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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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ABSTRACT

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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(2001), Granet et al. (1995) and Hoernle et al. (1995), the primitive lavas are considered to represent partial melts of a deep mantle plume although there is considerable disagreement about the size and the number of plumes involved. Hoernle et al. (1995) suggested the involvement of a single large plume whereas Granet et al. (1995) and Ritter et al. (2001) invoked the presence of several small-scale "plumelets". Seismic mantle tomography shows a plume-like low velocity structure beneath the CEVP with an excess temperature of ca. 150–200 °C relative to the ambient mantle in which the 100 km-wide structure extends to at least 400 km depth (Ritter et al., 2001). Jung et al. (2012) suggested that such geophysical considerations require the simplification of an isochemical and isomineralogical mantle and it is equally possible that discontinuous seismic wave anomalies are caused by chemical and mineralogical anomalies rather than by temperature gradients. In this case the reported excess temperatures should be viewed as an upper limit.

Wedepohl et al. (1994) suggested that the lavas are partial melts from a metasomatically enriched asthenospheric mantle with some further evolution within the lithospheric mantle during ascend (Hegner et al., 1995; Jung et al., 2005), whereas others considered the lavas as partial melts from the lithosphere–asthenosphere boundary (Wilson et al., 1995a, 1995b). Based on mantle xenolith studies, the lithospheric mantle has also the potential to be the source for at least some CEVP lavas. Mantle xenoliths from CEVP alkaline rocks with a substantial geochemical diversity (Witt-Eickschen and Kramm, 1998) show that the lithospheric mantle beneath Europe is chemically heterogeneous as a result of mantle metasomatism. For other volcanic fields from the CEVP, interaction of partial melts from the metasomatized lithospheric mantle with asthenospheric melts has been proposed to explain the geochemical composition of the primitive alkaline rocks (Wilson and Downes, 1991; Wilson and Patterson, 2001). In addition, for a significant number of volcanic fields from the CEVP (Massif Central, Vogelsberg, Rhön, Urach–Hegau, Westerwald) crustal contamination has been documented (Jung and Masberg, 1998; Jung and Hoernes, 2000; Blusztajn and Hegner, 2002; Bogaard and Wörner, 2003; Haase et al., 2004; Jung et al., 2005; Jung et al., 2012; Mayer et al., 2013). Consequently an important question then is whether the geochemical and isotopic composition of the lavas reflects (1) the composition of the mantle source, (2) the processes of contamination by crustal material or (3) the mixing of melts from different mantle sources. In this context it is important to note that continental crust and enriched mantle can show similar chemical and isotopic characteristics because crustal recycling may lead to modification of mantle domains due to metasomatism.

In the CEVP, several volcanic fields such as the Siebengebirge and the Westerwald, have been investigated previously (Haase et al., 2004; Jung et al., 2012; Kolb et al., 2012). However, for the volcanic field in the transition area between the Siebengebirge and the Westerwald no geochemical or radiogenic isotope data are available. In our investigation, major and trace element data as well Sr–Nd–Pb isotope data are reported and are used to constrain the petrogenesis of the alkaline lavas. In addition, we present new $^{39}Ar/^{40}Ar$ ages on two selected whole rock samples.

Geological setting

The transition area between the Siebengebirge and the Westerwald is part of an east–west trending array of Tertiary and Quaternary volcanic fields in Germany including from west to east: the Eifel, the Siebengebirge, the Westerwald, the Vogelsberg, the Hessian Depression, the Rhön, the Heldburger dyke swarm and the Oberpfalz region (Jung et al., 2005;

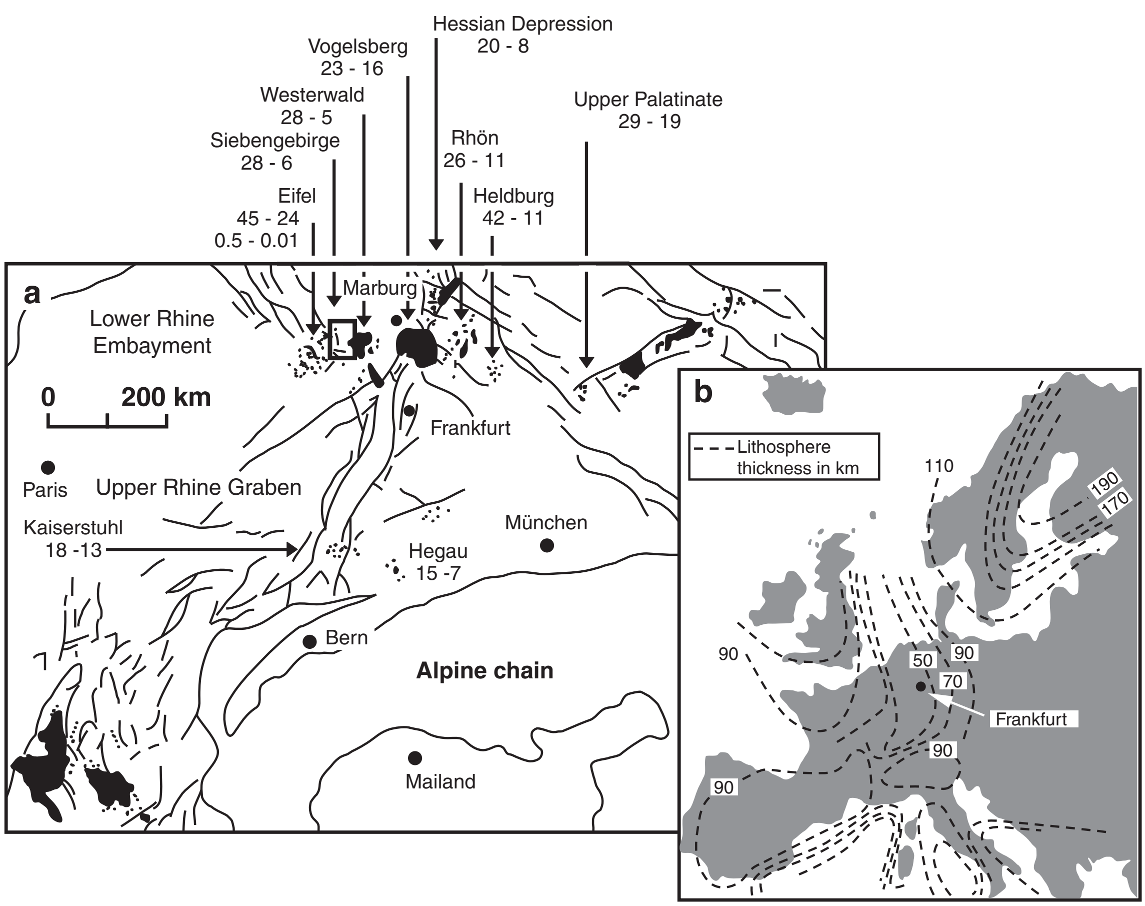

Fig. 1. (a) Distribution of Cenozoic volcanic rocks in Central Europe, modified from Wedepohl et al. (1994). Numbers denote K–Ar or Ar–Ar ages compiled from Lippolt (1982) and Wilson and Downes (2006). (b) Contour map of lithospheric thickness in Europe, modified from Wedepohl et al. (1994).