Lithos 106 (2008) 351–364

Contents lists available at ScienceDirect

Lithos

journal homepage: www.elsevier.com/locate/lithos

$^{40}Ar/^{39}Ar$-ages of phlogopite in mantle xenoliths from South African kimberlites: Evidence for metasomatic mantle impregnation during the Kibaran orogenic cycle

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ARTICLE INFO

Article history:
Received 19 May 2008
Accepted 12 September 2008
Available online 20 September 2008

Keywords:
Cratonic lithosphere
Ar–Ar dating
Metasomatism
Southern Africa

ABSTRACT

We applied the $^{40}Ar/^{39}Ar$ dating method to an extensive suite of phlogopites from kimberlite-hosted mantle xenoliths (dominantly garnet bearing) from the mines of Bultfontein (South Africa), Letseng-la-Terae and Liqhobong (Lesotho). Argon extraction was performed by conventional high resolution stepwise heating technique, laser incremental heating technique and laser spot analysis. All age spectra obtained by conventional analysis indicate various degrees of ^{40}Ar loss during kimberlite emplacement, but never resulted in a total reset of the argon system. Most intriguingly, the sample-specific maximum apparent ages cluster between 1.0 and 1.22 Ga for the phlogopites with the least disturbed age spectra. A maximum apparent age of 1.02 Ga was observed during laser heating analysis. Individual grains tend to yield older ages in their cores, with successively younger ages at their rims. The range in age obtained via the laser fusion technique and with conventional stepwise heating technique agrees with each other, as well as with literature data. The often inferred presence of excess ^{40}Ar in those phlogopites cannot explain the coherent age pattern in the large suite of samples. Hence, the age constraint of 1.0–1.25 Ga is regarded as geologically meaningful and assigned to metasomatism of the local cratonic mantle during the advent of Kibaran orogenesis (1.00–1.25 Ga). The major consequences of our findings are: (i) The argon system of phlogopite can remain closed for long time scales, even at ambient temperatures of 800–1200 °C within the mantle, most likely because the solid/solid partitioning behaviour of Ar between phlogopite and other major phases in the mantle strongly favours phlogopite, or because conventionally inferred diffusivity of argon in phlogopite is seriously overestimated. Thus, the $^{40}Ar/^{39}Ar$ phlogopite system appears to be a valuable tool for deciphering ancient metasomatic events affecting the lithospheric mantle. (ii) The cratonic lithospheric mantle below southern Africa may have been frequently influenced by different episodes of fluid or melt migration during subduction of oceanic crust at active continental margins.

1. Introduction

Since Archean times the evolution of the continental lithosphere has been characterized by amalgamation and disintegration of terranes and magmatism during the course of orogenic cycles leading to successive growth of the respective cratonic blocks. This is reflected in the history of the Kaapvaal craton, southern Africa (Fig. 1). Late Archean and Proterozoic-age mobile belts were episodically accreted onto a mid-Archean-aged core, considerably extending the continental lithosphere. Major geotectonic events include the Limpopo orogeny, that led to amalgamation of the Kaapvaal and Zimbabwe cratons (~ 2.7 Ga), and the Eburnian (~ 2.0–1.7 Ga), Kibaran (~ 1.25–1.0 Ga), Pan-African (~ 500 Ma) and Gondwanide (Cape Fold Belt, ~ 280–230 Ma) accretionary events (Thomas et al., 1993). In between these periods of crustal agglomeration continental rifting and rift-related magmatism occurred, particularly during the fragmentation of Gondwana (~ 180–130 Ma). Major magmatic events in southern Africa include the intrusion of the Bushveld Complex (~ 2.0 Ga), the Karroo flood basalts (~ 190 Ma), and several periods with a high rate of kimberlite emplacement (e.g. in the Kimberley and Lesotho areas, ~ 80–90 Ma ago). All these events could have had an impact on the composition and structure of the cratonic lithospheric mantle keel. In particular, observed local refertilization of initially strongly depleted mantle via introduction of melts and fluids enriched in incompatible elements might be explained by metasomatic processes during the Archean or Proterozoic (Pearson et al., 2003). This metasomatism may

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doi:10.1016/j.lithos.2008.09.001

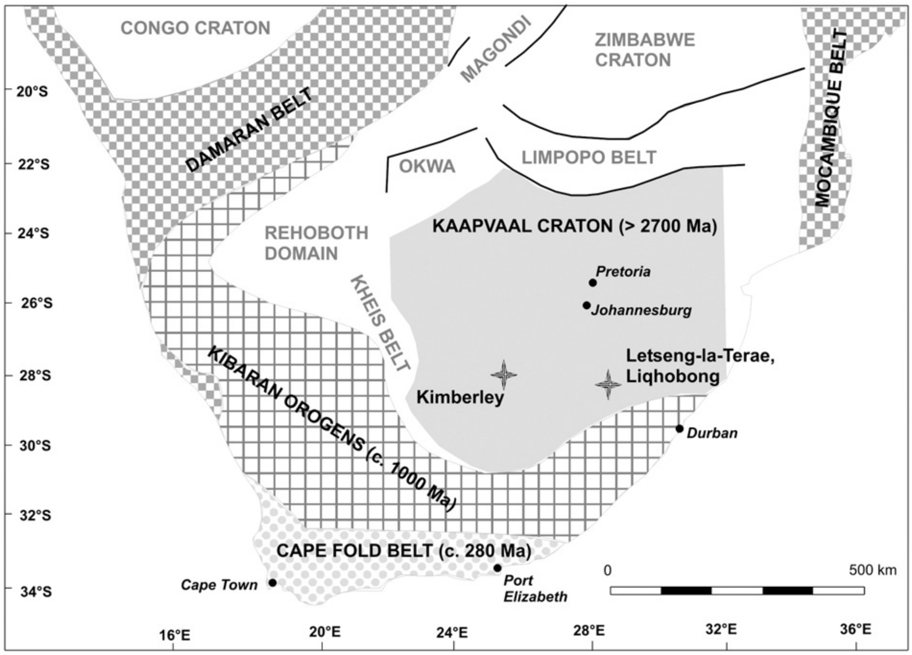

Fig. 1. Geotectonic map of southern Africa with locations of sampled kimberlite pipes of Bultfontein (South Africa), Letseng-la-Terae and Liqhobong (both Lesotho) (modified from Thomas et al., 1993). The latter two are emplaced close to the tectonic border between the Archean Kaapvaal Craton and the Mesoproterozoic Natal Fold Belt.

have been responsible for the formation of diamond and phlogopite within the mantle at different times.

Phlogopite is a possible candidate to determine the time of a metasomatic imprint and its potential association with major geotectonic events. Previous studies showed that $^{40}Ar/^{39}Ar$ ages of phlogopite in mantle xenoliths (garnet peridotites, phlogopite nodules, e.g. Kaneoka and Aoki, 1978; Phillips and Onstott, 1988; Pearson et al., 1997; Johnson and Phillips, 2003) are significantly older than the emplacement age of the kimberlite host. This was often ascribed to the presence of excess (mantle) ^{40}Ar (Kaneoka and Aoki, 1978; Phillips and Onstott, 1986, 1988; Johnson and Phillips, 2003). More recently, $^{40}Ar/^{39}Ar$ ages of phlogopite from Siberian kimberlites were partly interpreted as relict ages (Pearson et al., 1997). A different view is shared by Kelley and Wartho (2000) who demonstrated that the K–Ar-system can be regarded as a closed system even over extended time scales at temperatures far above the commonly accepted closure temperature of phlogopites (~ 450 °C, e.g. Reiners and Brandon, 2006). The authors argue that since K and Ar are highly incompatible in the major mantle minerals, both elements tend to favour the phlogopite lattice. This interpretation is consistent with results from the Baltic shield, that exhibit a consistent chronology with a variety of dating methods (Kempton et al., 2001). However, Johnson and Phillips (2003) have questioned the relevance of this result for phlogopites from xenoliths in kimberlites. In any case, $^{40}Ar/^{39}Ar$ dating of phlogopite in high pressure mantle rocks has only rarely been applied. This is mainly due to difficulties in interpreting of the obtained age spectra related to late-stage disturbance of the K–Ar system during transport in the host kimberlite. In addition, this late interaction might be different at the scale of a single grain, leading to highly variable ages from different individual grains. Hence, the common application of laser-dating might introduce a statistical bias that could be circumvented by $^{40}Ar/^{39}Ar$-dating of a larger subset of phlogopites with the conventional step-heating method.

In this study we applied the $^{40}Ar/^{39}Ar$ dating method for dating phlogopite from both garnet and spinel-bearing peridotite xenoliths from South Africa and Lesotho. We demonstrate that $^{40}Ar/^{39}Ar$ dating can be a useful tool in deciphering the timing of mantle metasomatism in spite of the high mantle *P*–*T* conditions, which exceed the commonly assumed closure temperature of Ar in phlogopite.

2. Sample locations

The xenoliths studied are from the Cretaceous kimberlite pipes at Kimberley, South Africa, and Letseng-la-Terae and Liqhobong, Lesotho (Fig. 1). The latter two kimberlite pipes intruded into the Tugela

Table 1
P–*T* conditions of xenolith samples

Sample	Rock type	*P* [GPa]	*T* [°C]
02 Bult 2	Grt-lherzolite	3.20 [BK90]	850 [BK90]
02 Bult 5	Spl-lherzolite	–	–
02 Bult 6	Grt-lherzolite	3.25 [BK90]	845 [BK90]
02 Bult 7	Grt-lherzolite	2.93 [BK90]	815 [BK90]
02 Bult 9	Cpx-Megacryst	–	–
Kim 1[a]	Grt-lherzolite	4.37 [BK90]	1112 [BK90]
Kim 3	Spl-lherzolite	–	–
Kim 5[a]	Grt-harzburgite	4.26 [BK90]	1082 [L95]
Kim 8[a]	Spl-harzburgite	<4.60[b]	997 [BK90]
Kim 9	Spl-amphibole lherzolite	–	–
Kim 17[a]	Grt-harzburgite	4.64 [BK90]	1196 [BK90]
Kim 25[a]	Grt-lherzolite	4.30 [BK90]	1048 [BK90]
Kim 31	Grt-harzburgite	–	–
Let 14[a]	Grt-lherzolite	4.45 [BK90]	1108 [BK90]
Let 39[a]	Grt-lherzolite	4.64 [BK90]	1083 [BK90]
Liq 1[a]	Grt-lherzolite	4.63 [BK90]	1157 [BK90]
Liq 9[a]	Spl-harzburgite	<3.00[b]	920 [BK90]
Liq 11[a]	Grt-lherzolite	4.47 [BK90]	1083 [BK90]
K 3[c]	Grt-lherzolite	4.56 [BK90]	1075 [BK90]
K 5[c]	Phl-peridotite	–	–
K 19[c]	Grt-lherzolite	3.75 [BK90]	925 [BK90]
K 22[c]	Phl-K-richterite peridotite	–	–
Let 2[d]	Grt-harzburgite	3.0 [BK90]	930 [H84]
Let 64[d]	Grt-lherzolite	3.8 [BK90]	990 [H84]

[BK90]: Al-in-opx barometer / 2-px-thermometer, Brey and Köhler (1990); [H84]: grt-opx-thermometer, Harley (1984); [L95]: ol-spl-thermometer, Li et al. (1995).
[a] Woodland and Koch (2003).
[b] Maximum pressure after Carroll Webb and Wood (1986).
[c] Simon et al. (2007).
[d] Simon (2004).