Evolution and composition of the lithospheric mantle underneath the western Arabian peninsula: constraints from Sr-Nd isotope systematics of mantle xenoliths

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Abstract. On the basis of their textures and mineral compositions spinel-peridotite xenoliths of the Cr-diopside group (group I) from Cenozoic volcanic fields of Arabia can be classified into different subtypes. Type IA is of lherzolitic to harzburgitic composition; mineral compositions are similar to those of group I mantle xenoliths from worldwide occurrences. Type IB xenoliths have lherzolitic to wehrlitic compositions; Mg/(Mg + Fe) ratios of the clinopyroxenes (0.862–0.916) and olivines (0.872–0.914) are similar too or slightly lower than those of typical IA minerals. Texturally, type IB xenoliths are distinguished from type IA rocks by the presence of intragranular spinel, intragranular relict Cr-pargasite, and subordinate intergranular Ba-phlogopite (11.1% BaO). The hydrous minerals in type IB xenoliths are interpreted to document an earlier metasomatism which did not affect type IA lithospheric mantle. Subsequent recrystallization caused the partial replacement of Cr-pargasite in type IB materials and resulted in the formation of less hydrous mineral assemblages. Some of the type IA xenoliths are characterized by secondary intergranular amphibole which must have formed recently. The absence or presence of this intergranular amphibole is used to distinguish an anhydrous subtype IA1 from a hydrous subtype IA2. Type IB xenoliths may also contain secondary intergranular amphibole (similar to the one in subtype IA2) or they contain abundant former melt patches now consisting of glass and phenocrysts of olivine, clinopyroxene, amphibole, and spinel. The secondary intergranular amphiboles and the former melt patches, both are interpreted as results of a second metasomatism (metasomatism 2). In their trace element and isotopic characteristics, type IA1 and type IA2 clinopyroxenes do not exhibit any systematic differences. Furthermore, type IA2 clinopyroxenes are in Sr isotopic disequilibrium with intergranular amphiboles. This suggests that type IA2 clinopyroxenes were not modified during the second metasomatism 2. All type IA clinopyroxenes have low Sr contents (< 100 ppm); most of them show Sm/Nd ratios higher than inferred for bulk earth. In their 87Sr/86Sr and 143Nd/144Nd ratios, type IA clinopyroxenes exhibit a large spread from 0.70226–0.70376 and from 0.51375–0.51251, respectively. Highly variable Sm/Nd ratios (5.0–79.3) and variable TUR and TCHUR model age relationships require different evolutions of the respective mantle portions. Nevertheless, all but two type IA clinopyroxenes form a linear array in a Sm-Nd isochron diagram which probably can not be explained by mixing. If taken as an “isochron” the slope of the array corresponds to an age of around 700 Ma. The mean initial εNd of 5.8 ± 1.7 (1σ) is similar to values for juvenile Pan-African (i.e. 850–650 Ma old) crust of the Arabian-Nubian shield. It is suggested that type IA lithospheric mantle and the juvenile Pan-African crust are two counterparts fractionated from a common source during the earlier stages of the Pan-African. Type IB clinopyroxenes have high Sr contents (≥ 200 ppm), variable Sm/Nd ratios (9–111) and Sm/Nd ratios generally below that inferred for bulk earth, and show a small spread in their Sr and Nd isotopic compositions (0.70299–0.70318 and 0.51285–0.51278, respectively). In a Sm-Nd isochron diagram the data points form a linear, horizontal array indicating a close-to-zero age for the earlier metasomatism and suggesting a close genetic relationship to mantle processes related to the formation of the Red Sea.

Introduction

Knowledge of the evolution and present-day composition of the continental lithospheric mantle is a prerequisite for a better understanding of the chemical differentiation of the earth and for an evaluation of asthenospheric versus lithospheric sources of intra-plate volcanism. From the geochemical point of view the continental lithospheric mantle may represent an open system. Additions of melts and/or fluids derived from the asthenosphere are likely to take place in the lower-most parts

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of the lithosphere. Furthermore, the lithospheric mantle may be modified by intra-system chemical fractionation. Melts or fluids may be extracted from lower levels and transferred to the upper parts of the lithospheric mantle and/or the continental crust.

Mantle-derived xenoliths hosted in anorogenic basalts offer a direct insight into the lower lithosphere. Recent attempts to decipher the chemical evolution of the continental lithospheric mantle beneath young volcanic fields from xenoliths have not yielded unambiguous results; the data indicated that the sampled portions of the lithosphere have complex histories which cannot be modelled in detail (e.g. Stosch and Lugmair 1986; Stosch et al. 1986; McDonough and McCulloch 1987; Downes 1987; Downes and Dupuy 1987; Roden et al. 1988). All these studies were performed in areas with multi-stage crustal histories, i.e. with several periods of crustal growth and recycling. Using the xenolith approach, it therefore seems more promising to study the evolution of the lithospheric mantle beneath a piece of continental crust with a relatively simple history. One such area is the central part of the Arabian-Nubian shield which consists of juvenile Pan-African (i.e. 850–600 Ma old) crust (Bokhari and Kramers 1981; Duyverman et al. 1982; Claesson et al. 1984; Harris et al. 1984; Stoeser and Camp 1985; Vail 1987; Dixon and Golombek 1988) and in which Cenozoic rifting and related volcanism took place leading to the formation of the Red Sea (Fig. 1).

Most of the volcanic fields contain mantle-derived xenoliths (Varne 1970; Hutchison and Gass 1971; Ottonello et al. 1978; Ghent et al. 1980; Thornber and Pallister 1985; Kuo and Essene 1986; Henjes-Kunst 1987; McGuire 1988a, b; Nasir and Al-Fuqha 1988). In this contribution we present petrographical, geochemical and Nd-Sr isotopic data on numerous spinel peridotite xenoliths of the Cr-diopside group (group I of Frey and Prinz 1978) and on one granulitic xenolith from the volcanic fields (harrats) As Shamah, Uwayrid, Lunayyir, Hutaymah, Kishb, Al Birk, and Jizan (Fig. 1) and we discuss the constraints from these data on the chemical evolution and present composition of the lithospheric mantle.

Geology

Rifting in the Red Sea area started in Oligocene times and was not preceded by updoming. Major shoulder uplift did not occur before mid-Miocene times (Bohannon et al. 1989). The narrow axial trough of the Red Sea was formed by seafloor-spreading during the last 5 Ma. Whereas the continental crust underneath the Arabian rift shoulder has a thickness of around 40 km, the Red Sea shelf and coastal plains are characterized by crustal thicknesses of less than 20 km (e.g. Mechie and Prodehl 1988). There is a controversy debate as to what percentage of the present crust underneath the shelves and coastal plains is stretched original continental crust and what percentage is new crust, whether it be truly oceanic or basic intrusions into continental crust (e.g. Bohannon et al. 1989).

Volcanic activity related to the formation of the Red Sea started around 32 Ma ago and continued to historic times. The bulk of the exposed volcanic rocks were erupted during the last 10 Ma. Aside from Afar, volcanism was almost exclusively confined to the Arabian side of the Red Sea; in Egypt and Sudan Cenozoic volcanics are sparse (Camp and Roobol 1989; Bohannon et al. 1989). Xenoliths derived from the mantle and lower crust have been found in most of the volcanic fields and are especially abundant in Quaternary volcanics. Geothermobarometric data on xenolith suites from Harrats Kishb (Arabian rift shoulder) and Al Birk (Red Sea Coastal plain) indicate a higher thermal gradient for the Red Sea coastal plain than for the Arabian rift shoulder and suggest that the lithosphere underneath the rift shoulder is less than 80 km thick (McGuire 1988a; McGuire and Bohannon 1989). Neodymium-strontium isotopic systematics of basalts from the Red Sea axial trough and from Arabia are strongly influenced by their tectonic setting. Quaternary magmas erupted above continental crust of normal thickness and moderately thinned lithospheric mantle (i.e. rift shoulder) are characterized by relatively low Nd isotopic ratios (143Nd/144Nd ratios as defined by Hart et al. 1986) compared to Quaternary magmas erupted inside the Red Sea rift where subcontinental lithosphere is either absent or strongly thinned (Altherr et al. 1990). Oligocene-Miocene basalts from the Red Sea coastal plain also tend to have relatively low 143Nd/144Nd ratios (Hegner and Pallister 1989). The loNd-array signatures were attributed to the pre-rift lithospheric mantle by Altherr et al. (1990).

Uplift and erosion have exposed the crystalline basement over a large area called the Arabian-Nubian Shield. The central part of this shield consists of juvenile mantle-derived oceanic and intra-oceanic island-arc crust of late Precambrian (Pan-African) age. The western and eastern parts of the shield mainly consist of older continental rocks reworked during the Pan-African (e.g. Bokhari and Kramers 1981; Duyverman et al. 1982; Stacey and Stoeser...