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An $^{40}$Ar–$^{39}$Ar investigation of high-pressure metamorphism and the retrogressive history of mafic eclogites from the Lanterman Range (Antarctica): evidence against a simple temperature control on argon transport in amphibole

Received: 17 March 2000 / Accepted: 13 November 2000 / Published online: 7 February 2001
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Abstract Mafic eclogites sampled from a restricted area in the Lanterman Range (Antarctica) retrogressed variably under amphibolite facies metamorphism. Assemblages range from well-preserved eclogite, with minor growth of Na–Ca amphibole, to strongly retrogressed ones with extensive development of Ca amphibole. $^{40}$Ar–$^{39}$Ar furnace step-heating experiments on the different amphiboles yield results varying from plateau ages of ~498 Ma to a near-plateau age of ~490 Ma, and the greater the amphibolite retrogression, the younger the age. $^{40}$Ar–$^{39}$Ar infrared laser-probe analyses on rock chips from a well-preserved eclogite and a slightly retrogressed one reveal the presence of an excess argon component. Whereas excess argon is invariably present in garnet and clinopyroxene developed under high-pressure metamorphism, it is heterogeneously distributed in amphibole on a millimetre scale. Results indicate that excess argon was incorporated during high-pressure metamorphism; this component was then lost during retrogression, while a change in composition of ambient argon to atmospheric argon occurred. New $^{40}$Ar–$^{39}$Ar data and previously published Sm–Nd garnet and U–Pb rutile ages obtained from the same well-preserved eclogite sample suggest that the oldest Na–Ca amphibole age is reliable and not an artefact due to the incorporation of excess argon. The variably retrogressed eclogites are thought to derive from different parts of the enclosing metasedimentary rocks that were variably invaded by fluids during amphibolite facies metamorphism. Thus the circulation of fluids promoting (re)crystallisation, and not temperature, was the main process controlling the rate of argon transport in the studied eclogites. The different $^{40}$Ar–$^{39}$Ar ages are interpreted to record diachronous amphibole growth at different crustal levels during exhumation. Data indicate that there was about a 10-Ma interval between the eclogite facies stage (at ≥1.5 GPa) and the Ca amphibole-hydration forming reaction (at 0.3–0.5 GPa); this translates into an average exhumation rate of 3–4 km/Ma.

Introduction

The argon dating method is one of the most widely used techniques for deriving age information on metamorphic rocks and for placing constraints on the thermal history and exhumation rate of crystalline basement. Different minerals with different closure temperatures are employed for this purpose; micas and amphiboles are mainly used for metamorphic terranes. In general, the use of the closure temperature (Dodson 1973) for a given mineral phase requires that (1) temperature was the only parameter controlling the rate of isotope transport and that, (2) radiogenic daughters diffusing out of the mineral are lost instantaneously and the concentration of that isotope at the grain boundary is zero. In a recent paper, Villa (1998) pointed out that temperature is often not the only parameter controlling the rate of isotope transport in minerals; the involvement of additional, fast processes which promote recrystallisation (i.e. fluid circulation and strain) is probably the rule and not the exception. More specifically, examples from nature have shown the impact of deformation and the circulation of fluids on the behaviour of argon in metamorphic rocks. Reddy et al. (1997) suggest that during deformation, localised fluid infiltration may produce spatially and compositionally different argon reservoirs within

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Editorial responsibility: I. Parsons
samples, which on a submillimetre scale remained isolated from argon in grain boundaries and in mineral phases. Thus in some circumstances even the second assumption for the use of closure temperatures may be violated. An additional problem in applying the argon dating method to high-pressure metamorphic rocks is that different minerals may be affected by the incorporation of excess argon (e.g. Tonarini et al. 1993; Li et al. 1994; Arnaud and Kelley 1995).

This study addresses these issues by applying the $^{40}$Ar--$^{39}$Ar dating method to mafic eclogites from the Lanterman Range (Antarctica). These rocks display different degrees of retrogression under amphibolite facies metamorphism and provide an excellent setting to study the effects of retrogression promoted by fluid circulation on argon dating. Both furnace step-heating and laser microprobe $^{40}$Ar--$^{39}$Ar techniques were applied to amphibole from one of the well-preserved eclogite samples previously investigated by the Sm--Nd and U--Pb dating methods (Di Vincenzo et al. 1997) and from three other samples from the same locality (from an area less than 300 m long), representing different stages of retrogression under amphibolite facies metamorphism. This study illustrates the complex behaviour of argon in rock samples that experienced a complex metamorphic history. It also shows that great care must be taken in deriving cooling histories from a small sample set, especially when the role of additional processes promoting recrystallisation (e.g. fluid circulation) is neglected.

Geological background, eclogite occurrence and previous geochronology

Northern Victoria Land is located at the Pacific termination of the Transantarctic Mountains (Fig. 1a), and is made up of three tectono-metamorphic terranes (Fig. 1b; Bradshaw and Laird 1983): (1) the Robertson Bay Terrane, a flysch-type sequence of Cambrian–early Ordovician age, (2) the Bowers Terrane, a Cambrian island arc with related sediments, and (3) the Wilson Terrane, composed of a metasedimentary sequence that experienced low- to high-grade metamorphism and was extensively intruded by calc-alkaline magmas during the Early Paleozoic Ross Orogeny. In the Early Paleozoic, both Bowers and Robertson Bay terranes experienced very low to low grade metamorphism (Buggisch and Kleinschmidt 1989), whereas the Wilson Terrane experienced a more complex metamorphic evolution. Along the inner margin of the Wilson Terrane, i.e. to the west of the Rennick and Aviator Glaciers (Fig. 1b), there is a low-pressure belt (Palmeri et al. 1994) which includes remnants of a polymetamorphic granulite complex (Castelli et al. 1991). In contrast, along the outer margin, i.e. at the boundary with the allochthonous Bowers Terrane, it is characterised by an intermediate-pressure belt (Grew et al. 1984) including metabasites with eclogitic assemblages (Ricci et al. 1996).

The mafic eclogites occur as lenses and pods (centimetre to metre) enclosed in quartzo-feldspathic and pelitic gneisses along the Antarctic paleo-Pacific margin of Gondwana in the Lanterman Range (Fig. 1; Ricci et al. 1996). They occur in a narrow belt, intercalated with amphibolite facies metasediments, extending along the fault contact between the Wilson Terrane and the Bowers Terrane. The main foliation in both host gneisses and boudined mafic rocks strikes northwest and is defined by the amphibolite facies minerals which overprinted the eclogite facies structures (Capponi et al. 1997; Talarico et al. 1998). Ricci et al. (1997) proposed that both formation and exhumation of the Lanterman eclogites occurred during the Cambro-Ordovician Ross orogenic cycle. Some mafic bodies exhibit a well-preserved eclogite assemblage with minor amphibolite retrogression evidenced by the formation of diopside + Na-rich plagioclase symplectite and Na–Ca amphibole. In contrast, Ca amphibole developed so extensively in some bodies that only a few relics of the earlier high-pressure metamorphic phase are preserved. Still other mafic bodies display intermediate features. Di Vincenzo et al. (1997) identify three main metamorphic stages: (1) an eclogite facies stage at temperatures of up to ~850 °C and a minimum pressure of 1.5 GPa; (2) a medium-pressure amphibolite facies stage, with temperatures ranging from 630–750 °C and pressures of 0.7–1.0 GPa, during which the symplectite began to form and Na–Ca amphibole first appeared; (3) a low-pressure amphibolite facies stage with temperatures ranging from 500–650 °C and pressures of 0.3–0.5 GPa, as shown by the extensive development of Ca amphibole. In addition, based on microstructural evidence and on the overlapping of Sm–Nd garnet ages and $^{238}$U–$^{206}$Pb rutile ages, Di Vincenzo et al. (1997) infer that these rocks experienced fast cooling and exhumation and that the high-pressure metamorphic event occurred ~500 Ma ago. Goode and Dallmeyer (1996) for samples from the same area (less than ~10 km from the outcrop sampled for this study; Fig. 1c) report an $^{40}$Ar–$^{39}$Ar plateau age of 487.5 ± 0.4 Ma (486.1 ± 0.4 Ma intercept date from isochron plot) for one hornblende from an amphibolite, interpreted to date cooling through ~530 °C, and ages of ~482 Ma for four muscovite separates derived from micaschists, interpreted to date final cooling through ~375 °C. Based on these data, Goode and Dallmeyer (1996) infer that after the amphibolite facies metamorphism, the average cooling rate was ~30 °C/Ma.

Sample description and petrological data

The samples selected for this study come from an outcrop ~300 m long, located on the ridge between the Husky Pass and Hunter Glacier (Fig. 1c). Samples represent different stages of the evolution of mafic eclogites: (1) sample TC13 is a well-preserved eclogite, (2) G19 is a slightly retrogressed eclogite, (3) CP20 is a retrogressed eclogite which still preserves mineralogical and structural relics of the eclogite stage, and (4) TC7D is an amphibolite whose microstructural features suggest a complete retrogression of an earlier eclogite assemblage. The main textural and compositional features of investigated samples are summarised in Table 1.

Eclogites (samples TC13 and G19) are fine grained with a grano-nematoblastic structure and consist of omphacite, garnet and rutile, with accessory quartz, apatite, epidote and ilmenite. Rare phengite and biotite are also present in sample G19; the former is found as a relic within symplectitic pseudomorphs of biotite and plagioclase. Moreover, the rocks display channelled portions composed of a symplectitic association of Na-poor clinopyroxene + plagioclase after the omphacite which formed during decompression. The channelled symplectite is scarce in sample TC13 but widespread in sample G19. Amphibole (5 and 15 vol% of the mineral assemblage in samples TC13 and G19 respectively) shows three different microstructural and compositional sites (Table 1): type-I Na–Ca amphibole (barroisite, Mg-taramite, Mg-kataphorite – Leake et al. 1997) in the well-preserved eclogite portions (Fig. 2a); type-2 Na–Ca amphibole poikiloblasts, occasionally showing tschermakite rims, in the symplectite-rich channels (Fig. 2b);