Proceeding of the IGCP-440 and LEGENDS International Symposium and Field Workshop on "The Role of Sri Lanka in Rodinia and Gondwana Assembly and Break-up", March-april 2003, Centenary Publication, Geological Survey & Mines Bureau, Sri Lanka (K.V.W. Kehelpannala Ed) pp 18-21

Cooling Rates of the Precambrian Basement of Sri Lanka: Problems and Perspectives

Fernando, G.W.A.R.[1], Baumgartner, Lukas P.[2], Hauzenberger, C.A.[3], and Hofmeitster, W.[4]

1. Department of Geology, University of Peradeniya, Peradeniya, Sri Lanka
2. Institute of Mineralogy and Petrology, BFSH2, CH 1015 Lausanne, Switzerland
3. Institute für Mineralogie und Petrologie, Universität Graz, A-8010 Graz, Austria
4. Institut für Geowissenschaften, Johannes Gutenberg-Universität Mainz, D-55099 Mainz, Germany

Introduction

Understanding the pressure-temperature-time history of high-grade metamorphic terranes is critical in order to evaluate the thermal and tectonic processes in the lower continental crust. The evaluation of P-T-t history relies primarily on metamorphic P-T conditions, effects on the role of fluids and the cooling history. Cooling rates can serve the majority of information on the exhumation history.

Cooling rate of the rocks is usually determined by three different ways; (i) radiogenic isotopes (e.g. Mezger, 1990), (ii) stable isotopes (e.g. Eiler et al. 1992, 1995), (iii)analyses of ion-exchange diffusion zoning in the metamorphic minerals (e.g. Dodson, 1973, 1986; Lasaga, 1983; Florence and Spear, 1995). Although the first method has been widely used, the last one has been developed extensively to calculate the cooling history in the recent times.

Radiogenic isotope systems has long been known as a better method in the calculation of cooling rates if a better knowledge of closure temperatures of radiogenic minerals is available. However, reasonable cooling history can be elucidated using the age determination of a series of radiogenic minerals like zircon, monazite, allanite, biotite, garnet, and titanite etc. Fast Grain Boundary (FGB) model describes stable isotope fractionations and inter-crystalline zonation of co-existing mineral pairs, and this can be used to calculate the cooling rates of a metamorphic terrane (Eiler et al. 1992, 1995). The high temperatures and long cooling durations associated with granulite-grade metamorphism provide an ideal setting for test application of the FGB model. Application of the model has been greatly limited by the lack of published $\delta^{18}O$ data that include all the minerals present along with the rock mode and mineral grain sizes. One of the most frequently used approache on cooling rate calculations has been on zoning in garnets. Considerable attention was paid on garnet co-existing with biotite (Florence and Spear, 1995 and references therein). The method is based on the assumption that the observed zoning is diffusion controlled where the diffusion is driven by compositional changes at the rim of the garnet with biotite contact. It is believed that driving force for diffusion, which leads to change the composition of garnet at the rim, is strongly temperature dependent and constraints by Fe-Mg exchange between slower diffusing garnet and faster diffusing biotite. This is indicated by uniform composition of biotite and compositional zoning of garnet, which is characterized by flat core and steep zoning at the rim in many granulite terranes (e.g. Kinzigite from Black Forest, Germany-Weyer et al., 1999).

The granulite facies gneisses of the Highland Complex (HC) of Sri Lanka have long been regarded as part of an extensive Proterozoic terrane of Gondwana. The high-grade granulites of Sri Lanka are thus interpreted as having attained their metamorphic peak simultaneously to the final amalgamation of Gondwana. Near-isobaric cooling is consistent within the deep crust after the metamorphic peak (Hölzl et al. 1991). Cooling and uplift history of Sri Lankan basement has yet poorly been defined by either method. To date only a few studies have been done on cooling of Sri Lankan granulites using thermochronology (Hölzl et al., 1991; Burton and O'Nions, 1990). The recently published cooling rates inferred from garnet diffusion have given renewed interest to evaluate the internal consistency of cooling rates of Sri Lankan granulites (Fernando et al. 2003).

The purpose of this paper is to explore cooling rate calculations in the Sri Lankan Precambrian using thermochronology and diffusion modeling and to discuss some of the pitfalls that encountered in such calculations. We outline the combined method for calculation of cooling rates that may possibly provide less ambiguous results.

Pressure-Temperature Estimates

Estimation of peak metamorphic pressure-temperature conditions in high-grade rocks using thermobarometry is subject to considerable uncertainty because of the propensity of these rocks to re-equilibrate during exhumation. However, the chemical equilibrium of minerals can be destroyed to variable extents by continuation of inter and intra-crystalline cation exchange along with net transfer reactions at the mutual contacts of minerals from their peak metamorphic values and thus obscure attempt to reconstruct the peak conditions (e.g. Eiler et al., 1992; Florence and Spear, 1995).

Pyroxene granulites and garnet-biotite gneisses from the central granulite belt in Rupaha, Sri Lanka bear the near equilibrium assemblages, thus allowing the application of ion – exchange thermobarometry. Metamorphic peak temperatures and pressures, estimated with two-pyroxene thermometry and garnet-clinopyroxene-plagioclase-quartz (GADS) barometry, yield 875 ± 20^{o}C and 9.0 ± 0.1 kbar. These peak metamorphic conditions are significantly higher than those obtained by garnet-biotite Fe-Mg exchange thermometry of 820 ± 20^{o}C. Maximum calculated core temperatures of approximately 875^{o}C are to be expected in most garnets from garnet-biotite assemblages and calculated core temperatures were as low as 800^{o}C because of reset flat zoning profiles of garnets. Only narrow garnet rims touching biotite exhibit retrograde zoning in terms of Fe and Mg exchange.

Results and Discussion

The quantification of cooling rates using diffusion modelling is mainly based on the combination of peak P-T conditions with published closure temperatures of some radiogenic minerals. The original garnet composition has to recover prior to diffusion modelling as it was noticed that garnet core has been modified completely during retrogression. This was accomplished by using the modal abundances of the Fe-Mg phases in the rock (garnet, biotite and clinopyroxene), from which the bulk Fe-Mg was calculated. Consequently, the equilibrium composition was calculated with respect to Fe-Mg for this bulk rock composition and the different thermometric calibrations at 875^{o}C and 9 kbar. This was achieved by simultaneously solving the mass balance equation for Fe and Mg and the mass action equations describing Fe-Mg exchange. For these calculations it was assumed that no net transfer reaction had occurred during cooling. This assumption supported by the fact that no retrograde growth of any high temperature phases can be observed in the samples studied *(see Fernando et al. 2003 for more details)*.

The U-Pb data from metamorphic zircons from syntectonic granitoids yield an age of 608 ± 3Ma, which is interpreted as the timing of peak metamorphism (Fig. 1). The first cooling had occurred at a cooling rate of 1 – 5^{o}C/Ma starting at 608 ± 3Ma, 875^{o}C and 9 kbar. During this period, grain boundary and volume diffusion in garnet is fast and garnets are homogenously reset. Further cooling to lower temperatures at about the same rate of 1-5^{o}C/Ma slowed down volume diffusion in garnet producing the observed retrograde rims in garnet. The deduced slow cooling rate is probably due to a prolonged crustal residence time and slow ascent of this unit. This slow ascent can be explained as a consequence of erosion at the surface and isostatic compensation (see also Fernando et al. 2003). The Rb-Sr biotite ages of 439 ± 10 Ma (Hölzl et al. 1991), which are believed to record the time at temperatures around 300 ± 30 (Spear 1993), indicates the final cooling during the uplift of the basement.

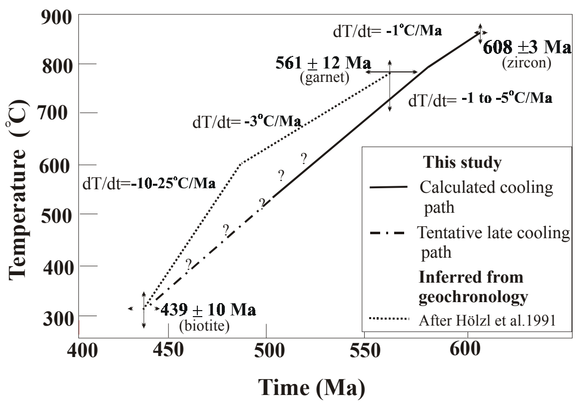

Fig. 1 calculated cooling paths of granulites from Sri Lanka from diffusion modelling (Fernando et al. 2003) compared with cooling rates inferred from geochronology (Hölzl et al. 1991). The U-Pb zircon age of 608± 3 Ma (Hölzl et al. 1991) was assumed to represent the age of peak metamorphism in this diagram

Some radiometric data available for Sri Lankan crystalline rocks provide a useful comparison with results of diffusion modelling (Fig. 1). Hölzl et al. (1991) have tentatively constructed a two stage cooling history from Sm-Nd garnet ages and Rb-Sr/whole rock biotite ages from the rocks of the HC. The cooling rate of 2 to 3^{o}C/Ma was determined from the garnet dating followed by a significantly higher rate of around 10 to 25^{o}C/Ma from biotite ages. These results are not exactly in agreement with the conclusions of cooling rate estimation of diffusion modelling, especially the last step of cooling. This discrepancy had occurred probably because the cooling rates were derived assuming the blocking temperature of garnet at 800^{o}C, which is significantly higher as proposed by Mezger et al. (1992). They reported that the closure temperature for Sm-Nd exchange in garnet would be significantly lower, probably about 600^{o}C. This suggests that the first stage of cooling inferred from Sm-Nd garnet ages is misleading. Relating the garnet age to a closure temperature at around 600°C and the biotite age to a closure temperature around 300°C, the resulting cooling history is in relatively good agreement of cooling rates of diffusion modelling. Burton and O'Nions (1990) calculated the cooling rate of orthopyroxene-bearing hornblende-biotite gneisses at Kurunegala and suggested the single cooling rate of ~10^{o}C/Ma in the first 50Ma subsequent to regional metamorphism. It seems the data available to interpret the cooling history of such rocks are insufficient because calculation is mainly based on Rb-Sr ages of hornblende and biotite.

The determination of cooling rates from thermochronological and diffusion-based may be different because temperature range over which the cooling rate was determined with the two methods were also different. Diffusion profiles are developed mostly near the metamorphic peak, whereas cooling rates determined from geochronology generally require a larger range of temperature up to 300^{o}C. It is concluded that these two independent measures of cooling rate do not overlap sufficiently to be used to support one another in typical regional metamorphic terranes. In addition, it is extremely difficult to obtain cooling rates for the high-temperature parts of the P-T path due to none-existence of suitable minerals. However, modelling of diffusion profiles can be effectively used to fill this important gap in the determination of cooling rates at the near-peak metamorphic conditions.

In conclusion, it can be stated that correct identification of co-existing phase compositions at different stages of the P-T evolution for diffusion modelling is the key to any valid interpretation of such rocks from high-grade granulite facies environments. Direct age determination of radiogenic minerals (monazite, zircon, garnet etc) in several samples of Sri Lankan Precambrian rocks may have the potential of contributing significantly to our understanding of cooling and exhumation history of Sri Lanka.

References

Burton KW, O'Nions RK (1990) The timescale and mechanism of granulite formation at Kurunegala, Sri Lanka. Contrib Mineral Petrol 106: 66-89

*Dodson MH (*1973) Closure temperature in cooling geochronological and petrological systems. Contrib Mineral Petrol 40: 259-274

Eiler JM, Baumgartner LP, Valley JW (1992) Intercrystalline stable isotope diffusion: a fast grain boundary model. Contrib Mineral Petrol 112: 534-557

Eiler JM, Valley JW, Graham CM, Baumgartner LP (1995) The oxygen isotope anatomy of a slowly cooled metamorphic rock. Am Mineral 80: 757-764

Fernando GWAR, Hauzenberger CA, Baumgartner LP, Hofmeister W (2003) Modeling of retrograde diffusion zoning in garnet. Evidence for slow cooling of granulites from the Highland Complex of Sri Lanka. Mineral Petrol. 77(1-2) *(in press)*

Florence FP, Spear FS (1995) Intergranuler diffusion kinetics of Fe and Mg during retrograde metamorphism of a pelitic gneiss from the Adirondack mountains Earth Planet Sci Lett 134: 329-340

*Ganguly J, Cheng W, Chakraborti S (*1998) Cation diffusion in aluminosilicate garnets: experimental determination in pyrope-almandine diffusion couples. Contrib Mineral Petrol 131:171-180

*Hölzl S, Köhler H, Kröner A, Jaeckel P, Liew TC (*1991) Chronology of Sri Lankan basement. In: *Kröner A* (ed) The Crystalline crust of Sri Lanka, Part 1, summary of research of the German-Sri Lankan consortium, Part 1, Geol. Surv. Dep., Prof. Pap. 5: 237-257

Lasaga AC (1983) Geospeedometry: An extension of geothermometry. In: *Saxena SK (ed)* Kinetics and equilibrium in mineral reactions. Adv Phy Geochem. 3: 243-284

Mezger K, Essene EJ, Halliday AN (1992) Closure temperature of the Sm-Nd system in metamorphic garnets Earth Planet Sci Lett 113: 397-409

Wayer S, Jarick J, Mezger K (1999) Quantitative temperature-time information from retrograde diffusion zoning in garnet: constraints for the P-T-t history of the Black Forest, Germany J metamorphic Geol 17:449-461