^{87}Sr/^{86}Sr$ ratios (0.7058 and 0.7076) imply derivation from an aged metasomatized lithospheric mantle. Other mafic samples have MgO abundances and compatible element concentrations that exceed the values commonly accepted for primary mafic melts implying some accumulation of clinopyroxene and amphibole. The granodiorites form a homogenous group in which the isotope data (initial ε Nd: −12.4 to −14.1; initial $^{87}Sr/^{86}Sr$: 0.7083–0.7096) imply a lower crustal source. The granites are also magnesian and calc-alkaline but two of them are strongly peraluminous. Their isotope data (initial ε Nd: −13.2 to −18.8; initial $^{87}Sr/^{86}Sr$: 0.7099 to 0.7123) imply derivation from more ancient sources, alternatively these samples gained their isotope systematics through extensive AFC processes from parental granodiorites. A common subduction zone environment as suggested from negative Nb-Ta anomalies in multi-element diagrams seems unlikely for all samples because of a lack of isotopically depleted signatures. The data from the Oamikaub diorite and other mafic complexes are better explained by a "flat" subduction model involving mainly continental mantle lithosphere and crust with limited, if any, melting of asthenospheric mantle.

1. Introduction

The composition of the bulk continental crust is broadly granodioritic and is vertically stratified from a mafic lower crust to a felsic upper crust (Rudnick and Fountain, 1995; Rudnick and Gao, 2004). Thus, a key question, central to understanding the evolution of continental crust, concerns the origin of granodiorites and more mafic igneous rocks that dominate the lower crust. Mafic magmas parental to more voluminous granodiorites can represent near-primary mantle-derived melts or originate by partial melting of older crustal rocks, i.e., amphibolites or eclogites (i.e., LeBel et al., 1985; Rogers and Hawkesworth, 1989; Gromet and Silver, 1987; Tepper et al., 1993). A distinction between these two endmembers is important as studies on lower crustal rocks (Percival et al., 1992; Rudnick and Taylor, 1987) have shown that underplating of mantle-derived mafic magmas is an important process during crustal growth (Voshage et al., 1990). On the other hand, reprocessing older mafic rocks does not result in new crust. However, both processes ultimately result in a mafic composition of the lower crust (Dawson et al., 1986).

In addition, an understanding of formation of mafic melts that were

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Petrogenesis of early syn-tectonic monzonite-granodiorite complexes – Crustal reprocessing versus crustal growth

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ABSTRACT

The 563.7 ± 6.1 Ma old, early-syntectonic Mon Repos complex is a predominantly metaluminous, magnesian, calc-alkalic granodioritic to granitic intrusion. Major and trace element variations imply that the rocks evolved through fractional crystallization processes involving amphibole, biotite, Fe-Ti oxides, zircon, and apatite. Rocks less evolved than granodiorite show evidence of hornblende accumulation. Initial Sr ($^{87}Sr/^{86}Sr$: 0.7090–0.7111) and Nd (εNd: −5.3 to −12.3) isotopic compositions of the granodiorites and granites are highly heterogeneous and vary with SiO_2 contents indicating that assimilation of older crustal components occurred. Initial $^{206}Pb/^{204}Pb$ (16.65–17.65) and $^{207}Pb/^{204}Pb$ ratios (15.52–15.60) are similar to other mafic-intermediate complexes from the Damara belt. One monzodiorite and two quartz monzonites are K_2O-, LILE-, and HFSE enriched and have similar SiO_2 contents as the granodiorites. These samples are similar to post-collisional mafic magmas from elsewhere in the world. Their ε Nd values (−3.8 to −4.3), $^{87}Sr/^{86}Sr$ ratios (0.7051–0.7073) and trace-element characteristics imply that their unexposed parental melts are derived from a lithospheric mantle source that was contaminated and metasomatized by crustal material during ancient subduction processes. The data are explained by assuming a "flat" subduction model where melting predominantly involves ancient continental mantle lithosphere and crust with limited, if any, melting of the underlying asthenospheric mantle. During flat subduction, a sliver consisting of buoyant oceanic lithosphere was amalgamated with the base of the ancient continental lithosphere of the overriding plate. The oceanic mantle lithosphere and the oceanic crust dehydrated (but did not melt) and these fluids lowered the solidus of the overlying continental mantle lithosphere and crust. This scenario can explain the occurrence of rare K_2O- and LILE-enriched monzodiorites and quartz monzonites with crustal-like isotopic compositions observed in this study as well as some more alkaline rocks in the belt. Because the metasomatized continental lithospheric mantle has lower solidus temperatures than peridotitic mantle, it is very likely that such metasomatized rocks may melt early during flat subduction. Thus, K_2O-enriched monzodiorites to monzogranites are not restricted to late stages of the evolution of an orogen but may already form at the onset of an orogeny.

1. Introduction

Among the plutonic rock associations, granodiorites, and granites are the most common igneous rocks worldwide but the source of heat required for melting, the origin and nature of their parental magmas as well as the nature of post-melting processes that occur prior to and concurrently with intrusion and solidification are a matter of intense debate. Key questions concern the potential protoliths and their tectono-thermal and magmatic evolution, as well as melting and assimilation-fractional crystallization processes subject to the parental melts of these intermediate igneous rocks that dominate the bulk continental crust (Rudnick & Gao, 2004). Granodiorites are very common in continental margin, subduction zone settings and in this case originate from volatile-triggered melting of the sub-arc mantle wedge and subsequent melt differentiation either with (DePaolo, 1981; Chen and Tilton, 1991) or without assimilation (Coleman et al., 1992). Alternative models

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Quaternary ring plain- and valley-confined pyroclastic deposits of Aragats stratovolcano (Lesser Caucasus): Lithofacies, geochronology and eruption history

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ABSTRACT

Aragats stratovolcano, located on the South Armenian block, a micro-plate in the Arabian-Eurasian collision zone, has a complex and long-lasting Quaternary eruption history. Cataclysmic eruptions formed widespread pyroclastic deposits, which are interrupted by numerous basaltic to trachytic lava flows as well as lacustrine and lacustrine-alluvial sediments. Contrary to previous concepts, detailed mapping of lithofacies variation combined with stratigraphic documentation and new high-precision $^{40}Ar/^{39}Ar$ ages revealed four eruption cycles, each started with mafic lavas and generally finalized with pyroclastic deposits. These data contributed to a fundamental reinterpretation of the development of the Aragats Volcanic Province (AVP). Within an estimated activity of one million years, Aragats itself experienced three eruption stages, two of which culminated in pyroclastic deposits of remarkable lithofacies variability with ages of 0.97 to 0.90 Ma and 0.75 to 0.65 Ma, respectively. Vertical and lateral changes in proximal and distal facies distribution of pyroclastic flow deposits indicate temporal variations in eruption intensity and periods of relative volcanic quiescence.

Aragats' explosive activities were dominated by Plinian eruptions with columns as high as 25 km, while others are characterized by low eruption columns followed by instantaneous collapse, in one case associated with vent widening, possible caldera collapse and breccia formation. Furthermore, one AVP unit features juvenile lapilli and blocks including banded and armored pumice, indicating magma mingling and their involvement in the erupting mixture before magma fragmentation.

1. Introduction

The Quaternary Aragats Volcanic Province (AVP), with Aragats volcano as its main volcanic complex, comprises high-volume ignimbrites and fallout deposits - an ideal area to study the products of explosive eruptions in intraplate post-collisional settings. Cyclic magmatism generated four distinct stages in AVP (Ghukasyan, 1985), three of which mainly refer to central vent eruptions of the Aragats stratovolcano and one to lateral monogenetic volcanic centers (Chernyshev et al., 2002). Each stage started with mafic lava flows and has been completed by intermediate to felsic pyroclastic flow deposits. Similar eruption cycles have been observed at other stratovolcanoes, such as Kanaga in the western Aleutian Islands (Waythomas et al., 2001) or Erciyes and Nemrut in Turkey (Şen et al., 2003; Çubukçu et al., 2012). Lebedev et al. (2010) described analogous patterns of discontinuous multistage magmatic activity for the Elbrus volcanic region in Greater Caucasus.

The AVP pyroclastic flows have been deposited in a valley-confined environment and as extended pyroclastic sheets at the slope-ring plain transition, indicating the complex nature of explosive activities at AVP. Therefore, sequences of overlapping AVP ignimbrites are valuable archives to decipher the Quaternary eruption history and the dynamics of the related magmatic system (Gevorgyan et al., 2018). AVP magma - which comprises predominantly dry mineral assemblages - is characterized by a relatively small degree of depletion of the initial melt and by a gradual depletion of volatile elements (Gevorgyan et al., 2018). The fluctuation of volatile content and magma ascent rate, as well as magma mingling and fragmentation, are part of the complex processes in magma chamber-conduit systems highly reflecting on eruption dynamic and diversity of ignimbrite composition (Hildreth and Mahood, 1985; Civetta et al., 1997; Bear et al., 2009; Gevorgyan et al., 2018). In addition, a remarkable lithofacies variation in pyroclastic

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Tectonics

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Key Points:
- The Alichur dome was tectonically exhumed from 10–15 km depth between ~16 and 4 Ma at ~1.1 km/Myr by syn-collisional ~N–S extension
- Dome-scale boudinage and divergent footwall exhumation reflect subordinate westward lateral extrusion coeval with dominant ~N–S extension
- Basal shear imposed by the underthrusting Indian lithosphere enabled ~N–S extension in the South Pamir to outlast that in the Central Pamir

Supporting Information:
- Supporting Information S1
- Figure S1
- Figure S2
- Figure S3
- Figure S4
- Figure S5
- Data Set S1
- Data Set S2
- Data Set S3
- Data Set S4
- Table S1-S9

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The Alichur Dome, South Pamir, Western India–Asia Collisional Zone: Detailing the Neogene Shakhdara–Alichur Syn-collisional Gneiss-Dome Complex and Connection to Lithospheric Processes

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Abstract Neogene, syn-collisional extensional exhumation of Asian lower–middle crust produced the Shakhdara–Alichur gneiss-dome complex in the South Pamir. The <1 km-thick, mylonitic–brittle, top-NNE, normal-sense Alichur shear zone (ASZ) bounds the 125 × 25 km Alichur dome to the north. The Shakhdara dome is bounded by the <4 km-thick, mylonitic–brittle, top-SSE South Pamir normal-sense shear zone (SPSZ) to the south, and the dextral Gunt wrench zone to its north. The Alichur dome comprises Cretaceous granitoids/gneisses cut by early Miocene leucogranites; its hanging wall contains non/weakly metamorphosed rocks. The 22–17 Ma Alichur-dome-injection-complex leucogranites transition from foliation-parallel, centimeter- to meter-thick sheets within the ASZ into discordant intrusions that may comprise half the volume of the dome core. Secondary fluid inclusions in mylonites and mylonitization-temperature constraints suggest Alichur-dome exhumation from 10–15 km depth. Thermochronologic dates bracket footwall cooling between ~410–130 °C from ~16–4 Ma; tectonic cooling/exhumation rates (~42 °C/Myr, ~1.1 km/Myr) contrast with erosion-dominated rates in the hanging wall (~2 °C/Myr, <0.1 km/Myr). Dome-scale boudinage, oblique divergence of the ASZ and SPSZ hanging walls, and dextral wrenching reflect minor approximately E–W material flow out of the orogen. We attribute broadly southward younging extensional exhumation across the central South Pamir between ~20–4 Ma to: (i) Mostly northward, foreland-directed flow of hot crust into a cold foreland during the growth of the Pamir orocline; and (ii) Contrasting effects of basal shear related to underthrusting Indian lithosphere, enhancing extension in the underthrust South Pamir and inhibiting extension in the non-underthrust Central Pamir.

1. Introduction

Gneiss domes—dome-shaped culminations of higher-grade rocks mantled by lower-grade rocks—express the geodynamics that govern their hosting orogens (e.g., Whitney et al., 2004; Yin, 2004). In general, gneiss domes in both Cordilleran-style and collisional orogens record an early phase of burial during plate convergence, followed by exhumation during either lithosphere-scale extension (for Cordilleran-style domes) or continued plate convergence (for syn-collisional domes). Cordilleran-style gneiss domes, exemplified by the metamorphic-core complexes in the North American Cordillera (e.g., Coney & Harms, 1984), are exhumed by bounding extensional shear zones that are kinematically congruent with a tectonic

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Dating multiply overprinted granites: The effect of protracted magmatism and fluid flow on dating systems (zircon U-Pb: SHRIMP/SIMS, LA-ICP-MS, CA-ID-TIMS; and Rb–Sr, Ar–Ar) – Granites from the Western Erzgebirge (Bohemian Massif, Germany)

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ABSTRACT

The Variscan granites from the Western Erzgebirge were repeatedly dated by various methods, but no consensus has been reached about their exact intrusion ages. This study presents a multi-dating approach for the four largest intrusions from the Western Erzgebirge (Aue-Schwarzenberg, Bergen, Eibenstock, Kirchberg). We analysed several samples from each pluton/suite with zircon U–Pb CA-ID-TIMS (chemical abrasion-isotope dilution-thermal ionization mass spectrometry) to obtain robust temporal information on their age and tempo of intrusion. These data enable us for the first time to define three intrusive episodes of 1–2 Ma each, separated by quiet periods of several Ma. The Aue-Schwarzenberg suite represents the oldest granites that intruded at ~323–322 Ma followed by the granites from Bergen and Kirchberg 2–4 Ma later. The highly evolved ore-bearing granites from the Eibenstock pluton intruded after a time lag of ~5 Ma at ~315–314 Ma. The new data show that there is a resolvable age difference between the two known granite groups. Granite group 2 (also assigned as younger igneous complex, represented by the Eibenstock pluton) is ≥5 Ma younger than granite group 1 (assigned as older igneous complex, represented by granites from Aue-Schwarzenberg, Bergen and Kirchberg).

Protracted magmatism and late-/post-magmatic fluid flow partly reset the U–Pb system of these granites to variable degrees, making a precise and accurate dating of their intrusion ages challenging. Pb loss in zircons is often combined with high common Pb (Pb_c). SHRIMP/SIMS (sensitive high mass resolution ion microprobe/secondary ion mass spectrometry) and LA-ICP-MS (laser ablation-inductively coupled plasma-mass spectrometry) on non-CA zircons document that Pb loss and high Pb_c is quite variable within zircon grains and may be located in micro-fractures. We demonstrate that chemical abrasion (CA) clearly minimizes or removes both Pb loss and Pb_c. Results from prior LA-ICP-MS and SHRIMP dating on non-CA zircons from the same samples considerably helped the interpretation of the CA-ID-TIMS data when Pb loss was not completely erased by CA. In such cases we often had to choose the oldest analyses for mean age calculation in contrast to the common practice of the CA-ID-TIMS community to choose the youngest dates.

Rb–Sr and Ar–Ar dating systems revealed age differences between the older group and the younger ore-

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Geology, sulfide mineralogy and petrogenesis of the Angstberg Ni-Cu-(PGE) sulfide mineralization (Lausitz Block, Bohemian Massif, Germany): A potential Ni-Cu exploration target in Central Europe?

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Melonite

A B S T R A C T

Germany's largest known magmatic Ni-Cu-(PGE) sulfide enrichment is associated with the gabbroic Angstberg intrusion that is one of several small-scaled, Ni-Cu sulfide-bearing intrusions in the northern Bohemian Massif (Central European Variscan Belt). The intrusions are part of a Middle Devonian to Early Carboniferous, mafic-(ultramafic) magmatic system that emplaced within Cadomian granodiorites of the Lausitz Block. The Angstberg intrusion represents an exposed sub-vertical, dike-like body (320 × 60 m in plan view) and comprises olivine-gabbronorite, olivine-gabbro, gabbro, olivine-hornblende-gabbro, and hornblende-pyroxene-gabbro. The hornblende-bearing and hornblende-free lithologies originate from at least two variably fractionated basaltic parental magma batches which differ in their Ti, LREE, HREE and volatile contents. Fractionation probably took place in deeper-seated sections of the magmatic system, possibly within staging magma chamber(s). Overall enriched incompatible trace-element patterns suggest that the Angstberg lithologies are linked with intra-plate magmatism, likely associated with a transtensional setting in the course of the Variscan orogeny. The previously suggested Devonian age of the intrusion is confirmed by an ^{40}Ar-^{39}Ar biotite age of 373.4 ± 0.9 Ma for the olivine-gabbro. The magmatic sulfide mineralization is predominated by disseminated sulfides that are hosted in the olivine-richest parts of the olivine-gabbronorite and olivine-hornblende-gabbro lithologies. In addition, some sulfide-matrix breccias (up to 70 modal % sulfides) occur directly on the footwall contact of the intrusion to granodiorite. Both mineralization types are characterized by a predominance of pyrrhotite over pentlandite and chalcopyrite with minor secondary violarite and pyrite, and accessory PGE, Au, and Ag phases. Nickel-rich bismuthotellurides of the melonite–merenskyite solid-solution series and froodite are the most common platinum-group minerals. Disseminated sulfides are characterized by high Ni, moderate Cu, and low Pt and Pd tenors (~4–9 wt% Ni, ~2–6 wt% Cu, ~200–800 ppb Pt, ~200–1000 ppb Pd). Sulfide-matrix breccias feature comparable Ni, but lower Cu, Pt and Pd tenors (~4–6 wt% Ni, ~0.3–1 wt% Cu, ~10–100 ppb Pt, ~40–200 ppb Pd). Fractional crystallization and wall-rock assimilation of granodiorite are regarded as key factors for sulfide saturation in the magmas associated with the Angstberg intrusion. Sulfur isotope compositions of pyrrhotite-pentlandite-chalcopyrite assemblages (−1.4 to −0.2‰ VCDT) propose a mantle-origin of S, whereas addition of crustal S cannot be completely ruled out as the S isotope values of the sulfides overlap with those of the granodiorite (−7 to +4‰ VCDT). Olivine- and sulfide-textures suggest that disseminated sulfides likely originate from sulfide melts that were entrained in an olivine-rich crystal mush during magma rise to upper levels. The sulfide-matrix breccias also resulted from entrained sulfide melts, or from gravity-driven downward percolation of sulfide melts from stratigraphically higher, now-eroded levels. In both cases, the formation of sulfide-matrix breccias most likely was amplified by in-situ thermomechanical erosion of the granodioritic wall-rock, caused by flash-boiling of thermally dehydrating biotite. Despite spatial limitations of the mineralized zones and limited information about the architecture of the intrusions in the northern Bohemian Massif, the Angstberg intrusion, as well as other neighboring magmatic sulfide occurrences, may represent a new exploration target for Ni and Cu in Central Europe.

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K-rich hydrous mantle lithosphere beneath the Ontong Java Plateau: Significance for the genesis of oceanic basalts and Archean continents

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Abstract

Olivine-free metasomatic mantle-derived xenoliths, frequently recovered from kimberlite and lamprophyre intrusions on the continents, are seldom described from oceanic settings. We report the mineralogy, geochemistry and Sr-Nd-Hf-Pb-Os isotopic compositions of a unique K-rich, hydrous mantle nodule sourced from a 34 Ma ultramafic lamprophyre (alnöite) pipe on the island of Malaita, Ontong Java Plateau, SW Pacific. The Ontong Java Plateau, the most voluminous oceanic large igeous province, has a >100 km thick lithospheric root reminiscent of thick lithospheres that characterize cratonic settings. The phlogopite, amphibole, clinopyroxene and ilmenite-rich nature of the Malaita metasomatic nodule bears striking similarity to cratonic mica-amphibole-rutile-ilmenite-diopside (MARID) suite xenoliths, and it provides a tangible example of heavily overprinted oceanic mantle lithosphere.

The nodule phlogopite $^{40}Ar/^{39}Ar$ age of 44.7 ± 1.8 Ma (95% confidence level) predates the 34 Ma alnöites, but is contemporaneous with 44 Ma alkali basalts on Malaita. Geodynamic reconstructions of the Ontong Java Plateau position within the Pacific realm demonstrate that alnöite magma and K-rich metasomatic nodule formation occurred within a strictly oceanic environment during the Eocene, away from subduction zones. The elevated incompatible trace element concentrations coupled with low highly siderophile element contents suggest that the K-rich metasomatic nodule formed by olivine-absent crystallisation from low-volume mantle-derived melt comparable to alnöite, but not the Malaita alkali basalts. A genetic link between the Malaita metasomatic nodule and alnöite is further suggested by overlapping Sr-Nd-Hf-Pb isotopic compositions ($^{87}Sr/^{86}Sr_{45Ma} = 0.70419$–$0.70423$; $\varepsilon Nd_{45Ma} = +3.5$; $\varepsilon Hf_{45Ma} = +5.3$; $^{206}Pb/^{204}Pb_{45Ma} = 18.66$–$18.71$; $^{207}Pb/^{204}Pb_{45Ma} = 15.61$). These isotopic compositions are generally more enriched than those of mantle-derived peridotites and 122 Ma plateau-building basalts at Ontong Java, but share similarities with pyroxenite xenoliths from Malaita previously interpreted to represent ancient recycled crustal material. Mixing models between melts derived from fertile mantle and the more enriched pyroxenite, as well as recycled sedimentary material, can account for the composition of the K-rich metasomatic nodule. Extremely low contents of highly siderophile elements and high $^{187}Os/^{188}Os_{45Ma}$ (0.1824–0.1997) can also be reconciled with the involvement of recycled crustal components in the complex origin of the K-rich hydrous nodule.

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Born in the Pacific and raised in the Caribbean: construction of the Escambray nappe stack, central Cuba. A review

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Abstract: The Escambray Massif of central Cuba is the largest metamorphic complex exposed in the Greater Antilles of the northern Caribbean area. It can be viewed as an extraordinarily rich archive, documenting (1) processes accompanying early rifting between North and South America, (2) the subsequent eastward passage of the intra-oceanic subduction-zone and island-arc complex of the ''Great Caribbean Arc'' (GCA) originally bridging the Farallon rims of the Americas to its present position of the Lesser Antilles, (3) the interaction of the northwestern GCA with the northern continental border, and (4) final collision of the GCA with the Bahamas crustal section of North America. The Escambray Massif has recently received renewed attention for its role in allowing Caribbean tectonic history to be studied. In this review, we summarize data and information from both published and unpublished Spanish, Russian, German, and English sources and augment this with our own unpublished geochemical and geochronological data to provide a comprehensive overview. The Escambray Massif is a nappe pile of five major tectonic units with different protoliths and pressure-temperature-time paths, indicative of distinct geodynamic settings. The tectonically uppermost Mabujina Amphibolite Complex (MAC) overlies four units of the Escambray Complex (EC) *s.str.* It is a lithologically heterogeneous unit that underwent low- to medium-pressure amphibolite-facies metamorphism at about 90 Ma. The lithology of the MAC is similar to that described for the active margin of western Mexico. The two directly underlying high-pressure (HP) metamorphic nappes of the EC represent former oceanic crust (Yayabo Unit) and a mélange-like mix of sedimentary and igneous rocks derived from a passive margin with exotic slivers of oceanic crust and serpentinite (Gavilanes Unit). Pressures of 14–15 kbar were reached in the Yayabo amphibolites and 25 kbar in the eclogite-bearing Gavilanes Unit. The diachronous timing of maximum HP-metamorphism (80 Ma and 70 Ma, respectively) is due to the oblique collision of the GCA with the southern Yucatán block during subduction. The MAC and the Yayabo Unit were juxtaposed between 75 and 80 Ma, and joined by the Gavilanes Unit at 68–65 Ma. The tectonically lowest units reached lawsonite-grade, high-pressure greenschist-facies conditions at variable temperatures during subduction at ~60 Ma and were stacked with the other units at ~50 Ma, before the complete metamorphic nappe pile was thrust over the southern Bahamas margin and exposed to erosion. Both the MAC and the EC units bear evidence of tectonic transport by oblique subduction and collision extending from the active Pacific margin along the northern Proto-Caribbean passive continental margins to a final position in the thrust belt bordering the southern Bahamas platform.

Key-words: Escambray metamorphic complex; North Caribbean Suture zone; high-pressure metamorphism; Lu–Hf, U–Pb and Ar–Ar geochronology; Cuba.

1. Introduction

1.1. Regional setting of subduction-related rocks in the northern Caribbean

During the Late Jurassic and Early Cretaceous the North and South American continental plates rifted apart, leading to the formation of oceanic crust in the so-called Proto-Caribbean area and the Gulf of Mexico (*e.g.*, Pindell & Kennan, 2009; Pindell *et al.*, 2012; Boschman *et al.*, 2014). Much debate has arisen on the nature of the evolving intra-oceanic plate boundary connecting the east-dipping subduction zones of the North and South American Cordillera at the mouth of this widening seaway. Further debate involves the question of how an east-dipping subduction zone can realistically evolve into the west-dipping juvenile oceanic island-arc system that will become the intra-oceanic Great Caribbean Arc

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New geochemical results indicate a non-alpine provenance for the Alpine Spectrum (epidote, garnet, hornblende) in quaternary Upper Rhine sediment

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ABSTRACT

The heavy mineral assemblage of late Pleistocene to Modern Rhine river sediment in the Upper Rhine Graben is dominated by garnet, green amphibole and epidote. This so-called Alpine Spectrum has been taken to indicate an exclusive derivation from the Alps and has hitherto been investigated with optical methods only. We present the first single-grain geochemical data set of garnet and amphibole from the upper Rhine river and some of its main tributaries. We use the new data to test the alleged Alpine provenance in the Rhine.

Our results show that the provenance of garnet, mostly pyrope-rich almandine is grain-size dependent. Particularly the pyrope content indicates that the 0.063–0.25 mm size fraction has an Alpine provenance whereas 0.25–0.5 mm grains derived from the Black Forest and the Vosges, which flank the Upper Rhine Graben. They mainly comprise of Paleozoic metamorphic and igneous rocks supplying a suite of heavy minerals similar to the Alpine Spectrum to the Rhine river. Amphibole, mostly Mg-hornblende, has an increasing TiO_2 content from the south to the north of the graben, which also indicates an input from the graben shoulders. The new data indicate that the so-called Alpine Spectrum of heavy minerals in Rhine river sediment of the upper Rhine derived to significant degrees from non-Alpine sources. Furthermore, our results indicate a relatively uniform provenance for the Rhine River system during the past 1 Ma.

1. Introduction

The temporal and spatial evolution of the sedimentary fill of peri-orogenic basins reflects the exhumation history of mountain belts. The volume and composition of sediment exported from an orogen is the product of the interplay of tectonic activity and climate (Gulick et al., 2015). The sediment offers insights into the source-rock assemblages and may allow for establishing a sediment transfer budget. Detrital single grain analysis provides the geochemical composition and conditions of formation of the source rocks and can therefore help to trace changes in provenance and changes in the relative influence of different sources. In the best case, this can help to quantify the amount of material that was eroded from certain sources (Weltje and von Eynatten, 2004; von Eynatten and Dunkl, 2012).

The Upper Rhine Graben is located in Central Europe along the border between Germany, France, and Switzerland (Fig. 1a) and is a sink for detritus from the Alps. It is part of the European Cenozoic Rift System that runs from the Mediterranean Sea in the south to the North Sea in the north (Ziegler and Dezes, 2007). Since its opening during the late Eocene the graben was repeatedly connected to the northern Alpine drainage system (Ziegler and Fraefel, 2009). The last reorganisation of the northwestern alpine drainage network at around 2.9 Ma established today's conditions and led to a significant change in the Upper Rhine Graben sand-sized sediments, in the heavy mineral composition (Hagedorn, 2004; Hagedorn and Boenigk, 2008) as well as in thermochronological data (Tatzel et al., 2015). The heavy mineral assemblage of sediment older than 2.9 Ma is dominated by stable minerals like zircon, tourmaline and rutile, whereas in younger strata garnet, green amphibole and epidote dominate. This association is called the Alpine Spectrum (van Andel, 1950). Zircon fission-track data show a similar shift from Permo-Mesozoic ages in sediment older than 2.9 Ma to an age spectrum dominated by Cenozoic cooling ages in younger sediment (Tatzel et al., 2015). However, the age distribution of detrital zircon fission-track ages is changing in the course of the Rhine along the Upper Rhine Graben. Bernet et al. (2004) showed that the alpine rivers and the alpine Rhine contain relatively young zircon grains between 10 and 30 Ma with a unimodal age distribution. At the northern margin of

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Single grain heavy mineral provenance of garnet and amphibole in the Surveyor fan and precursor sediments on the Gulf of Alaska abyssal plain — Implications for climate-tectonic interactions in the St. Elias orogen

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ABSTRACT

The St. Elias orogen formed as a result of the northwestward drift of the Yakutat terrane along and final collision with the Alaska margin in the Miocene. Its exhumation coincided with changing glacial conditions that are considered to have strongly interacted with mountain building processes. A significant part of the record of these tectonic-climatic interactions is stored in sediments on the Gulf of Alaska abyssal plain including the Surveyor fan. Our study examines temporal provenance changes of Miocene through Pleistocene sediments of the Surveyor fan, Gulf of Alaska, to constrain the dynamics of exhumation and mass transfer from the evolving St. Elias orogen to the adjacent Surveyor deep sea fan. We present single grain geochemical data of amphibole and garnet and $^{40}Ar/^{39}Ar$ cooling ages of biotite and amphibole together with point counting data of heavy minerals from sands and silts from two sites in the distal and proximal fan, drilled by IODP expedition 341 in 2013 (sites U1417 and U1418, respectively).

A shift in heavy mineral composition during the Miocene, predating the onset of glaciation, points to a tectonically-induced change in erosion centers and sediment transport, probably caused by the rise of the St. Elias Mountains. Garnet and amphibole data suggest the Chugach metamorphic complex is the main sediment source, implying input to the Surveyor fan from sources relatively far in the north during the Miocene. Changing provenance signals from the Miocene to Pliocene suggest rising input from the lower grade metamorphic areas at the southern flanks of the orogen, indicating the advance of glaciers to the tidewater line, providing material from this flanking region. Higher input from the Chugach metamorphic complex in all Pleistocene sediments suggests the Northern Hemisphere glaciation at the Plio-Pleistocene boundary caused erosion and sediment yield from the interior of the orogen. Climatic changes at the mid-Pleistocene transition did not cause significant changes in the provenance signal.

1. Introduction

In active orogens, tectonically-driven deformation and climate-induced removal and redistribution of mass show complex interactions (e.g., Molnar and England, 1990; Meigs et al., 2008; Adlakha et al., 2013). The style of feedback between and coupling of climate and tectonics continues to be controversially discussed (e.g., Molnar and England, 1990; Raymo and Ruddiman, 1992; Meigs and Sauber, 2000; Peizhen et al., 2001; Molnar, 2004; Clift, 2006; Huntington et al., 2006; Clift et al., 2008; Gulick et al., 2015; Enkelmann et al., 2015a; Worthington et al., 2018). The evolution of the St. Elias orogen at the southern Alaska continental margin (Fig. 1A) is connected to subduction of the Yakutat plate under the North American Plate, and coincides with pronounced climatic changes. The relative contribution of climate and tectonics to exhumation is the subject of ongoing research (e.g., Spotila et al., 2004; Berger and Spotila, 2008; Meigs et al., 2008; Berger et al., 2008a,b; Enkelmann et al., 2009, 2010, 2015b, 2017; McAleer et al., 2009; Headley et al., 2012, 2013; Pavlis et al., 2012; Gulick et al., 2015). Onshore studies in the St. Elias Mountains are hampered by the ongoing glaciation (Fig. 1B). Most of the orogenic detritus has been delivered to the Gulf of Alaska forearc, shelf and abyssal plain including the Surveyor deep sea fan, potentially storing information on the evolving orogen and sediment routing into the ocean (Jaeger et al., 1998; Expedition 341 Scientists, 2014).

Provenance research on offshore sediments in other regions has demonstrated its usefulness in deciphering regional changes in tectonics and sediment dispersal mechanisms and pathways (e.g., Usman et al., 2014; Pandey et al., 2016). Zircon U-Pb ages and Hf-isotope data obtained for IODP sites U1417 and U1418 drilled in the Surveyor fan (Huber et al., unpublished manuscript) identify the Chugach-Prince William and Yakutat terranes and the Chugach metamorphic complex

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ORIGINAL PAPER

Geochemical and geochronological evidence for a Middle Permian oceanic plateau fragment in the Paleo-Tethyan suture zone of NE Iran

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Abstract

The mafic–ultramafic Fariman complex in northeastern Iran has been interpreted as a Paleo-Tethyan ophiolitic fragment with subduction- and plume-related characteristics as well as a basin deposit on an active continental margin. Contributing to this issue, we present geochemical, geochronological, and mineralogical data for transitional and tholeiitic basalts. Thermodynamic modeling suggests picritic parental magmas with 16–21 wt% MgO formed at plume-like mantle potential temperatures of ca. 1460–1600 °C. Rare pyroxene spinifex textures and skeletal to feather-like clinopyroxene attest to crystallization from undercooled magma and high cooling rates. Chromium numbers and TiO_2 concentrations in spinel are similar to those in intraplate basalts. ^{40}Ar–^{39}Ar dating of magmatic hornblende yielded a plateau age of 276 ± 4 Ma (2σ). Transitional basalt with OIB-like trace element characteristics is the predominant rock-type; less frequent are tholeiitic basalts with mildly LREE depleted patterns and picrites with intermediate trace element characteristics. All samples show MORB-OIB like Pb/Ce, Th/La, and Th/Nb ratios which preclude subduction-modified mantle sources and felsic crustal material. Tholeiitic basalts and related olivine cumulate rocks show MORB-like initial ε_{Nd} values of +9.4 to +6.2 which define a mixing line with the data for the transitional basalts (ε_{Nd} ca. +2.6). Initial $^{187}Os/^{188}Os$ ratios of 0.124–0.293 support mixed sources with a high proportion of recycled mafic crust in the transitional basalts. High concentrations of highly siderophile elements are in agreement with the high mantle potential temperatures and inferred high-melting degrees. It is argued that the Fariman complex originated by melting of a mantle plume component as represented by the OIB-like transitional basalt and entrained asthenosphere predominant in the MORB-like tholeiites. Two lines of evidence such as association of the Fariman complex with pelagic to neritic sedimentary rocks and the tectonic position at the boundary of two continental blocks defined by ophiolites and accretionary complexes of different ages suggest formation in an oceanic domain. Thus, we interpret it as a fragment of an oceanic plateau, which escaped subduction and was accreted as exotic block in the Paleo-Tethyan suture zone.

Keywords Picrite · Nd and Os isotopes · Geochemistry · Mantle plume · Oceanic plateau · Paleo-Tethys · The Mashhad–Fariman complex · Iran

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ORIGINAL PAPER

High-resolution $^{40}Ar/^{39}Ar$ geochronology of volcanic rocks from the Siebengebirge (Central Germany)—Implications for eruption timescales and petrogenetic evolution of intraplate volcanic fields

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Abstract A key parameter in understanding mantle dynamics beneath continents is the temporal evolution of intraplate volcanism in response to lithospheric thinning and asthenospheric uplift. To contribute to a better understanding of how intraplate volcanic fields evolve through time, we present a high precision $^{40}Ar/^{39}Ar$ age dataset for volcanic rocks from the Siebengebirge volcanic field (SVF) from central Germany, one of the best studied and compositionally most diverse intraplate volcanic fields of the Cenozoic Central European Volcanic Province (CEVP). Petrological and geochemical investigations suggest that the formation of the different rock types that occur in the SVF can be explained by a combination of assimilation and fractional crystallisation processes, starting from at least two different parental magmas with different levels of silica saturation (alkali basaltic and basanitic), and originating from different mantle sources. These evolved along two differentiation trends to latites and trachytes, and to tephrites and tephriphonolites, respectively. In contrast to their petrogenesis, the temporal evolution of the different SVF suites is poorly constrained. Previous K/Ar ages suggested a time of formation between about 28 and 19 Ma for the mafic rocks, and of about 27 to 24 Ma for the differentiated rocks. Our results confirm at high precision that the differentiated lithologies of both alkaline suites ($^{40}Ar/^{39}Ar$ ages from 25.3 ± 0.2 Ma to 25.9 ± 0.3 Ma) erupted contemporaneously within a very short time period of ~ 0.6 Ma, whereas the eruption of mafic rocks (basanites) lasted at least 8 Ma ($^{40}Ar/^{39}Ar$ ages from 22.2 ± 0.2 Ma to 29.5 ± 0.3 Ma). This implies that felsic magmatism in the central SVF was likely a single event, possibly triggered by an intense phase of rifting, and that ongoing melting and eruption of mostly undifferentiated mafic lavas dominate the > 8 Ma long magmatic history of this region. Among the mafic lavas, most basanites and tephrites predate the alkali basalts and hawaiites, suggesting an overall temporal evolution towards less SiO_2-undersaturated primary melts and increasing degrees of melting over time. The peak in alkali basaltic to hawaiitic magmatism slightly post dates the flare-up of genetically related felsic magmatism, by no more than ~ 1 Ma. This is consistent with a model in which the magmatic plumbing system erupted successively from upper to lower levels, i.e. from more evolved to more primitive compositions. One young age for a basanitic sample suggests that silica saturation decreased again towards the end of volcanic activity. This chronology of volcanic events is in good agreement with previous models, suggesting continuous lithospheric thinning beneath the SVF as a response to an extensional regime and asthenospheric uplift in the northern alpine realm.

Keywords Siebengebirge · $^{40}Ar/^{39}Ar$ Geochronology · Central European volcanic province · Intraplate magmatism

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Original Article

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Recurrent Local Melting of Metasomatised Lithospheric Mantle in Response to Continental Rifting: Constraints from Basanites and Nephelinites/Melilitites from SE Germany

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ABSTRACT

Cenozoic primitive basanites, nephelinites and melilitites from the Heldburg region, SE Germany, are high-MgO magmas (8·5–14·1 wt % MgO), with low SiO_2 (34·2–47·1 wt %) and low to moderately high Al_2O_3 (9·0–15·5 wt %) and CaO (8·7–12·7 wt %). The Ni and Cr contents of most samples are up to 470 ppm and 640 ppm, respectively, and match those inferred for primary melts. In multi-element diagrams, all samples are highly enriched in incompatible trace elements with chondrite-normalised La/Yb = 19–45, strongly depleted in Rb and K, with primitive mantle normalised K/La = 0·15–0·72, and moderately depleted in Pb. The initial Sr–Nd–Hf isotope compositions ($^{87}Sr/^{86}Sr$ = 0·7033–0·7051, $^{143}Nd/^{144}Nd$ = 0·51279–0·51288 and $^{176}Hf/^{177}Hf$ = 0·28284–0·28294) fall within the range observed for other Tertiary volcanic rocks of the Central European Volcanic Province, whereas $^{208}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ (38·42–38·88 and 18·49–18·98) are distinctly lower at comparable $^{207}Pb/^{204}Pb$ (15·60–15·65). Trace element modelling and pressure–temperature estimates based on major element compositions and experimental data suggest that the nephelinites/melilitites formed within the lowermost lithospheric mantle, close to the lithosphere–asthenosphere boundary, by ~3–5% partial melting of a highly enriched, metasomatised, carbonated phlogopite-bearing garnet–lherzolite at temperatures <1250 °C and pressures of ~2·8 GPa. This corresponds to a melting depth of less than ~85 km. Formation and eruption of these magmas, based on $^{40}Ar/^{39}Ar$ dating, started in the late Eocene (38·0 Ma) and lasted until the late Oligocene (25·4 Ma). Basanite eruptions occurred in the same area in the middle Miocene, about 7·7 Myr after nephelinite/melilitite generation has ceased, and lasted from 17·7 to 13·1 Ma. The basanites were generated at lower pressures (2·2–1·7 GPa) at similar temperatures (~1220–1250 °C) within the spinel stability field in the lithospheric mantle by 2–6% partial melting. Isotope and trace element systematics indicate that the lithospheric mantle source of the Heldburg magmas was affected by metasomatism associated with long-lasting subduction of oceanic and continental crust during the Variscan orogeny. Aqueous or supercritical fluids that formed at temperatures <1000 °C and pressures of likely >4 GPa infiltrated the thermal boundary layer at the base of the lithospheric mantle and imprinted a crustal lead isotope, and to a minor extent crustal Sr, Nd and Hf isotope signatures. They also reduced Nb/U, Ce/Pb, Lu/Hf, Sm/Nd, U/Pb and Th/Pb, but increased Rb/Sr and Nb/Ta and

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RESEARCH ARTICLE

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This article is a companion to *Rutte et al.* [2017] doi:10.1002/2016TC004294; and *Rutte et al.* [2017] doi:10.1002/2016TC004293.

Key Points:

- Burial and exhumation depths, temperatures, and rates are constrained for five Pamir domes
- Central Pamir exhumed from 600 to 675°C and 25 to 35 km by 22–19 Ma
- South Pamir exhumed from 750 to 800°C and >50 km by ~20 Ma

Supporting Information:

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- Figure S1
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- Table S7

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Building the Pamir-Tibet Plateau—Crustal stacking, extensional collapse, and lateral extrusion in the Pamir: 3. Thermobarometry and petrochronology of deep Asian crust

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Abstract Large domes of crystalline, middle to deep crustal rocks of Asian provenance make the Pamir a unique part of the India-Asia collision. Combined major-element and trace element thermobarometry, pseudosections, garnet-zoning deconstruction, and geochronology are used to assess the burial and exhumation history of five of these domes. All domes were buried and heated sufficiently to initiate garnet growth at depths of 15–20 km at 37–27 Ma. The Central Pamir was then heated at ~10–20°C/Myr and buried at 1–2 km/Myr to 600–675°C at depths of 25–35 km by 22–19 Ma. The Shakhdara Dome in the South Pamir was heated at ~20°C/Myr and buried at 2–8 km/Myr to reach 750–800°C at depths of ≥50 km by ~20 Ma. All domes were exhumed at >3 km/Myr to 5–10 km depths and ~300°C by 17–15 Ma. The pressures, temperatures, burial rates, and heating rates are typical of continental collision. Decompression during exhumation outpaced cooling, compatible with tectonic unroofing along mapped large-scale, normal-sense shear zones, and with advection of near-solidus or suprasolidus temperatures into the upper crust, triggering exhumation-related magmatism. The Shakhdara Dome was exhumed from greater depth than the Central Pamir domes perhaps due to its position farther in the hinterland of the Paleogene retrowedge and to higher heat input following Indian slab breakoff. The large-scale thickening and coincident ~20 Ma switch to extension throughout a huge area encompassing the Pamir and Karakorum strengthens the idea that the evolution of orogenic plateaux is governed by catastrophic plate-scale events.

Plain Language Summary In the Pamir we can see deep into the crust of the India-Asia collision, something that cannot be done elsewhere. By measuring and interpreting mineral compositions, we determine that the Central Pamir was heated at ~10–20°C/Myr and buried at 1–2 km/Myr to 600–675°C at depths of 25–35 km by 22–19 Ma. The South Pamir was heated at ~20°C/Myr and buried at 2–8 km/Myr to reach 750–800°C at depths of ~55 km by 20 Ma. All domes were exhumed at >3 km/Myr to 10–15 km depths and 300°C by 17–15 Ma.

1. Introduction

The Pamir is the western part of the high plateau created by the India-Asia collision (Figure 1). Although geographically and geologically contiguous, the Pamir differs markedly from Tibet. Both have ~70 km thick crust [*Mechie et al.*, 2011, 2012] and absorbed ~2100–1800 km of Cenozoic India-Asia convergence [*Le Pichon et al.*, 1992; *Johnson*, 2002], but the N-S extent of the Pamir is 2 to 3 times less than Tibet, resulting in concentrated Cenozoic shortening and exposure of deep crustal rock [*Schmidt et al.*, 2011]. These exposures provide an opportunity to understand the behavior of the Asian middle to lower crust during the India-Asia collision.

Understanding large-scale processes in orogens—mechanisms and rates of crustal thickening, extrusion, thinning, and foundering—hinges on reconstructing as much of the material flow paths as possible. Herein we use thermobarometry and geochronology to do this for the Pamir deep crust, using the rocks that are exposed in metamorphic domes. Because the Pamir includes a large fraction of the Cenozoic deep crust

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OIB signatures in basin-related lithosphere-derived alkaline basalts from the Batain basin (Oman) — Constraints from $^{40}Ar/^{39}Ar$ ages and Nd–Sr–Pb–Hf isotopes

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ABSTRACT

Tertiary rift-related intraplate basanites from the Batain basin of northeastern Oman have low SiO_2 (<45.6 wt.%), high MgO (>9.73 wt.%) and moderate to high Cr and Ni contents (Cr >261 ppm, Ni >181 ppm), representing near primary magmas that have undergone fractionation of mainly olivine and magnetite. Rare earth element systematics and p-T estimates suggest that the alkaline rocks are generated by different degrees of partial melting (4–13%) of a spinel-peridotite lithospheric mantle containing residual amphibole. The alkaline rocks show restricted variations of $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ranging from 0.70340 to 0.70405 and 0.51275 to 0.51284, respectively. Variations in Pb isotopes ($^{206}Pb/^{204}Pb$: 18.59–18.82, $^{207}Pb/^{204}Pb$: 15.54–15.56, $^{208}Pb/^{204}Pb$: 38.65–38.98) of the alkaline rocks fall in the range of most OIB. Trace element constraints together with Sr–Nd–Pb isotope composition indicate that assimilation through crustal material did not affect the lavas. Instead, trace element variations can be explained by melting of a lithospheric mantle source that was metasomatized by an OIB-type magma that was accumulated at the base of the lithosphere sometimes in the past. Although only an area of less than 1000 km^2 was sampled, magmatic activity lasted for about 5.5 Ma with a virtually continuous activity from 40.7 ± 0.7 to 35.3 ± 0.6 Ma. During this period magma composition was nearly constant, i.e. the degree of melting and the nature of the tapped source did not change significantly over time.

1. Introduction

A serious controversy on the origin of rift-related continental basalts exists and mainly results from different interpretations of trace element and Sr, Nd and Pb isotopic data and the tectonic setting in which they occur (e.g., active rifting due to lithospheric stretching vs. passive rifting due to plume impingement). Trace element and isotope data may yield ambiguous results because the interplay of depleted or enriched asthenospheric mantle, lithopheric mantle and continental crust during magma genesis can impart similar characteristics to continental basalts. In addition, the chemical and isotopic compositions of the various endmember mantle reservoirs are created, at least in part, through crustal recycling or are susceptible to modification through metasomatism. Based on the similarity to most ocean island basalts (OIBs; Allégre et al., 1981; Fitton and Dunlop, 1985; Thompson and Morrison, 1988), there is some consensus that the source of common Na-dominated alkaline volcanic rocks erupted in continental areas is either the subcontinental lithospheric mantle (SCLM), the shallow asthenospheric mantle or a deep plume-related mantle, or a combination of these (Arndt and Christensen, 1992; Hawkesworth et al., 1990; Wilson and Downes, 1991). One interpretation of the commonly observed lithospheric signature in continental basalts (e.g. negative K anomalies in primitive mantle-normalized diagrams) is that they are primarily signs of contamination or re-equilibration of asthenospheric melts by either lithospheric mantle or continental crust. Another interpretation is that melting of continental lithosphere itself is aided by the presence of water and/or hydrous mafic veins with low solidus temperatures, making the lithospheric mantle the main contributor to continental basaltic volcanism (Gallagher and Hawkesworth, 1992; Harry and Leeman, 1995; Pilet et al., 2008). There is increasing evidence that the upper mantle host significant amounts of non-peridotitic material,

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Anomalously old biotite $^{40}Ar/^{39}Ar$ ages in the NW Himalaya

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ABSTRACT

Biotite $^{40}Ar/^{39}Ar$ ages older than corresponding muscovite $^{40}Ar/^{39}Ar$ ages, contrary to the diffusion properties of these minerals, are common in the Himalaya and other metamorphic regions. In these cases, biotite $^{40}Ar/^{39}Ar$ ages are commonly dismissed as "too old" on account of "excess Ar." We present 32 step-heating $^{40}Ar/^{39}Ar$ ages from 17 samples from central Himachal Pradesh Himalaya, India. In almost all cases, the biotite ages are older than predicted from cooling histories. We document host-rock lithology and chemical composition, mica microstructures, biotite chemical composition, and chlorite and muscovite components of biotite separates to demonstrate that these factors do not offer an explanation for the anomalously old biotite $^{40}Ar/^{39}Ar$ ages. We discuss possible mechanisms that may account for extraneous Ar (inherited or excess Ar) in these samples. The most likely cause for "too-old" biotite is excess Ar, i.e., ^{40}Ar that is separated from its parent K. We suggest that this contamination resulted from one or several of the following mechanisms: (1) ^{40}Ar was released during Cenozoic prograde metamorphism; (2) ^{40}Ar transport was restricted due to a temporarily dry intergranular medium; (3) ^{40}Ar was released from melt into a hydrous fluid phase during melt crystallization. Samples from the Main Central Thrust shear zone may be affected by a different mechanism of excess-Ar accumulation, possibly linked to later-stage fluid circulation within the shear zone and chloritization. Different Ar diffusivities and/or solubilities in biotite and muscovite may explain why biotite is more commonly affected by excess Ar than muscovite.

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INTRODUCTION

In most applications, a $^{40}Ar/^{39}Ar$ mineral age is interpreted as the time since cooling through its closure temperature (T_c; Dodson, 1973; McDougall and Harrison, 1999). At temperatures above T_c, Ar diffuses out of the mineral into an external reservoir; at temperatures below T_c, Ar is quantitatively retained in the mineral. Dodson (1973) defined the closure temperature as

$$E/(R \times T_c) = \ln(A \times \tau \times D_0 / a^2), \quad (1)$$

where E is the activation energy, R is the gas constant, A is the grain geometry factor, τ is the time constant, D_0 is the diffusion coefficient, and a is the radius of the effective diffusion domain. The concept of closure temperature is based on the assumptions that (1) the cooling history is characterized by a linear increase in $1/T$; (2) Ar transport in the mineral is controlled by volume diffusion; (3) Ar escapes into an "infinite" reservoir, and the concentration of Ar at the grain boundary remains zero ("zero-concentration boundary condition"). Experimental diffusion data suggest that the T_c of Ar in muscovite and biotite is ~400–500 °C and ~300–400 °C, respectively, depending on grain size, mineral chemistry, and cooling rate (Harrison et al., 1985; Grove, 1993; Grove and Harrison, 1996; Harrison et al., 2009).

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Mineral $^{40}Ar/^{39}Ar$ ages may deviate from the inferred time of cooling through T_c for several reasons. The $^{40}Ar/^{39}Ar$ ages can be reset by neocrystallization or dynamic recrystallization (e.g., Dunlap 1997; Mulch and Cosca, 2004). Hydrothermal fluids may displace radiogenic ^{40}Ar through chemical reactions (e.g., Miller et al., 1991). Both mechanisms result in $^{40}Ar/^{39}Ar$ ages that may be younger than the expected cooling ages, depending on the timing of crystallization or fluid flow during cooling. In other cases, calculated $^{40}Ar/^{39}Ar$ ages are "too old"; a short metamorphic pulse may be insufficient to completely degas Ar from a mineral (e.g., Viete et al., 2011), or ^{40}Ar may become trapped, for example, in fluid inclusions (Cumbest et al., 1994) or lattice defects (Camacho et al., 2012). The problem of anomalously old $^{40}Ar/^{39}Ar$ ages is particularly known from biotite (e.g., Roddick et al., 1980; Baxter et al., 2002) and is commonly attributed to the presence of excess Ar.

The ^{40}Ar accumulating in a mineral may originate from different sources. Slightly different nomenclature is used throughout the literature; we follow the terminology of Dalrymple and Lanphere (1969) and McDougall and Harrison (1999): Radiogenic Ar is ^{40}Ar produced within the mineral by radioactive decay of ^{40}K. Inherited Ar is essentially radiogenic ^{40}Ar that remained in the mineral during incomplete resetting (e.g., older core with younger rim) or was introduced in the form of older material into the mineral (e.g., older K-bearing particles become incorporated into younger volcanic rocks). Nonradiogenic Ar includes Ar of atmospheric composition (here we use $^{40}Ar/^{36}Ar = 295.5$) and excess Ar. Excess Ar is parentless ^{40}Ar, i.e., ^{40}Ar that has been separated from its

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Key Points:
- South and Central Pamir crust thickened from >37 to ~22 Ma and since ~12 Ma by thrust-sheet and fold-nappe emplacement
- Northward crustal collapse formed the Central Pamir gneiss domes at ~22- ≥12 Ma by ~N-S extension during ongoing India-Asia convergence
- Pamir crustal evolution was governed by Indian slab breakoff and subsequent shallow underthrusting of cratonic Indian lithosphere

Supporting Information:
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- Table S8
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- Figure S1
- Figure S2

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Building the Pamir-Tibetan Plateau—Crustal stacking, extensional collapse, and lateral extrusion in the Central Pamir: 2. Timing and rates

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Abstract Geothermochronologic data outline the temperature-deformation-time evolution of the Muskol and Shatput gneiss domes and their hanging walls in the Central Pamir. Prograde metamorphism started before ~35 Ma and peaked at ~23–20 Ma, reflecting top-to- ~N thrust-sheet and fold-nappe emplacement that tripled the thickness of the upper ~7–10 km of the Asian crust. Multimethod thermochronology traces cooling through ~700–100°C between ~22 and 12 Ma due to exhumation along dome-bounding normal-sense shear zones. Synkinematic minerals date normal sense shear-zone deformation at ~22–17 Ma. Age-versus-elevation relationships and paleoisotherm spacing imply exhumation at ≥3 km/Myr. South of the domes, Mesozoic granitoids record slow cooling and/or constant temperature throughout the Paleogene and enhanced cooling (7–31°C/Myr) starting between ~23 and 12 Ma and continuing today. Integrating the Central Pamir data with those of the East (Chinese) Pamir Kongur Shan and Muztaghata domes, and with the South Pamir Shakhdara dome, implies (i) regionally distributed, Paleogene crustal thickening; (ii) Pamir-wide gravitational collapse of thickened crust starting at ~23–21 Ma during ongoing India-Asia convergence; and (iii) termination of doming and resumption of shortening following northward propagating underthrusting of the Indian cratonic lithosphere at ≥12 Ma. Westward lateral extrusion of Pamir Plateau crust into the Hindu Kush and the Tajik depression accompanied all stages. Deep-seated processes, e.g., slab breakoff, crustal foundering, and underthrusting of buoyant lithosphere, governed transitional phases in the Pamir, and likely the Tibet crust.

1. Introduction

At the northwestern tip of the India-Asia collision zone (Figure 1a), Cenozoic gneiss domes, bounded by normal-sense shear zones, cover ~30% of the Central, South, and East Pamir; together with their hanging walls, they expose the upper ~30–40 km of the crust (Figure 1b) [*Schwab et al*., 2004; *Robinson et al*., 2004; *Schmidt et al*., 2011; *Stübner et al*., 2013a]. The 60–70 km thick [*Mechie et al*., 2012] Pamir crust is underlain by a NW-convex arc of intermediate-depth seismicity interpreted to result from Asian lower crust and mantle that is delaminating and rolling back (the Asian slab; Figure 1c) [*Schneider et al*., 2013; *Sippl et al*., 2013a]. The Pamir gneiss domes allow insight into the processes and rates of the Cenozoic construction of the Asian crust in the Pamir-Tibetan Plateau and permit speculations about the interaction between deep crustal/upper mantle and middle-upper crustal processes.

In part 1 of this paper series, *Rutte et al*. [2017] detailed the geometry, kinematics, and amount of deformation during the evolution of the eastern Central Pamir—a history of convergence-driven, upper crustal thrust-sheet and midcrustal fold-nappe stacking, interrupted by synconvergent, orogen-normal, middle-upper crustal extension. The latter likely reflects dynamic adjustment of the Central Pamir to crustal thickening that was destabilized by deep lithospheric processes: Indian slab breakoff enhanced the gravitational potential energy stored in the thermally weakened crust of the Pamir Plateau and increased the basal heat flow; together with a weak foreland rheology, this resulted in extensional collapse of thick and high Plateau crust into the northern and western foreland depressions and in

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Proterozoic–Mesozoic history of the Central Asian orogenic belt in the Tajik and southwestern Kyrgyz Tian Shan: U-Pb, $^{40}Ar/^{39}Ar$, and fission-track geochronology and geochemistry of granitoids

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ABSTRACT

Multimethod geochronology (U-Pb zircon; $^{40}Ar/^{39}Ar$ hornblende, biotite, feldspar; apatite fission track) on granitoids, gneisses, and Cenozoic intramontane basin clastics of the Gissar-Alai ranges, South Tian Shan collisional belt, west of the Talas-Fergana fault, elucidates a history of Neoproterozoic magmatism, late Paleozoic magmatism and metamorphism, and Mesozoic–Cenozoic thermal reactivation. Zircon-core and grain-interior U-Pb ages of ca. 2.7–2.4, 2.2–1.7, 1.1–0.85, and 0.85–0.74 Ga tie the early evolution of the Gissar-Alai ranges to that of the Tarim craton. At least part of the Gissar range crystalline basement—the Garm massif—shows U-Pb zircon crystallization ages of ca. 661–552 Ma (median ca. 609 Ma), again suggesting a Tarim craton connection. Tarim collided with the Middle Tian Shan block at ca. 310–305 Ma, completing the protracted formation of the South Tian Shan collisional belt. The massive Gissar range granitoids intruded later (ca. 305–270 Ma), contemporaneous with peak Barrovian-type metamorphism in the Garm massif rocks. Major- and trace-element compositions suggest that the Gissar granitoid melts have continental arc affinity. Zircon ε_{Hf} and whole-rock ε_{Nd} values of –2.1 to –6.9 and –2.7 to –7.2, respectively. and Hf-isotope crustal model and Nd-isotope depleted mantle model ages of ca. 1.0–1.2 and ca. 1.1–2.2 Ga, respectively, suggest significant input of Precambrian crust in the Gissar granitoid and Garm orthogneiss melts, consistent with the U-Pb ages of inherited and detrital zircons. The distinct ca. 661–552 Ma Garm gneiss crystallization ages and the ca. 1.0–2.2 Ga model ages (and the lack of 2.4–3.4 Ga model ages) tie the Garm gneisses and the reworked crust of the Gissar range to the northern rim—the Kuqa and Kolar sections—of the Tarim craton, suggesting a united Karakum-Tarim craton. Although about contemporaneous with widespread postcollisional magmatism in the entire Tian Shan, the large volume and short duration of the Gissar range magmatism, including crustal thickening and prograde metamorphism during Tarim craton–Middle Tian Shan block collision, and formation and closure of an oceanic back-arc basin (the Gissar basin), indicate its origin in a distinct setting. Combined, this likely resulted in midcrustal melting and upper-crustal batholith emplacement. Mafic dikes and pipes intruded at ca. 256–238 Ma (median ca. 241 Ma); the source region of the parental melts was within the asthenospheric mantle. The simplest interpretation for these basanites is that they were part of the Tarim flood basalt province; this would extend this province westward from the Tarim craton into the southwestern Tian Shan and imply that the relatively short-lived flood basalt event (ca. 290–270 Ma) was followed by much less voluminous but longer-lasting hotspot magmatism. The $^{40}Ar/^{39}Ar$ and detrital apatite fission-track dates outline post–Gissar-Alai range granitoid emplacement cooling, Cimmerian collision events at the southern margin of Asia, Late Cretaceous crustal extension and local magmatism, and early Cenozoic shortening and burial in the far field of the India-Asia collision.

INTRODUCTION

The Tian Shan is part of Earth's largest accretionary orogen, the Central Asian orogenic belt (Figs. 1A and 1B). It consists of Precambrian to Paleozoic (micro)continents and magmatic arc complexes that amalgamated in the Paleozoic, following the closure of various basins of the Paleo–Asian Ocean (e.g., Şengör et al., 1993; Windley et al., 2007). Although subduction-accretion-collision were the primary processes that built the Central Asian orogenic belt, late- and postcollisional magmatism, folding-thrusting, wrenching, and related exhumation during the Cimmerian and India-Asia collisions reshaped the orogen (e.g., Buslov et al., 2007; Gao et al., 2009; Glorie et al., 2011). In particular, the Talas-Fergana strike-slip fault zone (Fig. 1A) displaced the initially continuous tectonic belts (e.g., Burtman et al., 1996; Solomovich, 2007). The widespread magmatic rocks provide—by their ages and geochemical characteristics—critical data for understanding the assembly of the Paleozoic Tian Shan orogen and the nature and composition of its preexisting crust.

Herein, we provide U-Pb zircon and $^{40}Ar/^{39}Ar$ (short Ar/Ar) amphibole, mica, and feldspar ages, and major- and trace-element, and Hf- and Nd-isotope geochemical data for granitoids, crystallization-pressure estimates for granitoids, Ar/Ar ages and geochemical data for basanite dikes and pipes, and detrital zircon U-Pb and apatite fission-track (AFT) ages for sandstones from Cenozoic intramontane basin strata of the southwestern Tian Shan, i.e., the Gissar-Alai ranges of Tajikistan and southwestern Kyrgyzstan (Figs. 1A and 2). To integrate our new results into the amalgamation history of the Tian Shan, we compiled and interpreted published U-Pb, K-Ar, and Ar/Ar data. Our data support interpretations that consider the Gissar-Alai ranges as the western continuation of the South Tian Shan collisional belt, i.e., the subduction-accretion complex between the Middle Tian Shan block and the Karakum-Tarim cratons (Figs. 1A and 2; herein, "block" describes a suture- or fault-bounded, often

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Möwe Bay Dykes, Northwestern Namibia: Geochemical and geochronological evidence for different mantle source regions during the Cretaceous opening of the South Atlantic

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ABSTRACT

Dyke emplacement in the course of Paraná-Etendeka volcanism in northwestern Namibia has been considered as a short-lived event related to a specific magma source at approximately 135–130 Ma. New geochemical, whole rock Sr-Nd-Pb isotope data and $^{40}Ar/^{39}Ar$ ages reveal that at least three geochemically and isotopically different tholeiitic dyke generations, with intrusion ages of 135.2 ± 0.7, 124.1 ± 0.8 Ma and 113.0 ± 0.5 Ma, can be distinguished in the Möwe Bay area, Skeleton Coast of northwestern Namibia. Distinct mantle source components were identified in the petrogenesis of the various dyke generations. Magma composition of the two older dyke suites, both of which were emplaced in a tectonic setting dominated by E-W extension, evolved from a within-plate to an enriched mid-ocean ridge basalt type. Contamination by continental crust and/or lithospheric mantel is suggested by a high $^{238}U/^{204}Pb$-value ($=\mu_2$) of 9.97, which is typical of the Kalahari Craton. The third dyke generation, which intruded in a tectonic regime dominated by SE-NW extension, corresponds to high-Ti ocean island-type basalt with unradiogenic isotopic compositions derived from a mantle source with a μ_2-value of 9.35. The formation of the older dykes is attributed to the presence of a thermal anomaly in the upper sublithospheric mantle. This anomaly was most likely caused by the peripheral part of a mantle plume that impinged at the base of the lithosphere and caused erosion of the subcontinental mantle lithosphere and melting above the plume head. The initial break-up of SW Gondwana and the formation of early oceanic crust were most likely due to passive rather than active rifting. Continued plume upwelling facilitated by progressive thinning of SW-Gondwana crust led to the formation of the younger, c. 113 Ma old dykes, which are chemically and isotopically identical to coeval rocks from the northeastern portion of the Walvis Ridge and thus are interpreted as onshore expressions of the Tristan-Gough plume head at that time. The difference in the dominant extension directions of the older and the younger dyke generations can be explained by rotation induced by the Aptian/Albian opening of the Equatorial Central Atlantic, accompanied by a substantial increase in the South Atlantic spreading rate.

1. Introduction

Continental flood basalt and associated intrusive rocks in the Paraná-Etendeka Large Igneous Province formed during Cretaceous rifting of Gondwana, break-up and subsequent opening of the South Atlantic (e.g., Erlank et al., 1984; Turner et al., 1994; Peate, 1997). The resulting passive margin that developed on the eastern side of the South Atlantic is divided by the aseismic Walvis Ridge (Fig. 1a) into a northern and southern segment with marked differences in magmatic, sedimentary and morphological features (e.g., Bolli et al., 1978; Gladczenko et al., 1998; Maystrenko et al., 2013; Koopmann et al., 2014). The Walvis Ridge extends to the continental margin of northwestern Namibia and is considered as the offshore continuation of the Paraná-Etendeka continental flood basalt province (e.g., O'Connor and Duncan, 1990; Renne et al., 1996). The Walvis Ridge has been the target of several drilling, dredging and mapping projects (e.g., Deep Sea Drilling Project Legs 40 and 74; Ocean Drilling Project Leg 208; Walvis Ridge Expedition MV1203; RV Sonne Cruise SO-233) and several geophysical surveys (e.g., Gladczenko et al., 1998; Maystrenko et al., 2013; Koopmann et al., 2014; Fromm et al., 2015). The geochemistry and isotopic composition of Walvis Ridge basalt were studied by various authors (e.g., Bolli et al., 1978; Richardson et al., 1982, 1984; Thompson and Humphris, 1984; O'Connor and Duncan, 1990; Salters and Sachi-Kocher, 2010; O'Connor et al., 2012) as was the timing of

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Late Carboniferous high-pressure metamorphism of the Kassan Metamorphic Complex (Kyrgyz Tianshan) and assembly of the SW Central Asian Orogenic Belt

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ABSTRACT

High-pressure (HP) metamorphism of the Kassan Metamorphic Complex (KMC) in the western Kyrgyz Tianshan has been related to either late Ordovician or late Carboniferous-Permian subduction processes. We report Sm-Nd ages for retrogressed eclogite samples and $^{40}Ar/^{39}Ar$ cooling ages for enclosing garnet-muscovite samples from the KMC as new age constraints on HP metamorphism and rock exhumation. These data will be used for an upgraded paleogeographic model for late Paleozoic crustal consolidation in the southwestern Central Asian Orogenic Belt. The retrogressed eclogite samples have transitional alkaline to tholeiitic affinity and trace-element patterns consistent with protoliths derived from garnet-bearing mantle sources at rifting plate margins. Geothermobarometric data for a retrogressed eclogite sample indicate peak-metamorphic conditions of 540 ± 30 °C at 1.6 ± 0.1 GPa. Samples from different lithotectonic units of the KMC provide coherent Sm-Nd garnet-whole rock ages of 317 ± 4 Ma and 316 ± 3 Ma (2σ). The prograde major-element zoning in the mm-sized garnets in combination with the moderate peak-metamorphic temperature, support our interpretation of the Sm-Nd garnet ages as unambiguous evidence for late Carboniferous HP metamorphism. The Sm-Nd garnet growth ages overlap within-error with the $^{40}Ar/^{39}Ar$ mica cooling ages of 314 ± 2 Ma and 313 ± 2 Ma (2σ) indicating rapid uplift of the subduction complex after peak metamorphism. The ca. 317-313 Ma HP-exhumation event of the KMC is contemporaneous with those of the Atbashi and Akeyazi (ca. 500 km east in NW China) HP complexes and implies similar collision histories at the South Tianshan Suture to the east and west of the Talas-Fergana Fault (TFF). The exhumation of the KMC and Atbashi HP complexes overlaps with the initiation of the TFF (Rolland et al., 2013) suggesting incipient separation of the Chatkal and Atbashi complexes during rock exhumation and early plate collision.

1. Introduction

The Kassan Metamorphic Complex (KMC) in the Chatkal Range of western Kyrgyzstan represents part of the late Carboniferous active plate margin of the southern Middle Tianshan Microcontinent (MTM) (Fig. 1). North directed subduction and collision of the Karakum-Alai Block with the MTM in the late Carboniferous resulted in nappe thrusting, oroclinal bending, and deformation of the magmatic arc. During the final stage of crustal consolidation in the southwestern Central Asian Orogenic Belt (CAOB), dextral offset of ca. 150-200 km along the Talas Fergana Fault (TFF) led to a northwesterly dislocation of the Chatkal Range and South Tianshan Suture zone from their continuations to the east (Fig. 1a).

The KMC comprises eclogite-facies metamorphic assemblages, representing exhumed parts of a former subduction zone, and its role in the assembly of the westernmost CAOB has been discussed controversially (e.g. Alexeiev et al., 2011, 2016; Bakirov et al., 2003; Loury et al., 2015a, 2015b). Furthermore, its geodynamic relationship with other HP complexes to the east of the TFF, in particular the Atbashi HP complex (Hegner et al., 2010; Simonov et al., 2008) has been debated due to uncertainties in the timing of HP metamorphism (see Alexeiev et al., 2016; Loury et al., 2015a). The latter authors have interpreted structural evidence and an apparent U-Pb age of 301 ± 15 Ma for allanite from a retrogressed eclogite sample of the KMC as evidence for a different geodynamic evolution in the Chatkal Range from regions

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Shear zone evolution and timing of deformation in the Neoproterozoic transpressional Dom Feliciano Belt, Uruguay

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New structural, microstructural and geochronological (U-Pb LA-ICP-MS, Ar/Ar, K-Ar, Rb-Sr) data were obtained for the Dom Feliciano Belt in Uruguay. The main phase of crustal shortening, metamorphism and associated exhumation is recorded between 630 and 600 Ma. This stage is related to the collision of the Río de la Plata and Congo cratons at ca. 630 Ma, which also involved crustal reworking of minor crustal blocks such as the Nico Pérez Terrane and voluminous post-collisional magmatism. Subsequent orogen-parallel sinistral shearing gave rise to further deformation up to ca. 584 Ma and resulted from the onset of the convergence of the Kalahari Craton and the Río de la Plata-Congo cratons. Sinistral shear zones underwent progressive strain localization and retrograde conditions of deformation during crustal exhumation. Dextral ENE-striking shear zones were subsequently active at ca. 550 Ma, coeval with further sinistral shearing along N- to NNE-striking shear zones. The tectonothermal evolution of the Dom Feliciano Belt thus recorded the collision of the Río de la Plata and Congo cratons, which comprised one of the first amalgamated nuclei of Gondwana, and the subsequent incorporation of the Kalahari Craton into Western Gondwana.

1. Introduction

Harland (1971) defined transpression as a combination of compression and transcurrence that results from oblique plate convergence at crustal scale. This term was then extended by Sanderson and Marchini (1984), who considered transpression as deformation developed between two undeformed blocks resulting from both simple and pure shear, independently of the scale. Subsequent contributions presented deviations from these first models and demonstrated the 3D complexity of transpressional orogens (Fossen et al., 1994; Fossen and Tikoff, 1998; Jones et al., 1997, 2004; Fernández and Díaz-Azpiroz, 2009; Fernández et al., 2013), especially when related to strain partitioning (Lister and Williams, 1983; Tikoff and Teyssier, 1994; Jones and Tanner, 1995; Teyssier et al., 1995). Although strain partitioning refers to heterogeneous spatial distribution of deformation, changes with time are also frequent (Lister and Williams, 1983), as in the case of shear zone nucleation due to strain localization (e.g., Hobbs et al., 1990; Platt and Behr, 2011).

The Dom Feliciano Belt represents a Neoproterozoic transpressional orogen that extends between eastern Uruguay and southeastern Brazil (Fragoso Cesar, 1991). During the Brasiliano–Pan-African Orogeny, the Dom Feliciano Belt was developed as a consequence of the closure of the Adamastor Ocean due to the amalgamation of African crustal blocks to the eastern margin of the Río de la Plata Craton (Basei et al., 2005, 2008; Chemale Jr. et al., 2012; Oyhantçabal et al., 2011a, 2011b; Rapela et al., 2011; Saalmann et al., 2011; Oriolo et al., 2016a). Due to similarities with the Kaoko and Gariep belts, the Dom Feliciano Belt was alternatively correlated with both African belts (e.g., Basei et al.,

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Petrogenesis and origin of modern Ethiopian rift basalts: Constraints from isotope and trace element geochemistry

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ABSTRACT

The source of continental rift-related basalts and their relation to rifting processes is a continuous matter of debate. We present major and trace element and Sr, Nd, Hf and Pb isotope data for axial rift basalts from eight volcanic centres (Ayelu, Hertali, Dofan, Fantale, Kone, Bosetti and Gedemsa, from NE to SW) in Afar and Main Ethiopian Rift (MER) to assess their source regions and their genetic relationships. These lavas have geochemical characteristics, i.e., a peak at Ba, Nb and troughs at K and Rb in primitive mantle-normalised multielement diagrams, which are consistent with predominant melting of an amphibole-bearing lithospheric mantle. However, the isotopic compositions for these lavas are heterogeneous ($^{87}Sr/^{86}Sr = 0.70354–0.70431$, $^{143}Nd/^{144}Nd = 0.51280–0.51294$, $^{176}Hf/^{177}Hf = 0.28301–0.28315$, $^{206}Pb/^{204}Pb = 18.48–19.31$, $^{207}Pb/^{204}Pb = 15.53–15.62$, $^{208}Pb/^{204}Pb = 38.61–39.06$) and require various mantle reservoirs with distinctive isotopic signatures. The range of isotopic compositions requires the involvement of three distinct source components from the asthenospheric and veined lithospheric mantle. Progressive rifting leads to lithosperic thinning and upwelling of hot asthenospheric mantle, which induces melting of the veined lithospheric mantle. The trace element characteristics of the lavas are dominated by the vein material, which has a higher trace element content than the surrounding mantle. The isotopic composition of the vein material, however, is not very different from the ambient mantle, giving rise of apparent uncoupling of trace element and isotope constraints for the melt source. The uprising basaltic liquids in part inherit a lithospheric trace element signature, while their isotopic compositions are mostly unaffected due to short residence times within the lithosphere in context with progressive rifting and lithospheric thinning. Thus, the geochemical and isotope data are consistent with a multi-component source prevailing beneath the Afar and MER areas in which the basalts are generated during progressive rifting and, thus, passive upwelling of a mantle source.

1. Introduction

The Main Ethiopian Rift (MER) constitutes a part of the East African Rift System (EARS) and merges with the oceanic Red Sea and Gulf of Aden rifts in a triple junction located in the Afar depression (Wolfenden et al., 2004). Rifting and volcanism in the MER has been considered to be related to mantle plume activity (e.g., Furman, 2007; Marty et al., 1996; Pik et al., 1999). The impinging Afar plume is assumed to have triggered flood basalt volcanism in the homonymous region ~30 Ma ago (Hofmann et al., 1997). There is no consensus on the number(s) of mantle plumes; some authors assume that recent eruptions in the Erta'Ale range in Afar are triggered by the Afar plume (Furman et al., 2006), while others argue that magmatism in southern Ethiopia is related to a Kenya mantle plume (Rogers et al., 2000) in agreement with the plate motion reconstructions from O'Connor et al. (1999) suggesting that the Afar plume is also presently impinging SW of its former location.

At present the MER is in an evolved stage of continental rifting, progressing towards continental breakup (e.g., Kurz et al., 2007; Wolfenden et al., 2004). A recent bimodal volcanic activity takes place exclusively in the axial portions of the rift and is, in most cases, confined to magmatic segments which are aligned en-echelon along the rift axis (Keranen et al., 2004; Kurz et al., 2007). The source of recent basaltic rocks in the MER and their possible interaction with the lithosphere remain controversial. Several authors suggested that at least two isotopically distinct mantle reservoirs contributed to the genesis of Quaternary basaltic lavas in the rift (e.g., Barberi et al., 1980; Hart

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- Multiple geochronometers were obtained for the Sarandí del Yí Shear Zone
- The Río de la Plata Craton and the Nico Pérez Terrane collided at 630–625 Ma
- Strain localization, magmatism, and fluids affect isotopic systems in mylonites

Supporting Information:

- Supporting Information S1
- Table S5

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Timing of deformation in the Sarandí del Yí Shear Zone, Uruguay: Implications for the amalgamation of western Gondwana during the Neoproterozoic Brasiliano-Pan-African Orogeny

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Abstract U-Pb and Hf zircon (sensitive high-resolution ion microprobe -SHRIMP- and laser ablation-inductively coupled plasma-mass spectrometry -LA-ICP-MS-), Ar/Ar hornblende and muscovite, and Rb-Sr whole rock-muscovite isochron data from the mylonites of the Sarandí del Yí Shear Zone, Uruguay, were obtained in order to assess the tectonothermal evolution of this crustal-scale structure. Integration of these results with available kinematic, structural, and microstructural data of the shear zone as well as with geochronological data from the adjacent blocks allowed to constrain the onset of deformation along the shear zone at 630–625 Ma during the collision of the Nico Pérez Terrane and the Río de la Plata Craton. The shear zone underwent dextral shearing up to 596 Ma under upper to middle amphibolite facies conditions, which was succeeded by sinistral shearing under lower amphibolite to upper greenschist facies conditions until at least 584 Ma. After emplacement of the Cerro Caperuza granite at 570 Ma, the shear zone underwent only cataclastic deformation between the late Ediacaran and the Cambrian. The Sarandí del Yí Shear Zone is thus related to the syncollisional to postcollisional evolution of the amalgamation of the Río de la Plata Craton and the Nico Pérez Terrane. Furthermore, the obtained data reveal that strain partitioning and localization with time, magmatism emplacement, and fluid circulation are key processes affecting the isotopic systems in mylonitic belts, revealing the complexity in assessing the age of deformation of long-lived shear zones.

1. Introduction

Exhumed long-lived shear zones represent fundamental structures that allow studying the coupling between crustal exhumation and strain localization processes as well as the timing at which they take place in the lithosphere. However, assessing the age of the deformation is not a simple task, due to the overprinting caused by the youngest events that may reset the isotopic systems that are used as thermochronometers. It is even more complex to integrate geochronological with macrostructural and microstructural data as well as kinematics in order to create a robust model of the tectonometamorphic evolution of the shear zones, which can further constrain the evolution at the orogen scale.

Several methods can be applied to study the temperature-time (*T-t*) paths of metamorphic rocks, which are based on closure temperatures of isotopic geochronometers (Table 1) [*Dodson*, 1973; *Villa*, 1998]. The most widespread methods to constrain the age of the deformation in shear zones consist in either dating synkinematic intrusions or minerals that were formed during mylonitization or constraining the *T-t* paths of adjacent blocks [*van der Pluijm et al.*, 1994]. All these methods, though potentially powerful, have some limitations. Dating synkinematic intrusions represents an indirect and interpretative method [*van der Pluijm et al.*, 1994], whereas dating minerals in the mylonites themselves may be limited by the problem of whether these ages represent neocrystallization or cooling ages [*Dunlap*, 1997; *Mulch and Cosca*, 2004]. On the other hand, establishing *T-t* paths of neighboring blocks may be helpful but nevertheless indirect and, in many cases, difficult to obtain due to the lack of equivalent datable mineral associations on both sides of the shear zones.

The Neoproterozoic Brasiliano-Pan-African Orogeny is ubiquitous in eastern South America and western Africa and represents a protracted amalgamation of major crustal blocks along several mobile belts, giving

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Key Points:
- Rapid Pliocene exhumation at syntaxis limited to temperatures of 300°C (~10 km)
- Applicability of cobbles for reconstruction of regional cooling histories
- Multidating of cobbles reveals cooling history of ice-covered rocks

Supporting Information:
- Text S1, Figures S1–S9, and Table S1
- Table S2
- Data Set S1
- Data Set S2

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Cooling history of the St. Elias syntaxis, southeast Alaska, revealed by geochronology and thermochronology of cobble-sized glacial detritus

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Abstract We investigate the spatiotemporal evolution of exhumation in the ice-covered St. Elias syntaxis area, southeast Alaska, using multiple thermochronometers and geochronometers from cobble-sized glacial detritus. Multiple thermochronometers reveal the cooling histories from 500 to 60°C of 27 glacially transported cobbles from the two largest catchments of the syntaxis. Cobble lithologies and 21 zircon U-Pb ages (~277–31 Ma) were examined to determine sample provenance. Furthermore, eight amphibole and seven biotite $^{40}Ar/^{39}Ar$ ages (~276–16 Ma and ~50–42 Ma, respectively), four zircon and six apatite (U-Th)/He ages (~35–4.8 Ma and ~4.2–0.6 Ma, respectively), and four apatite fission track ages (~17–1.6 Ma) were used to reconstruct the individual cobble cooling histories. An additional four bedrock samples from the Fairweather Range yielded three biotite $^{40}Ar/^{39}Ar$ ages between ~42 and 5 Ma. A compilation of published bedrock and new cobble cooling histories from the St. Elias Mountains and Fairweather Range reveals the regional Cenozoic cooling and exhumation history, emphasizing the position of the St. Elias syntaxis as a transitional zone between transpression and subduction settings. The new cobble and bedrock data indicate an onset of rapid exhumation at ~5 Ma that was limited in duration (2–3 Myr) and amount (~10 km) in the syntaxial region. This study also demonstrates the usefulness of cobbles for revealing thermal histories of otherwise inaccessible regions as cobble analysis combines advantages of bedrock and detrital thermochronology.

1. Introduction

Orogen syntaxes are sharp bends in orogenic belts [*Suess*, 1904]. Syntaxes constitute structurally complex zones that concentrate stresses and potentially influence far-field deformation [e.g., *Zeitler et al.*, 2001, 2014; *Mazzotti and Hyndman*, 2002; *Koons et al.*, 2010, 2013; *Bruhn et al.*, 2012]. Studying orogen syntaxes therefore improves the understanding of plate boundary deformation in these kinematic transition zones, which occur in variable geologic and climatic settings and exhibit variable deformational behavior [e.g., *Beaumont et al.*, 2001; *Zeitler et al.*, 2001; *Enkelmann et al.*, 2009; *Koons et al.*, 2013; *Bendick and Ehlers*, 2014]. A key component in the studies of syntaxes is the quantification of spatial and temporal variations in rock exhumation to both decipher the dynamics and relative contributions of different processes (climatic, erosional, and tectonic) to syntaxis formation and evaluate contending exhumation models [e.g., *Zeitler et al.*, 2001; *Enkelmann et al.*, 2009, 2015a; *Koons et al.*, 2010, 2013; *Bendick and Ehlers*, 2014].

One well-established location for studies of syntaxis deformation and exhumation is the glaciated St. Elias syntaxis in southeast Alaska and western Canada (Figure 1) [e.g., *Berger et al.*, 2008; *Enkelmann et al.*, 2009, 2015a; *Spotila and Berger*, 2010; *Chapman et al.*, 2012; *Falkowski et al.*, 2014]. Two different sampling strategies for thermochronology, namely, bedrock and detrital sampling, have previously been used to quantify the exhumation history of the St. Elias Mountains [e.g., *O'Sullivan et al.*, 1997; *Enkelmann et al.*, 2008, 2009, 2015a; *Berger et al.*, 2008; *McAleer et al.*, 2009; *Grabowski et al.*, 2013; *Falkowski et al.*, 2014]. Bedrock data suffer from a biased signal because those samples can only be taken in the foothills or at high-elevation, ice-free ridges, while the youngest rocks that record the most rapid exhumation are expected to occur at low elevations in the glaciated valleys [e.g., *Fitzgerald and Gleadow*, 1990]. Sand-sized detritus from rivers draining the glaciated valleys yields the cooling record from the entire catchment, including those parts above and below the ice [*Enkelmann and Ehlers*, 2015]. This sampling approach revealed the presence of very rapidly exhumed rocks in the syntaxis area through ≤5 Ma old zircon fission track (ZFT) ages [*Enkelmann et al.*, 2009, 2010; *Falkowski et al.*, 2014]. However, the inherent problem of using sand grains for dating is the decrease in spatial

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ORIGINAL PAPER

Geochemical composition, petrography and $^{40}Ar/^{39}Ar$ age of the Heldburg phonolite: implications on magma mixing and mingling

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Abstract Differentiated magmatic rocks such as trachyte and phonolite are volumetrically subordinate to mafic volcanic rocks within the Cenozoic Central European Volcanic Province (exceptions are the East Eifel and the Rhön volcanic fields). Within the volcanic field of the "Heldburg dike swarm" (Heldburger Gangschar), the phonolite of the Burgberg near Heldburg represents the only known occurrence of differentiated magmatic rocks. However, the Heldburg phonolite is famous foremost for containing mantle xenoliths (spinel lherzolite). Former studies proposing a cogenetic relationship between the phonolite and the peridotites concluded that the phonolite magma must have evolved under upper mantle conditions. Herewith, we present petrographic and geochemical evidence for magma mixing and mingling in the Heldburg phonolite melt due to the intrusion of mantle-derived basanitic magma, which is exposed today as dikes at the foot of the Heldburg Burgberg. During this process, the mantle xenoliths were introduced into the phonolite melt as they all contain rims of basanitic magma. Extensive mingling features (e.g., schlieren layers, load casts, flame structures, mafic enclaves) are developed, indicating that the basanite and the zoned phonolitic body were melts at the time of mixing. These petrographic and geochemical indications of two coeval melts of different composition are substantiated by $^{40}Ar/^{39}Ar$ dating, revealing identical ages of ca. 15 Ma.

Keywords Central European Volcanic Province · Heldburg phonolite · $^{40}Ar/^{39}Ar$ dating · Whole rock and mineral geochemistry · Magma mixing and mingling

Introduction

In magmatically active regions with bimodal magmatism (mafic/primitive vs. felsic/evolved), many examples of magma mixing can be found, which may lead to intermediate magma compositions (e.g., Browne et al. 2006; Emeleus and Bell 2005). Incomplete partial magma mixing, so-called mingling, with dark mafic magma enclaves within light-colored, differentiated magma is particularly spectacular and is described at several plutonic bodies worldwide (e.g., Blake et al. 1965; Wiebe 1994; Sheppard 1996; Di Vincenzo and Rocchi 1999; Baxter and Feely 2002; Wiebe et al. 2001; Sklyarov and Fedorovskii 2006). Since it has been accepted that many plutonic bodies represent fossilized magma chambers and mingling features thus display the initial stages of the invasion of mafic magma into a felsic magma chamber, the importance of replenishment processes for the evolution of differentiated magma has been studied intensely (e.g., Sparks and Marshall 1986; Poli et al. 1996; Folch and Marti 1998; Snyder and Tait 1998; Jellinek and Kerr 1999). The efficiency of magma interaction depends on several physical and geometrical parameters (e.g., viscosity contrasts, temperature difference, flow velocity, forced convection, flow in conduits) acting to disperse the mafic magma in the

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Petrogenesis of Tertiary continental intra-plate lavas between Siebengebirge and Westerwald, Germany: Constraints from trace element systematics and Nd, Sr and Pb isotopes

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A B S T R A C T

New $^{39}Ar/^{40}Ar$ ages and major- and trace-element and radiogenic isotope data are presented for basanites and alkali basalts from the transition area between the Westerwald and Siebengebirge volcanic fields (Germany) that belongs to the Central European Volcanic Province (CEVP). The $^{39}Ar/^{40}Ar$ ages indicate ages of c. 24 and c. 5 Ma which are fully compatible with previous K/Ar ages indicating that the evolution of this volcanic field belongs to the Westerwald area (28–22 Ma and 5 Ma) rather than to the Siebengebirge area (26–23 Ma). Based on the occurrence of >30 isolated volcanic plugs with a simple igneous history, this volcanic field can be viewed as a monogenetic volcanic field. Compositions of some basanites are primitive, whereas others and the alkali basalts show decreasing Cr and Ni contents and CaO/Al_2O_3 ratios. However, increasing TiO_2, Al_2O_3 and incompatible elements (Sr, Zr, Y, Hf, Ta) concentrations with decreasing MgO indicating fractionation of mainly olivine with minor amounts of clinopyroxene and spinel can be noticed. Rare earth element systematics suggest that most of the alkaline rocks are generated by different degrees of melting (5%–10%) of a garnet-bearing peridotite containing some residual amphibole. Negative anomalies of Rb and K in primitive mantle-normalized diagrams and a lack of Ba/Rb fractionation suggest that amphibole was the major OH-bearing mineral phase in the mantle. The alkaline rocks have a restricted range in $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios ranging from 0.7033 to 0.7044 and from 0.51275 to 0.51285, respectively. Lead isotope compositions ($^{206}Pb/^{204}Pb$: 19.21–19.65; $^{207}Pb/^{204}Pb$: 15.62–15.67; $^{208}Pb/^{204}Pb$: 39.10–39.46) of the alkaline rocks are within the range of most OIB in which the higher values approach the composition of the European Asthenospheric Reservoir (EAR). The correlation between Sr and Nd isotopes and trace element constraints (Ce/Pb; Nb/U) indicates that for some samples interaction with crustal rocks during fractionation has occurred. Miocene intraplate basaltic volcanism in the area probably occurred as a result of minor “baby plume” activity. Each volcanic plug records evidence of a specific stage of fractionation with or without assimilation; however, in summary the lavas plot on a single fractionation path. This implies that during evolution of the volcanic field initial melting took place in the asthenosphere or at the lithosphere–asthenosphere interface. The melts moved through the lithospheric mantle and stagnated at crustal levels, however the observed fractionation paths suggest that they were fed from a single reservoir. This model, which involves small-scale plume impact followed by asthenosphere–lithosphere interaction together with minor crustal contamination, should also be applicable to other intra-continental rift-related areas.

Introduction

Despite intense investigation the origin and evolution of rift related intra-plate alkaline basalts are still a matter of debate. This type of volcanism produced relatively small volumes of volcanic rocks over short time periods. The magma forming processes and the nature of the mantle sources differ from one volcanic field to the other and are not really fully examined until now. In Central Europe the Neogene rift system, caused by the alpine orogeny is associated with the Tertiary and Quaternary volcanism of the Central European volcanic province (CEVP). Most Na-dominated primitive alkaline volcanic rocks from the CEVP are geochemically similar to most OIBs (Allègre et al., 1981; Fitton and Dunlop, 1985; Thompson and Morrison, 1988 among many others). Based on the geochemical composition of the alkaline lavas in the CEVP, several highly debated models have been developed that try to explain the evolution of the various volcanic fields. After Ritter et al.

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^{40}Ar–^{39}Ar age constraint on deformation and brittle–ductile transition of the Main Central Thrust and the South Tibetan Detachment zone from Dhauliganga valley, Garhwal Himalaya, India

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ABSTRACT

^{40}Ar–^{39}Ar data from two sets of mylonitic two-mica granites present in the Main Central Thrust (MCT) and one leucogranite from the South Tibetan Detachment (STD) of Dhauliganga valley, Garhwal Himalaya are presented. The MCT and the STD bound the High Himalayan Crystallines (HHC) and are believed to facilitate its extrusion. Field evidence of ductile deformation in the form of tight isoclinal folding and brittle deformation in the form of back thrusts and transverse fractures are observed. The STD zone shows evidence of pervasive migration of leucogranitic melt through north dipping extensional shear zones. The ~19.5 Ma old Malari Leucogranite, present adjacent to the STD zone, experienced ductile and brittle deformation related to the tectonics of the STD. Muscovite analysis from the Malari leucogranite gives a cooling age of ~15.2 Ma suggesting that ductile deformation in the STD zone may have ceased by ~15 Ma. ^{40}Ar–^{39}Ar chronology of biotite from two mylonitic granites of the MCT yields cooling ages of 10.8 Ma and 9.7 Ma, which we correlate with activity of the MCT at ~10 Ma that caused rapid exhumation of the HHC. ^{40}Ar–^{39}Ar ages of 6.4 Ma and 6.2 Ma from white mica represent newly crystallized white mica post-dating biotite cooling and indicate late stage deformation. It is inferred that, as the HHC wedge started to exhume and erode rapidly along the MCT zone at ~10 Ma, the taper angle of the Himalayan wedge decreased to a 'sub-critical' stage. To regain the critical taper angle, the wedge underwent internal deformation in the form of back thrusts and duplex structures. Comparison of our data with earlier results from other sections of the MCT helps us envisage that the ~6 Ma white mica ages can be correlated with this internal deformation event and also with the transition of deformation regime in the MCT zone from ductile to brittle.

1. Introduction

The continued collision between India and Eurasia and northward underthrusting of the Indian plate beneath the Tibetan plateau is the primary driving force for the creation of the Himalayan mountain belt (Dewey and Bird, 1970; McKenzie and Sclater, 1971). One of the major tectonic features of the Himalaya is the north dipping intra-continental thrust known as the Main Central Thrust (MCT), which separates the Paleozoic ortho- and pelitic gneisses of the High Himalayan Crystallines (HHC) above and the Proterozoic metasediments, gneisses and metabasics of the Lesser Himalayan sequence (LHS) below (Heim and Gansser, 1939; Gansser, 1964; Le fort, 1996) (Fig. 1). In the Garhwal Himalaya, the MCT zone is further divided into two thrust systems called the Munsiari Thrust (MCT-I) and, at a higher structural level, the Vaikrita Thrust (MCT-II). Based on ^{40}Ar–^{39}Ar hornblende ages of amphibolite-grade rocks and also U–Pb ages of leucogranites that cut across the MCT, e.g. in the Annapurna region of Central Nepal (Hodges et al., 1996), it is inferred that the MCT is at least 20–23 Ma old (Hubbard and Harrison, 1989; Hodges et al., 1992, 1996; Parrish and Hodges, 1996; Coleman, 1998; Godin et al., 2001). The southern part of the MCT, beneath the Vaikrita Thrust, gives much younger ages of 5–3 Ma, as obtained by Th–Pb ages of monazite from synkinematic garnet (c.f. Yin, 2006; Harrison et al., 1997, 1998; Catlos et al., 2001, 2002) and ^{40}Ar–^{39}Ar muscovite ages (Macfarlane, 1993). The age of the MCT in the Bhagirathi valley of the Garhwal Himalaya is constrained to be 22–14 Ma by K–Ar cooling ages of muscovite in the HHC (Metcalfe, 1993). Th–Pb ion-microprobe dating of monazites (Catlos et al., 2002) suggests that thrusting was active between 6 and 2 Ma within the MCT zone below the Vaikrita

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- Metallic fluence monitors can partly replace geological age standards
- Rotating irradiation may not equilibrate radial fast-neutron fluence gradients

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Radial fast-neutron fluence gradients during rotating $^{40}Ar/^{39}Ar$ sample irradiation recorded with metallic fluence monitors and geological age standards

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Abstract Characterizing the neutron-irradiation parameter J is one of the major uncertainties in $^{40}Ar/^{39}Ar$ dating. The associated uncertainty of the individual J-value for a sample of unknown age depends on the accuracy of the age of the geological standards, the fast-neutron fluence distribution in the reactor, and the distances between standards and samples during irradiation. While it is generally assumed that rotating irradiation evens out radial neutron fluence gradients, we observed axial and radial variations of the J-values in sample irradiations in the rotating channels of two reactors. To quantify them, we included three-dimensionally distributed metallic fast (Ni) and thermal- (Co) neutron fluence monitors in three irradiations and geological age standards in three more. Two irradiations were carried out under Cd shielding in the FRG1 reactor in Geesthacht, Germany, and four without Cd shielding in the LVR-15 reactor in Řež, Czech Republic. The $^{58}Ni(n_f,p)^{58}Co$ activation reaction and γ-spectrometry of the 811 keV peak associated with the subsequent decay of ^{58}Co to ^{58}Fe allow one to calculate the fast-neutron fluence. The fast-neutron fluences at known positions in the irradiation container correlate with the J-values determined by mass-spectrometric $^{40}Ar/^{39}Ar$ measurements of the geological age standards. Radial neutron fluence gradients are up to 1.8 %/cm in FRG1 and up to 2.2 %/cm in LVR-15; the corresponding axial gradients are up to 5.9 and 2.1 %/cm. We conclude that sample rotation might not always suffice to meet the needs of high-precision dating and gradient monitoring can be crucial.

1. Introduction

The $^{40}Ar/^{39}Ar$ dating method has several advantages over the traditional $^{40}K/^{40}Ar$ method in geosciences. The parent and daughter isotopes are measured through the same element on the same aliquot in one mass spectrometer, increasing the analytical accuracy and allowing spot measurements using laser ablation. The thermal histories of the samples can be inferred from step-heating experiments that also provide internal consistency checks. The disadvantage is the need for fast-neutron irradiation to activate the $^{39}K(n_f,p)^{39}Ar$ reaction, after which ^{39}Ar serves as a proxy for the ^{40}K-content. Co-irradiated geological age standards are used to monitor the reaction rate. Several studies addressed the absolute and cross calibration of geological age standards and invested considerable effort in improving the precision of their reference ages [e.g., *Roddick*, 1983; *Baksi et al.*, 1995; *Renne et al.*, 1998; *Kuiper et al.*, 2008; *Renne et al.*, 2010, 2011; *Boehnke and Harrison*, 2014]. The irradiation also has undesirable nuclear effects. Recoil losses of ^{39}Ar after proton emission require additional analytical effort or correction, in particular for fine-grained samples [e.g., *Smith et al.*, 1993; *Onstott et al.*, 1995]. The production of interfering Ar isotopes from K, Ca, and Cl has to be minimized and corrected for [e.g., *Turner*, 1995; *Renne et al.*, 2005]. Recent improvements in the precision of the $^{40}Ar/^{39}Ar$ geochronometer are due to the refinement of the decay constants [*Renne et al.*, 2010, 2011] and the improved mass-spectrometric instrumentation [e.g., *Phillips and Matchan*, 2013].

Neutron fluences (ϕ; i.e., time integrated neutron fluxes, φ) in nuclear reactors are not homogeneous [e.g., *Dalrymple et al.*, 1981; *Renne et al.*, 2009]. Therefore, samples and geological age standards receive different neutron fluences. For irradiation facilities without sample rotation, this is accounted for by a three-dimensional distribution of the geological age standards and interpolation of determined J-values [e.g., *Morgan et al.*, 2013]. For rotating irradiation facilities, it is assumed that the rotation eliminates radial neutron

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Testing the influence of high-voltage mineral liberation on grain size, shape and yield, and on fission track and $^{40}Ar/^{39}Ar$ dating

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ABSTRACT

Mineral liberation and separation are fundamental for modern thermochronology. The fragmentation of rocks by high-voltage electrical pulses, called electrical fragmentation, is a new technology, only available since the development of a lab-sized machine a few years ago. The proposed advantages (e.g. disintegration along grain boundaries) compete with suspected negative effects of the locally occurring high temperatures (up to 10^4 K) on the physical properties of the liberated minerals. Comparison of electrical fragmentation with conventional mechanical fragmentation (jaw crusher) revealed similar amounts of liberated apatite and zircon from the same quantity of granite, but 45% production of fines (<80 μm) for mechanical fragmentation versus 5% for electrical fragmentation. Electrical fragmentation yielded larger-sized apatite grains (180–250 μm) compared to 80–125 μm for mechanical liberation, but no differences in shape factors (elongation, roundness, compactness). The liberation of idiomorphic crystals from coarse-grained rocks is ameliorated by the new method, as shown by the liberation of mm-sized idiomorphic biotite crystals from granite. Degassing curves of ^{40}Ar from electrically and mechanically liberated biotites from the same sample are nearly identical (maximum difference: six percentage points); $^{40}Ar/^{39}Ar$ ages of biotites from three samples (two mechanically, one electrically fragmented) from the same intrusion are identical within 2σ error. Length measurements of apatite fission tracks gave identical results within 2σ error regardless of fragmentation method used. In summary, the positive aspects of electrical fragmentation have been confirmed in this study, while effects negative for thermochronology are not observed.

1. Introduction

High-voltage electrical pulses can be used for the fragmentation of rocks. This technique has been studied since the 1960s, but only in 2007, a commercial lab-size machine was developed by SELFRAG AG. A potential advantage of this electrical method is that the minerals are disaggregated along grain boundaries. In consequence, resulting grain-size distribution should reflect crystal-size distribution of the specimen, broken grains should be less frequent, losses through abrasion should be minimised and grain aggregates should be concentrated in larger grain-size fractions, as compared to mechanical fragmentation. These factors should affect overall yield, size and shape of minerals liberated, for example, for radiometric dating. Although these effects seem advantageous, there is, on the other hand, a fear that temperature during electrical discharges could affect sensitive radiometric dating systems leading to Ar or He loss or annealing of fission tracks.

In this study, we present results of a comparison between mechanical fragmentation using a jaw crusher and electrical fragmentation using the SELFRAG lab, and we critically review some of the advantages of the latter method claimed by the manufacturer. We concentrated on the liberation of apatite and biotite used in thermochronology, and tested possible influences of high temperatures (up to 10^4 K) occurring during electrical fragmentation.

2. Rock fragmentation using high-voltage pulses

2.1. Historical overview

High-voltage short-duration electrical pulses can be used in two ways for crushing rocks: (1) by generating shock waves in water surrounding the sample (electrohydraulic fragmentation), and (2) by transferring pulse energy directly into the sample (electrical fragmentation; Fig. 1). For the latter different terms have been used in literature, most frequently *electrodynamic* or *electrical* fragmentation. In physics, *electrodynamics* is the branch studying the interaction between *moving* electrical charges and currents (electromagnetism), while electrical discharges are an *electrostatic* phenomenon. Therefore, *electrical fragmentation* seems to be more appropriate.

The electrohydraulic fragmentation method was first studied in Russia (Yutkin, 1955), later also in Europe and the USA (Bergstrom, 1961; Maroudas, 1967; Carley, 1968). The development of the electrical fragmentation method started in the 1960, again first in Russia (Maurer, 1968), and later in Europe (Andres, 1977) and the USA (Touryan et al.,

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New insights into the accretion of the Arabian-Nubian Shield: Depositional setting, composition and geochronology of a Mid-Cryogenian arc succession (North Eastern Desert, Egypt)

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ABSTRACT

The accretionary phase of the northern Arabian-Nubian Shield (ANS) is poorly constrained. For the first time, this study combines facies analysis, geochemistry, LA-ICP-MS U–Pb zircon geochronology and biotite and hornblende $^{40}Ar/^{39}Ar$ geochronology on a Mid-Cryogenian volcano-sedimentary succession situated in the North Eastern Desert (NED). The c. 550 m thick Wadi Malaak succession (WMS) nonconformably overlies c. 750 Ma granitoids and is, in turn, overlain by c. 617 Ma Dokhan Volcanics and Hammamat Group sediments on an angular unconformity. Facies evolution of the WMS switched from an alluvial plain receiving medial to distal felsic ignimbrite sheets to a lacustrine system with mafic phreatomagmatic activity, and then developed back to a subaerial environment with bimodal volcanism. Facies analysis suggests humid paleoclimatic conditions; (peri-)glacial features have not been detected. Reconnaissance geochemistry of WMS samples indicates a compositional range of volcanic and volcaniclastic rocks from basalt to rhyolite with calc-alkaline affinities. Incompatible trace element and REE patterns indicate formation in a subduction setting. Selected tectonic classification diagrams suggest a continental arc setting. U–Pb LA-ICP-MS analyses on zircon extracted from two felsic ignimbrites resulted in ages of 725 ± 7 Ma and 717 ± 8 Ma, constraining formation of the WMS to the Mid-Cryogenian. Hornblende and biotite separated from a subvolcanic gabbro that obviously had intruded the WMS yielded $^{40}Ar/^{39}Ar$ cooling ages of 747 ± 10 Ma and 743 ± 10 Ma, respectively. These $^{40}Ar/^{39}Ar$ ages are thus in conflict with the U–Pb crystallization ages. This is explained by the presence of excess Ar in biotite and hornblende. The new data presented here indicate that the WMS developed during the waning phase of Mid-Cryogenian ANS accretion, prior to the onset of Sturtian glaciation. It is the first known record of c. 720 Ma arc volcanism in the northernmost ANS.

1. Introduction

The Neoproterozoic was an important growth phase of continental crust (Stern, 2008); a period which is well exposed in the Arabian-Nubian Shield (ANS, Fig. 1). The formation of the shield followed initial rifting and break-up of Rodinia (870–800 Ma) with the final closure of the Mozambique Ocean and collision between east and west Gondwana fragments occurring 650–600 Ma ago (Jacobs and Thomas, 2004). Production of juvenile crust in the ANS mainly occurred in the Mid-Cryogenian from 800 to 690 Ma (Stern, 1994; Stern and Johnson, 2010). However, studies on respective supracrustal rocks in Egypt (referred to as ‘Metavolcanics’ including associated metasediments) and Saudi Arabia are scarce.

El-Ramly (1972) was among the first to describe metavolcanic rocks in the southern part of the Egyptian Eastern Desert (South Eastern Desert, SED, Stern and Hedge, 1985). For metavolcanic rocks in the Central Eastern Desert (CED) Stern (1981) introduced a subdivision based on stratigraphic position and composition into “Older Metavolcanics” (OMV) representing an oceanic crust association and non-ophiolitic arc-related “Younger Metavolcanics” (YMV). There is currently no subdivision for Cryogenian metavolcanics in the Northern Eastern Desert (NED).

The subdivision of metavolcanic rocks into OMV and YMV is widely used for the whole Eastern Desert, although recent studies suggest that this practice is questionable. For instance, Ali et al. (2009) and Andresen et al. (2009) indicated that OMV and YMV

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Clockwise rotation of the Baoshan Block due to southeastward tectonic escape of Tibetan crust since the Oligocene

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SUMMARY

Understanding the mode of deformation around the Eastern Himalayan Syntaxis (EHS) is crucial for models of Tibetan Plateau evolution. To constrain rotations and translation east of the EHS, we present new palaeomagnetic data from meta-basalt layers—possibly sills—of the Baoshan Block in western Yunnan, southeastern Tibet Plateau; the meta-basalts were either emplaced or metamorphosed to greenschist facies at ∼30 Ma (^{40}Ar–^{39}Ar whole rock ages). A detailed rock magnetic study—in combination with reflected and transmitted light microscopy—identifies magnetite and Ti-rich titanomagnetite as the main magnetic carriers. Using alternating field demagnetization, we separated well-clustered characteristic remanent magnetizations. A fold test indicates a syn-folding remanence acquisition, supporting an Oligocene magnetization due to evidence for regional Eocene–Oligocene shortening. The tilt corrected overall site mean direction at 30 per cent of unfolding yields declination/inclination = 042.2°/47.0°, corresponding to a clockwise rotation of 35.1° ± 12.7° with respect to stable Eurasia. This denotes an average rotation rate of 1.17 ± 0.42° Myr^{-1} since ∼30 Ma, ranging at the lower limit of the present-day, GPS-derived rotation rates. We explain the clockwise rotation by tectonic escape of the Baoshan and the Lanping-Simao blocks along the Ailao Shan shear zone. With the onset of shearing along the Chong Shan and Gaoligong Shan shear zones, the Baoshan Block continued its southeastward escape, decoupled from the Lanping-Simao Block between these two major shear zones. Crustal flow could explain rotation and southward escape after ∼20 Ma.

Key words: Palaeomagnetism applied to tectonics; Rock and mineral magnetism; Thermochronology; Asia.

1 INTRODUCTION

The collision of India and Eurasia at ∼50 Ma (Klootwijk *et al.* 1992; Leech *et al.* 2005; Najman *et al.* 2010) and the ongoing convergence of the continental plates resulted in the formation of the Tibetan Plateau and the Himalayan mountain range, and caused significant shortening and strike-slip faulting in Southeastern Asia (Fig. 1). Tracing movements of Tibetan crust around the Eastern Himalayan Syntaxis (EHS) is a key issue to understand the geodynamic processes after the India–Eurasia collision. In the last decades, several models have been proposed based on field studies, analogue-material laboratory experiments and numerical thermomechanic modelling (e.g. Tapponnier *et al.* 1982; England & Houseman 1986; Peltzer & Tapponnier 1988; Beaumont *et al.* 2004). Two end-member models are widely considered, that is, the classic 'tectonic escape' model (Molnar & Tapponnier 1975; Tapponnier *et al.* 1982) and the 'crustal flow' model (e.g. Royden *et al.* 1997; Clark & Royden 2000). GPS data show a wide area of clockwise rotations around the EHS and southward surface motion in Yunnan (Fig. 1; Wang *et al.* 2001; Zhang *et al.* 2004; Gan *et al.* 2007; Sol *et al.* 2007; Banerjee *et al.* 2008; Maurin *et al.* 2010). Several major deformation zones, mainly the Gaoligong Shan (GSSZ), the Chong Shan (CSSZ) and the Ailao Shan Red–River (ASSZ) shear zones, accommodated the southeastward displacement of crust in this area (Fig. 1; e.g. Leloup *et al.* 1995; Akciz *et al.* 2008; Lin *et al.* 2009).

Several palaeomagnetic studies have been carried out in the last decades in Southeastern Asia; they indicate clockwise rotation of blocks in the wide area east of the EHS (e.g. Funahara *et al.* 1992, 1993; Chen *et al.* 1995; Sato *et al.* 2001, 2007; Tanaka *et al.* 2008;

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Neogene to Quaternary ash deposits in the Coastal Cordillera in northern Chile: Distal ashes from supereruptions in the Central Andes

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ABSTRACT

Silicic volcanic ash deposits investigated at 14 localities between 22° and 25°S in the Chilean Coastal Cordillera are found to be the distal ash fall from supereruptions in the Central Andean cordillera several hundreds of kilometers to the east. Depositional textures, modal composition and granulometry of the ashes and tuffs (the latter lithified by halite and gypsum under ultra-arid conditions) allow for a distinction between primary fallout/aeolian deposits (mean 4–5 Φ, sorting 1.5–2 Φ) and secondary deposits that formed by down wash from hill slopes during local rain fall. Primary volcanic components comprise two types of glass shards (with small stretched vesicles and coarse-walled with rounded to elliptic vesicles), and biotite. Previously published studies on ash deposits in the north Chilean Coastal Cordillera reported 14 $^{40}Ar/^{39}Ar$ and K/Ar ages on biotite or sanidine ranging between 6.66 ± 0.13 and 0.6 ± 0.4 Ma. In this project, three $^{40}Ar/^{39}Ar$ ages on biotite have been determined for samples from the Cuenca del Tiburón, the northern margin of Salar de Navidad and from the Quebrada de la Chimba (3.9 ± 0.1 Ma, 4.1 ± 0.1 Ma, 6.0 ± 0.1 Ma, respectively). The range of the 17 ages coincides with the Late Miocene to Quaternary ages of the major ignimbrite-forming eruptions of the high Andes to the east such as the Altiplano Puna Volcanic Complex (APVC).
Electron microprobe data of glass and biotite of the Coastal Cordillera ashes have been compared with data from major ignimbrites of the APVC, of other major Central Andean volcanic fields, and of marine ashes (ODP Leg 201). Additional new biotite microprobe data from three APVC ignimbrites (Pastos Grandes, Pujsa and Guacha) have been included in the present study. Biotite composition of the investigated Coastal Cordillera ashes is similar to those of ignimbrites from the APVC. In particular, based in Fe, Mg, Mn and Ti, distal equivalents of the 3.96 ± 0.08 Ma Atana and/or 4.09 ± 0.02 Ma Puripicar and of the 5.6 ± 0.2 Ma Pujsa and/or the 5.56 ± 0.01 Ma Guacha eruptions can be identified. In addition, based only on age relations, distal ash units of the Pastos Grandes, Tatio and Purico eruptions may be present in the Coastal Cordillera. Composition of glass is comparable to APVC ignimbrite matrix glass and to marine glass, however, significant alkali depletion and SiO_2 enrichment is attributed to in situ alteration.
The identification of these ashes demonstrates for the first time that the supereruptions in the southern Central Andes gave rise to voluminous ash clouds, most likely co-ignimbrite. The present outcrops represent ash dispersed by easterly winds, consistent with atmospheric models that show favorable westward-directed winds existing in the upper troposphere/stratosphere during the southern summer in the southern Central Andes. This requires that current volume estimates for the major eruptions to be considered minima with a significant augmentation likely.

1. Introduction

The Neogene evolution of the Central Andes was dominated by an ignimbrite flare-up that is expressed as the Neogene Ignimbrite Province of the Central Andes (de Silva et al., 2006). The Late Miocene to late Quaternary volcanic stratigraphy is dominated by regionally extensive ignimbrites (ash-flow tuffs), the products of supereruptions, that cover several thousand square kilometers and represent erupted magma volumes of several hundreds to two thousand km^3 each (Sparks et al., 1985; de Silva, 1989a; de Silva and Francis, 1989; Ort, 1993; Lindsay et al., 2001a; Soler et al., 2007; Folkes et al., 2011; Salisbury et al., 2011; Ort et al., 2013). This platform of ignimbrite forms the base upon which the volcanoes of the modern volcanic arc are built. The ignimbrites were deposited by ground-hugging pyroclastic density currents (pyroclastic flows). Commonly, ignimbrites are associated with distal accumulations of crystal-depleted ash that originate from the eruption column or from ash clouds associated with

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Eclogitization of transient crust of the Aktyuz Complex during Late Palaeozoic plate collisions in the Northern Tianshan of Kyrgyzstan

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ABSTRACT

The Aktyuz Metamorphic Complex in the western Tianshan Mountains of Kyrgyzstan comprises high-pressure (HP) granitic gneisses and metasediments hosting mafic HP lithologies including eclogite. Geological relationships and geochemical-isotopic data of the different rock types of the Aktyuz Complex have been interpreted as a continental crustal fragment and the mafic rocks as former dykes. This study combines Sm–Nd and $^{40}Ar/^{39}Ar$ mineral ages, and P–T pseudosection modelling for a single retrogressed eclogite sample in order to shed light on the P–T–t evolution of the mafic HP rocks. The eclogite experienced a clockwise prograde P–T path with peak metamorphic conditions of ca. 2.1 GPa at ca. 670 °C, corresponding to a burial depth of ca. 70 km. The post-peak metamorphic P–T conditions suggest isothermal decompression and moderate initial uplift of the eclogite to ca. 40 km depth. A Sm–Nd isochron age of 462 ± 7 Ma for garnet, omphacite, and whole-rock is interpreted as time of cooling and retrogression of the eclogite sample below 650 to 600 °C at pressures <1 GPa. We suggest that the HP rocks of the Aktyuz Complex represent deeply subducted continental crust of one of the Palaeo-Kazakhstan terranes. During exhumation of the metasediments (now paragneiss), the mafic rocks were juxtaposed at variable depth and at low temperature (<400 °C, and in the case of the reported sample after ca. 462 Ma) with the more buoyant paragneisses in the subduction channel. This channel flow exhumation model can account for the different high-temperature petrological and geochronological histories of paragneiss and eclogite.

1. Introduction

The Tianshan Orogen extends over ca. 2500 km from Uzbekistan, via Tajikistan, Kyrgyzstan and Kazakhstan to northwestern China broadly east to west along the margin of the Altaids or Central Asian Orogenic Belt (CAOB) (Zonenshain et al., 1990; Sengör et al., 1993; Jahn et al., 2000a; Xiao et al., 2009; Fig. 1a). The geological-tectonic evolution of the CAOB is characterized by lateral accretion of young arc complexes and old micro-continents and their underplating with mantle-derived magmas (Jahn et al., 2000a,b; Chen and Jahn, 2004; Kröner et al., 2007; Windley et al., 2007; Kröner et al., 2008; Long et al., 2011). The Tianshan Orogen in Kyrgyzstan has been subdivided into the 'Northern Tianshan', 'Middle Tianshan' and 'Southern Tianshan' (Fig. 1b; Khain, 1985; Zonenshain et al., 1990; Volkova and Budanov, 1999; Bazhenov et al., 2003). Blueschists and eclogites, which are critical for elucidating the tectono-metamorphic framework of the Tianshan orogenic belt and thus the CAOB, occur in the Northern and Southern Tianshan (Tagiri et al., 1995; Bakirov et al., 1987, 1998, 2003; Simonov et al., 2008; Orozbaev et al., 2010). Late Palaeozoic peak metamorphism of eclogites and blueschists, which are considered to represent formerly subducted oceanic crust, is well constrained by several detailed geochronological studies in the Southern Tianshan of Kyrgyzstan and northern China (e.g., Gao and Klemd, 2003; Stupakov et al., 2004; Klemd et al., 2005; Simonov et al., 2008; Hegner et al., 2010; Klemd et al., 2011). High-pressure (HP) and ultrahigh-pressure (UHP) rocks are intimately interlayered on a metre scale (e.g., Lü et al., 2009), which has been interpreted as due to juxtaposition during plate subduction and exhumation in the subduction channel (Klemd et al., 2011). Recently published ages for the Late Paleozoic HP rocks suggest a Carboniferous age for the peak of metamorphism. The geological framework has been established with a Lu–Hf isochron age of ca. 315 Ma (omphacite–garnet–whole rock), U–Pb ages of 319 ± 3 Ma for eclogite-facies, metamorphic zircon rims, Rb–Sr isochron ages of 313–302 Ma (mica-whole rocks), $^{40}Ar/^{39}Ar$ phengite ages of ca. 310 Ma (Chinese Tianshan; cf., Klemd et al., 2005; Su et al., 2010; Klemd et al., 2011), $^{40}Ar/^{39}Ar$ phengite and glaucophane ages of 327–316 Ma, and a Sm–Nd isochron age of 319 ± 4 Ma (Kyrgyz Tianshan; cf., Simonov et al., 2008; Hegner et al., 2010). The mineral isochron ages were interpreted to represent the age of the eclogite-facies metamorphism, and younger $^{40}Ar/^{39}Ar$ and Rb–Sr ages as due to resetting during exhumation of the high-pressure rocks (Klemd et al., 2005; Hegner et al., 2010; Klemd et al., 2011). Eclogites and associated high-pressure rocks were also described from two localities in the Northern Tianshan of Kazakhstan and

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High-resolution $^{40}Ar/^{39}Ar$ dating using a mechanical sample transfer system combined with a high-temperature cell for step heating experiments and a multicollector ARGUS noble gas mass spectrometer

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Abstract $^{40}Ar/^{39}Ar$ dating of young (<1 Ma) and/or low potassium samples requires degassing of large amounts of material either by a laser or a furnace. A furnace excels in precise and reproducible temperature control and in providing a homogeneous temperature distribution even for relatively large sample amounts. For most systems, however, the degassed mineral or whole-rock residues remain in the crucible after measurement. This reduces the thermal conductivity and increases the blank levels and baking times. To mitigate these problems, we combined a mechanical sample transfer system with a low volume (~90 mL) high-temperature cell. The system operates under ultrahigh vacuum and uses Mo-crucibles, in which up to 1000 mg of sample is transferred into the furnace and taken out after degassing. The system has short baking times (20–30 min), highly reproducible heating conditions and an overall low blank level due to the absence of silicate (glassy) sample residue in the main crucible of the furnace. The system interconnects through a gas purification line with a low volume, high sensitivity multicollector ARGUS noble gas mass spectrometer. Intraday reproducibility of $^{40}Ar/^{36}Ar$ ratios measured on air aliquots of $>5 \times 10^{-16}$ mol ^{36}Ar is better than 0.5‰–1.0‰ (1σ, $n = 4$–8). We illustrate the system performance by $^{40}Ar/^{39}Ar$ dating of whole-rock samples and mineral separates from the Oman ophiolite as well as from the Siebengebirge, Heldburg, and Rhön volcanic provinces in Central Germany.

1. Introduction

$^{40}Ar/^{39}Ar$ dating is widely applied to obtain radioisotopic ages and thermal histories of geologic processes from extraterrestrial and terrestrial K-bearing rocks and minerals [see *McDougall and Harrison*, 1999, for a review]. The isotope composition of the thermally released Ar from a neutron-irradiated sample supplies the required age information. The potassium content of a sample is hereby determined indirectly by the measured ^{39}Ar, which has been produced by the $^{39}K(n,p)^{39}Ar$ reaction during neutron irradiation. Step wise Ar release by incremental heating provides a number of individual ages from a single sample and allows an internal control on the robustness of the derived age.

Commonly, a thermal laser or a vacuum furnace suitable to reach temperatures >1700°C achieves the step heating in ultrahigh vacuum. A critical issue during heating is the temperature control of the individual heating steps. In most laser heating experiments, the laser power provides a relative measure for the temperature during degassing. This approach makes laser heating unreliable for the determination of Ar diffusion parameters and closure temperatures of minerals [*Dodson*, 1973], or the application of the multidomain diffusion (MDD) analysis of feldspars [e.g., *Lovera et al.*, 1989, 1991]. This problem is mitigated by the use of thermocouples and pyrometer systems [*Cassata and Renne*, 2013], but their application and calibration is complex. The limited mass of sample that can be degassed and the temperature gradient within an unwrapped sample produced by the unidirectional heat supply further hampers thermal laser dating of very young and/or K-poor samples. Although wrapping the sample into Mo foil or Pt-Ir alloy foil and/or movement of the laser beam over a sample in part limit these shortcomings, a homogeneously distributed and constant temperature over a defined period of time (i.e., thermal equilibrium) is difficult to achieve. Tests made in our lab on unwrapped, 80–250 µm

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ORIGINAL PAPER

Amphibole in alkaline basalts from intraplate settings: implications for the petrogenesis of alkaline lavas from the metasomatised lithospheric mantle

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Abstract Kaersutite to pargasite phenocrysts from Tertiary alkali basalts (Rhön, Central European Province, Germany) yield new high-precision $^{40}Ar/^{39}Ar$ ages of 24.0–24.1 Ma. Major and trace element compositions demonstrate that these high-TiO_2 (4–7 wt%) amphiboles are in equilibrium with their host rock. Chemically, these amphibole phenocrysts resemble amphibole from magmatic veins in upper mantle rocks but differ from disseminated amphibole from peridotite. Most amphiboles have similar isotope characteristics to their alkaline basaltic host rocks ($^{87}Sr/^{86}Sr_{24} = 0.7035–0.736$, $\varepsilon Nd_{24} = +3.8–+4.0$, $^{206}Pb/^{204}Pb_{24} = 19.21–19.37$, $^{207}Pb/^{204}Pb_{24} = 15.58–15.62$, $^{208}Pb/^{204}Pb_{24} = 38.95–39.16$), but two samples show contrasting isotopic compositions ($\varepsilon Nd_{24} = -4.0$ and -2.9; $^{206}Pb/^{204}Pb_{24} = 17.08$ and 18.11; $^{207}Pb/^{204}Pb_{24} = 15.51$ and 15.58; $^{208}Pb/^{204}Pb_{24} = 37.41$ and 37.99), indicating involvement of an ancient crust-derived component during melting. The O isotopic composition of the amphibole phenocrysts ranges from 5.4 to 7.5 ‰, reflecting O isotope heterogeneity of the upper mantle sources. The contrasting isotopic composition of amphibole and host rock pairs furthermore indicates that phenocrysts record the early stages of the volcanic history of the Rhön volcanic field on a regional scale and at a

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Cenozoic clockwise rotation of the Tengchong block, southeastern Tibetan Plateau: A paleomagnetic and geochronologic study

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ABSTRACT

Paleomagnetic data from ~50–35 Ma (likely ~40 Ma) mafic dykes in Yunnan, southeastern Tibetan Plateau, cutting ~115 Ma granitoids record the rotation of the Tengchong (Lhasa) block around the East Himalayan Syntaxis (EHS). Ti-rich titanomagnetite and magnetite carry a primary magnetic component (Group1); a magnetic overprint resides in magnetite (Group2), likely induced by low-grade metamorphism between ~30 and 10 Ma. The tilt-corrected overall mean directions are D/I = 89.8°/35.1° for Group1 and D/I = 33.3°/41.4° for Group2. These data imply a clockwise rotation of ~87° (87.3 ± 12.5°) of the Tengchong block since remanence acquisition at ~40 Ma with respect to stable Eurasia. The average rotation rate of 2.18 ± 0.31°/Myr is at the upper limit of the present-day rotation rates around the EHS obtained from GPS velocities and Quaternary strain rates. The remagnetized Group2 indicates a—poorly defined—rotation of ~31° (31.2 ± 32.9°). Our key results – the detection of ~87° clockwise rotation, with high rotation rates following the India–Asia collision, and a decrease in rotation rates during the Miocene – suggest that first the Tengchong block rotated rapidly around the EHS, synchronous with eastward tectonic escape of lithospheric blocks. The later, slower, clockwise rotation—similar to those recorded geodetically—may be related to viscous flow of Tibetan crust.

1. Introduction

Intra-continental convergence between India and Asia since ~50 Myr (e.g. Klootwijk et al., 1992; Leech et al., 2005; Najman et al., 2010) has caused significant deformation and rotation in Southeastern Asia; both paleomagnetic (e.g. summarized in Otofuji et al. (2010)) and geodetic data (e.g. Banerjee et al., 2008; Gan et al., 2007; Maurin et al., 2010; Sol et al., 2007) record these crustal movements around the Eastern Himalayan Syntaxis (EHS). Two end-member models are commonly used to describe these crustal movements: The 'tectonic escape' model implies lateral displacement of rigid blocks along lithosphere-scale shear zones (e.g. Molnar and Tapponnier, 1975; Tapponnier et al., 1982; Replumaz and Tapponnier, 2003). The 'crustal flow' models describe material transfer from the orogenic interior to the exterior regions, channelized within a vertically decoupled lithosphere (e.g. Bird, 1991; Clark and Royden, 2000; Royden et al., 1997). These groups of models are called 'escape' and 'crustal flow' models in the following.

Western Yunnan is a key area for tracing material transport around the EHS and for understanding the processes responsible for this motion. Present-day surface velocities observed by GPS geodesy show a wide area of clockwise rotations around the EHS and S-ward crustal flow in this region (Fig. 1a; Banerjee et al., 2008; Gan et al., 2007; Maurin et al., 2010; Sol et al., 2007); the clockwise rotation resumes south of ~25°N with SW-ward flow into Myanmar and Thailand. Paleomagnetic results from the area east of the EHS, in the Shan–Thai and Lanping–Simao blocks, also record clockwise rotations (Fig. 1a; Chen et al., 1995; Funahara et al., 1992, 1993; Huang and Opdyke, 1991, 1993; Sato et al., 2007; Tanaka et al., 2008). Almost all of these paleomagnetic data stem from Paleozoic–Mesozoic rocks; only the studies of Chen et al. (1995), Sato et al. (2001), and Tong et al. (2013) include data from Paleogene to Neogene rocks. The available results thus record the rotation accumulated since pre-Cenozoic times, but cannot resolve movements within specific periods of the India–Asia collision and the Cenozoic development of the Tibetan Plateau.

In this paper, we present new paleomagnetic data from the Tengchong block, acquired from mafic dykes that intruded granitoids of the Gaoligong Mountains (Gaoligong Shan), a part of the Gangdese magmatic arc built on the Lhasa block (e.g. Xu et al., 2008, 2012; this study). The sampling area is located southeast of the town of Pianma (referred to as the Pianma–Nujiang section; Fig. 1b). Below, we argue that these

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The giant Shakhdara migmatitic gneiss dome, Pamir, India-Asia collision zone: 2. Timing of dome formation

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[1] Cenozoic gneiss domes—exposing middle-lower crustal rocks—cover ~30% of the surface exposure of the Pamir, western India-Asia collision zone; they allow an unparalleled view into the deep crust of the Asian plate. We use titanite, monazite, and zircon U/Th-Pb, mica Rb-Sr and $^{40}Ar/^{39}Ar$, zircon and apatite fission track, and zircon (U-Th)/He ages to constrain the exhumation history of the ~350 × 90 km Shakhdara-Alichur dome, southwestern Pamir. Doming started at 21–20 Ma along the Gunt top-to-N normal-shear zone of the northern Shakhdara dome. The bulk of the exhumation occurred by ~NNW-ward extrusion of the footwall of the crustal-scale South Pamir normal-shear zone along the southern Shakhdara dome boundary. Footwall extrusion was active from ~18–15 Ma to ~2 Ma at ~10 mm/yr slip and with vertical exhumation rates of 1–3 mm/yr; it resulted in up to 90 km ~N-S extension, coeval with ~N-S convergence between India and Asia. Erosion rates were 0.3–0.5 mm/yr within the domes and 0.1–0.3 mm/yr in the horst separating the Shakhdara and Alichur domes and in the southeastern Pamir plateau; rates were highest along the dome axis in the southern part of the Shakhdara dome. Incision along the major drainages was up to 1.0 mm/yr. Thermal modeling suggests geothermal gradients as high as 60°C/km along the trace of the South Pamir shear zone and their strong N-S variation across the dome; the gradients relaxed to ≤40–45°C/km since the end of doming.

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1. Introduction

[2] The Pamir—the western prolongation of the Tibet-Himalaya orogen—resulted from N-S convergence between India and Asia (Figure 1). In the Pamir, the Cenozoic orogeny formed a high-relief mountain knot of ~500 km N-S extent, which contrasts with the ~1000 km wide, low-relief Tibet Plateau. About ~30% of the surface exposure of the Pamir comprises high-grade, middle to lower crustal metamorphic rocks exhumed in Cenozoic syn-orogenic domes (Figure 1; *Schmidt et al*. [2011], *Stübner et al*. [2013]). Understanding the evolution of these domes is central to understanding the behavior of the Himalaya-Tibet-Pamir orogen because the domes expose a range of shallow to deep structural levels. *Brunel et al*. [1994] and *Robinson et al*. [2004, 2007] explained the formation of the eastern Pamir Muztagh-Ata and Kongur Shan domes by Miocene top-to-S flow and Pliocene/Pleistocene E-W extension, and *Hubbard et al*. [1999], *Schwab et al*. [2004], and *Schmidt et al*. [2011] suggested Miocene formation of the central and southern Pamir domes. In part I of this paper series, *Stübner et al*. [2013] investigated the structural geometry and kinematics of the largest of these Pamir gneiss domes—the 350 × 90 km Shakhdara-Alichur composite gneiss dome in the southwestern Pamir—and established a model of ~N-S extensional doming with footwall exhumation along two low-angle, normal-shear detachments, the South Pamir and Alichur shear zones (SPSZ and ASZ; Figure 2).

[3] Herein, we address the following principal questions: when were the southern Pamir domes formed, and when in particular did ~N-S extension in the southern Pamir start and end? We integrate garnet Lu-Hf [*Smit et al*., 2012]; zircon, monazite, and titanite U/Th-Pb [*Schmidt et al*., 2011; this paper]; mica Rb-Sr and $^{40}Ar/^{39}Ar$; zircon and apatite fission track (AFT); and zircon (U-Th)/He [*Hubbard et al*., 1999; this paper] geo-thermochronology and reconstruct the exhumation history of the Shakhdara-Alichur crystalline rocks.

Additional supporting information may be found in the online version of this article.

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The Heart of China revisited: II Early Paleozoic (ultra)high-pressure and (ultra)high-temperature metamorphic Qinling orogenic collage

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[1] Orogens with multiple (ultra)high-pressure ((U)HP) and (ultra)high-temperature ((U)HT) metamorphic events provide a complex but telling record of oceanic and continental interaction. The Early Paleozoic history of the "Heart of China," the Qinling orogenic collage, offers snapshots of at least three (U)HP and two (U)HT metamorphic events. The preservation of remnants of both oceanic and continental domains together with a ≥110 Myr record of magmatism allows the reconstruction of the processes that resulted in this disparate metamorphism. Herein, we first illuminate the pressure-temperature-time (P-T-t) evolution of the Early Paleozoic (U)HP and (U)HT events by refining the petrographic descriptions and P-T estimates, assess published, and employ new U/Th-Pb zircon, monazite, and titanite, and ^{40}Ar-^{39}Ar phengite geochronology to date the magmatic and metamorphic events. Then we explore how the metamorphic and magmatic events are related tectonically and how they elucidate the affinities among the various complexes in the Qinling orogenic collage. We argue that a Meso-Neoproterozoic crustal fragment—the Qinling complex—localized subduction-accretion events that involved subduction, oceanic-arc formation, and back-arc spreading along its northern margin, and mtantle-wedge exhumation and spreading-ridge subduction along its southern margin.

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1. Introduction

[2] Stretching E-W more than 2000 km between the North China craton (NCC) and the South China craton (SCC), the Qilian-Qinling-Tongbai-Dabie-Sulu (herein Qinling-Tongbai) orogen constitutes the geographic, geologic, and cultural "Heart of China" (Figure 1) [e.g., *Zhang et al.*, 2001]. The Qinling-Tongbai evolution comprised subduction-accretion-collision events in the Neoproterozoic [e.g., *Wang et al.*, 2003], Cambrian [e.g., *Yang et al.*, 2003], Carboniferous [e.g., *Sun et al.*, 2002], and Triassic [e.g., *Okay et al.*, 1993]. The study of this orogen has yielded insights into (ultra) high-pressure ((U)HP) and (ultra) high-temperature ((U)HT) metamorphism and tectonics [e.g., *Hacker et al.*, 2004; *Liu et al.*, 2011; *Cheng et al.*, 2012], and the assembly and break-up of the core of the supercontinent Rodinia [e.g., *Li et al.*, 2008a; *Bader et al.*, 2013]. A decade ago, we [*Ratschbacher et al.*, 2003] combined new and published data into a tectonic model of the Qinling-Tongbai orogen. Numerous new data have appeared since. In this series of papers, we assess the literature accessible to us and combine it with our own new petrologic-geochronologic-structural data. The subject herein is the Early Paleozoic (~550–360 Ma) evolution of the Qin Mountains (Qinling) and the Tongbai Mountains (Tongbai Shan) with a focus on the Qinling complex and its relationships to the various rock units (complexes) of the Qinling-Tongbai orogenic collage (i.e., the NCC, Kuanping, Erlangping, Danfeng, Songshugou, and SCC subblocks; Figures 1 and 2).

[3] The principal questions this paper addresses are as follows: (1) What pressure-temperature-time (P-T-t) evolution do the Early Paleozoic (U)HP and (U)HT events in the Qinling-Tongbai orogen involve? We refine petrographic descriptions and P-T estimates of the metamorphic rocks, and employ published and new U/Th-Pb zircon, monazite, and titanite, and ^{40}Ar-^{39}Ar phengite geochronology to highlight the magmatic and metamorphic events. (2) How

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Multi-system geochronological and isotopic constraints on age and evolution of the Gaoligongshan metamorphic belt and shear zone system in western Yunnan, China

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ABSTRACT

The Gaoligongshan metamorphic belt, located east of the Eastern Himalayan Syntaxis (EHS) in the Yunnan province, southwestern China, is a compelling region in which to determine temporal constrains on crustal dynamic processes related to the Himalayan orogeny. We applied multi-system geo- and thermochronology (900 °C to <50 °C) to orthogneiss and mylonites from a major shear zone in the southern Gaoligongshan in order to elucidate the magmatic, cooling and exhumation history of this belt.

Zircon U/Pb data reveal three magmatic events at ∼486 Ma, ∼136 Ma and ∼76 Ma. Similar ages are found in orthoderivative rocks of the neighboring Tengchong and Baoshan blocks, and the Gangdese batholith, suggesting that the southern Gaoligongshan is composed of an assemblage of Lhasa and Qiangtang terrane derived rocks. Muscovite Rb/Sr ages of 35–21 Ma are coeval with the onset of lateral crustal displacement along major shear zones in Eastern Tibet and Indochina, and with the post-collision volcanic activity in western Yunnan. Biotite Rb/Sr and mica $^{40}Ar/^{39}Ar$ ages provide evidence that mylonitization along the Gaoligongshan shear zone and crustal rotation of the Tengchong and Baoshan blocks proceeded during the Miocene, between 19 and 12 Ma, when the rocks rapidly cooled through the 350–280 °C temperature range. Almost identical $^{40}Ar/^{39}Ar$ ages reported for the Karakorum–Jiali–Parlung Fault system in Western Tibet suggest that the Gaoligongshan shear zone is the southeastern continuation of this fault, recording the eastward extrusion of Tibet and crustal movement around the EHS. The final stage of exhumation of the Gaoligongshan occurred between 8 and 5 Ma at an average exhumation rate of ∼3 km/Ma as documented by apatite fission-track and apatite (U–Th–Sm)/He data. This rapid exhumation was triggered by crustal root delamination and opening of the Andaman sea.

Our results clearly show that the complex tectonothermal evolution of the Gaoligongshan was influenced by Tibetan extrusion and escape tectonics associated with lower crustal flow around the EHS and the southeastward movement of Indochina and back-arc extension in response to Andaman seafloor spreading.

1. Introduction

Ongoing convergence between India and Eurasia since early Eocene times has resulted in the formation of the Himalaya and Tibetan plateau (e.g. Yin and Harrison, 2000). This process induced the east- to south-directed flow (or extrusion) of eastern Tibetan crust around the Eastern Himalayan Syntaxis (EHS), that led to the southeastward movement of the Indochina block (Besse et al., 1984; Patriat and Achache, 1984; Royden et al., 1997; Tapponnier et al., 1990; Wang et al., 2006). The material flow was largely accommodated by lateral transfer along several large-scale and innumerous smaller-scale strike-slip faults and shear zones. These faults, which often experienced a complex evolution of multiple re-orientation, provide insights into the kinematics of crustal deformation in this region, which is essential to understanding the dynamics of plateau formation and extrusion (Schoenbohm et al., 2006; Searle, 2006; Socquet and Pubellier, 2005; Tapponnier et al., 1990).

The Western Yunnan region in southwestern China is a key area in which to study the southward extrusion of East Tibetan crust.

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Composite mesoscopic and magnetic fabrics of the Paleo-Proterozoic Wangtu Gneissic Complex, Himachal Himalaya, India: Implications for ductile deformation and superposed folding of the Himalayan basement rocks

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ABSTRACT

The present study demonstrates how the Paleo-Proterozoic Wangtu Gneissic Complex (WGC) of the Lesser Himalayan Crystalline sequence experienced superposed folding and doming prior to its exhumation, with the help of integrated field, microstructural, magnetic fabric anisotropy and geochronological studies. The WGC forms the basement of the Lesser Himalaya and is bounded by Vaikrita Thrust (VT) to the northeast and Munsiari Thrust (MT) to the southwest. The regional structure consists of upright large scale early folds (D1) trending NW–SE. The mesoscopic fabric is related to axial plane foliation of the D1 folds and, to a lesser extent, late D2 folds. The axis of maximum compression for D1 and D2 folds are mutually orthogonal. The D1 folds have formed simultaneously with the major Himalayan thrusts whereas the D2 folds have developed during a later deformation event. The magnetic lineation at the hangingwall of the VT is sub-horizontal indicating stretching along the strike of the thrust. In the interior parts of the WGC, the magnetic fabric is of two types: (i) magnetic lineation demarks the intersection of mesoscopic and magnetic foliation indicating superposed deformation and (ii) scattered distribution of magnetic lineations due to D2 folding on initially curved and non-cylindrical D1 surface. ^{40}Ar–^{39}Ar dating of biotite from one site from the core of WGC gives an age of 9.3 ± 0.3 (2σ) Ma. It is inferred that the doming of the WGC took place at ~9 Ma and, instead of large scale thrusting, it is characterized by superposed folding and strike-parallel stretching along the VT zone. It is suggested that the effect of superposed folding and ductile deformation of the Himalayan basement rocks has to be taken into account before cross-section balancing or any estimation of crustal shortening is attempted.

1. Introduction

An important issue regarding Himalayan geology is estimation of shortening caused by India-Asia collision. The amount of calculated shortening varies considerably depending on the methodology used, and there has been a marked difference between estimates based on volumetric analysis and on cross section balancing (Johnson, 2002). Whilst volumetric analysis suggests shortening of 1815–2100 km in west and 2750–2800 km in eastern part of the Himalaya (Dewey et al., 1989; Le Pichon et al., 1992), cross section balancing estimates shortening of only 85–700 km (c.f. Johnson, 2002) (Coward and Butler, 1985; Coward et al., 1988; Searle et al., 1988; Schelling and Arita, 1991; Ratschbacher et al., 1994; Srivastava and Mitra, 1994, etc.). One possible reason behind the much lower values obtained from cross section balancing is that it does not consider internal deformation of the basement, i.e. the effects of ductile deformation and superposed folding of the basement rocks. Any cross section restoration technique can only give the minimum amount of shortening in an orogen if ductile deformation of the basement rocks is neglected. This implies that proper analyses of internal deformation of the basement rocks are critical before any estimate of shortening can be made. The Paleo-Proterozoic Wangtu Gneissic Complex (WGC) lies in the Main Central Thrust (MCT) zone of the Himachal Himalaya (Fig. 1a) and forms the basement of the Lesser Himalayan Crystalline sequence. In the present study we have analyzed the combined mesoscopic, microscopic and magnetic fabric of the WGC to understand nature of ductile deformation including superposed folding.

Anisotropy of magnetic susceptibility (AMS) is one of the most important tools to evaluate fabric in natural rocks (Tarling and Hrouda, 1993; Borradaile and Henry, 1997). AMS is helpful in fabric quantification of rocks which do not have visible, mesoscopic fabric and it also assists to decipher signatures of deformation episodes which are not easily discernable in the field. For the past

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