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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.

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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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often loosely defined as pyroxenite or amphibolite. Pyroxenite may be a component in upwelling mantle plumes (Sobolev et al., 2007) or may result from hybridization of the ambient mantle through percolation of fluids or melts (Herzberg, 2011). This type of mantle metasomatism generated regions of modally or cryptically enriched regions in which the lithospheric mantle hosts significant amounts of amphibole or phlogopite. Recent experimental evidence (Pilet et al., 2008) suggest that melts within the lithospheric mantle are dominated by these hydrous phases with minor contribution from the ambient peridotite. Monogenetic volcanic fields such as the one of the Batain basin are characterized by small-volume, geographically-restricted basaltic rocks. Small-volume melts may have the potential to better characterize the isotope composition of the metasomatic domain from which they were derived as they are likely less diluted by melts from the ambient mantle. Hence, they are therefore best suited to constrain the composition of the potential source of the lavas. Another controversial issue is whether intra-continental rift-related volcanism is related to adiabatic decompression melting caused by thinning of the lithosphere during rifting, or due to raised mantle temperatures as a consequence of mantle plume activity.

In this contribution we present a comprehensive major and trace element and Nd, Sr, Pb, Hf isotope data set as well as high-resolution whole-rock $^{40}Ar/^{39}Ar$ ages from basin-related alkaline volcanic rocks from the Batain basin (Oman). These data provide qualitative and quantitative constraints on partial melting processes and the composition of the mantle source involved during petrogenesis. Additionally, inferences about minor effects of fractional crystallization and the lack of crustal contamination in the genesis of these alkaline lavas are drawn. Previous studies (Nasir et al., 2006; Worthing and Wilde, 2002) reported also major element, trace element and some Sr and Nd isotope data on a restricted range of samples. The data set presented in this study add new Pb and Hf isotope data and a full set of Ar–Ar ages that were previously not available and now cover the entire volcanic field. Due to extensive sand cover, the area show only a few isolated outcrops of basaltic plugs but the present data set may be used in conjuction with the already existing data to place more precise constraints on sources and processes during alkali basalt genesis. Specifically, we address the important point whether a modern plume source (the Afar plume) or a fossil plume source affected the source composition of the Oman alkaline lavas. To this end, we compare the data from the Oman basalts with basaltic rocks from elsewhere on the Arabian Peninsula.

2. Geological setting and sampling strategy

The Arabian shield is dominated by Neoproterozoic crust which is covered by Phanerozoic sedimentary rocks in the east (Nasir and Stern, 2012). Since late Neoproterozoic time, the Arabian Shield has been relatively stable although it was rejuvenated during different tectonic events (Nasir and Stern, 2012) between the late Pre-Cambrian and the Tertiary; the last time during the opening of the Red Sea in the last 30 Ma. Episodic basin formation is manifested in two major cycles of intracratonic rifting that formed the NE-SW trending basins in eastern and central Oman (Loosveld et al., 1996; Worthing and Nasir, 2008). The basin structure consists of NNE-SSW trending salt basins (Worthing and Wilde, 2002) which parallels the NNE-SSW trending Masirah Fault on the eastern edge (Figs. 1 and 2). The basanites studied here occur in the Batain basin that is part of the Mesozoic-Tertiary cover of the Arabian shield (Fig. 2). The alkaline magmatism affecting the eastern part of Oman is associated with periods of Cretaceous-Tertiary transpression and Eocene transtension (Nasir and Stern, 2012; Platel and Roger, 1989). Structural changes within the basins probably arise from Tertiary extensional tectonics, which is related to the opening of the Red Sea and the Gulf of Aden, followed by shortening during the Miocene collision of Arabia and Eurasia (Immenhauser et al., 2000). Therefore, tectonic instability related to major fracture zones (Nasir et al., 2006) probably led to the intrusion of the basanites in the Batain basin, which also occur along a NNE-SSW trending fracture zone (Gnos and Peters, 2003; Nasir et al., 2006; Worthing and Wilde, 2002). The morphological expression of these basanite extrusions are isolated volcanic plugs within the Batain plane that crosscut Tertiary carbonates, clays and sandstones. The sampled area in the NE part of the Sultanate of Oman extends by about 65 km in a SSW and about 12 km in a WSW direction (Fig. 2). Twelve basanites were sampled from different volcanic plugs within the Batain basin (Fig. 2, coordinates of sampling locations see Table 1). These occur as conical hills and are clearly distinguished from the surrounding sands. All samples are massive dark coloured volcanic rocks with a fine-grained texture, containing some phenocrysts.

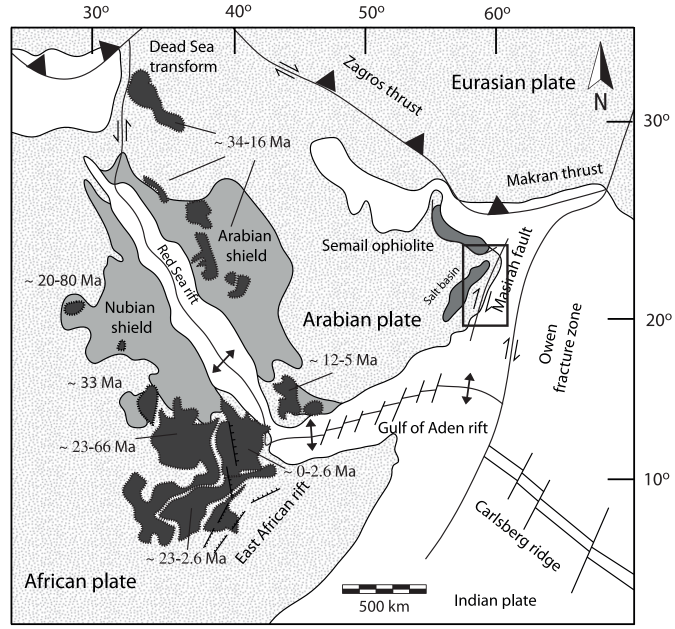

Fig. 1. Map of the Arabian region showing major plate boundaries, the outline of the Arabian–Nubian Shield and the distribution of major Oligocene to recent western Arabian volcanic fields (modified after Krienitz and Haase, 2011). Detailed area from Fig. 2 is shown as rectangle.

3. Methods

The electron microprobe analyses of olivine, clinopyroxene and plagioclase were performed with a Cameca SX50 microprobe at the Mineralogisch-Petrographisches Institut at Universität Hamburg and are listed in Table 2. Analytical conditions were 15 kV accelerating voltage, 15 nA beam current, and counting times of 20 s for peak and 10 s for the background signal. Prior to quantitative analyses all elements were standardized on matrix matched natural garnet standards (Mg, Si, Al, Ca, Fe, Mn) and synthetic (Ti, Cr) reference materials. The phi-rho-z correction was applied to all data and error on major oxides are in the range to be about 1–2% relative. To monitor accuracy and precision over the course of this study microanalytical reference materials were analysed and obtained results match published values within error.

Major and trace elements (except for REE) were measured on fused lithium-tetraborate glass beads using standard XRF technique at the Universität Hamburg using a PanAnalytical MagixPro X-ray fluorescence spectrometer and are presented in Table 3. Loss on ignition (LOI) was determined gravimetrically at 1050 °C (Lechler and Desilets, 1987). Trace elements were analyzed by inductively coupled plasma mass spectrometry (ICP-MS) at the Universität Kiel, following the method of Garbe-Schönberg (1993) (Table 3).

The Sr, Nd, and Pb isotopic compositions were analyzed at Deutsches GeoForschungsZentrum GFZ, Potsdam. Samples were dissolved with

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