Pressure-Temperature-time-Deformation paths derived from FIAs, pseudosections and zoned garnets: significance and potential for ~1700 Ma deformation and metamorphism in the Big Thompson region of Colorado Rockies, USA

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Abstract

A progression of FIAs (foliation intersection/inflection axes preserved within porphyroblasts) in the foothills of the Colorado Rocky Mountains reveals three periods of garnet and staurolite growth and one growth phases each of cordierite and andalusite. These minerals grew in an overall prograde path, where the growth of garnet was always followed by the formation of staurolite for each FIA. For the last 1 period of FIA development the growth of staurolite was also followed by the development of andalusite and cordierite. Inclusions of earlier minerals within the younger phases have supported the porphroblastic mineral sequence obtained through FIAs. Thermodynamic modelling in the MnNCKFMASH system reveals that this episodic growth occurred over a similar bulk compositional range and PT path for each FIA in the succession. Multiple phases of growth by same series of reactions in these rocks strongly suggests that PT and X are not the only factors controlling the commencement and cessation of metamorphic reactions. The FIAs preserved by these porphyroblasts reveal that each stage of growth occurred during deformation and that the local partitioning of deformation at the scale of a porphyroblast was the controlling factor on whether or not the reaction took place. In-situ dating of monazite grains preserved within porphyroblasts from each FIA set has revealed that the first period of tectonism occurred around 1758.8±9 Ma, recorded within the porphyroblasts of FIA set 1, where garnet nucleated at 540-550°C and 3.8-4.0 kbars. The intersection of Ca, Mn, and Fe isopleths in garnet cores for 3 samples, containing FIA set 1, set 2 (1758.8±9, 1720.5±6.1 Ma) and set 3 (1674±7.6 Ma), trending NE-SW, E-W and SE-NW respectively, indicate that these rocks never got above 4kbars throughout the Colorado Orogeny. A slightly clockwise P-T path occurred for this orogeny.

Introduction

In multi-deformed and metamorphosed rocks the calculation of the precise Pressure-Temperature-time and Deformation (P-T-t-d) information of different events preserved within metamorphic index minerals is important step towards an understanding of orogenic belts. A main characteristic of orogens is such regions are a multiphase deformation history involving various complicated tectonic processes which result in overprinting of deformational and metamorphic information (such as early structural, textural and mineralogical features) preserved within the matrix. Therefore, the prograde paragenesis and kinematic indicators typical of crustal thickening are often uncertain. Deciphering of a plausible P-T-t-D path in such a region is often difficult. However, the porphyroblast are commonly considered to preserve a much longer history than matrix and hence, are traditionally considered as robust candidates to understand and decode the complex deformation and metamorphic history of such a region (e.g.

Spear, 1995). The matrix foliations, can easily be reactivated or re-used, during each younger deformation (Bell et al., 1998; Hickey and Bell and Welch., 2002) causing it to re-equilibrate to a different P-T condition. Therefore, relative to the total chronology of burial, deformation and uplift that the rocks have experienced standard microstructural practices provide insufficient information on the detailed topology of the P-T-t-D path associated with porphyroblastic growth.

The deconstruction of a reliable P-T-t-D path can be made possible by using foliation intersection axes preserved within porphyroblasts (FIAs), together with the microstructural, monazite chronology and thermodynamic modeling approaches. The FIAs tool uses the porphyroblasts which preserve inclusion trails. If garnet porphyroblast preserves a FIA set, its nucleation P-T information for that particular FIA forming event can be determined. This mineral is preferred because of its resistive nature and has the advantage to preserve growth zoning during a prograde metamorphic history, whereas most of the minerals in metapelites reach equilibrium at medium pressure-temperature conditions. Such dynamic conditions increase the overall reaction process by increasing diffusion rates and hence, the homogenization of phases. This makes it complicated for these minerals to preserve a record of their evolving chemistry. This is hard for conventional thermobarometry to predict, because the minerals which were in equilibrium with the core of the garnet at a given stage of the prograde history have disappeared, or have changed in composition, in response to P-T increase.

This contribution provides an example of an integrated approach by adapting the microstructural, FIAs, thermodynamic modelling (MnNCKFMASH) and chemical relationship reasons to investigate in details the overprinting effects of such a progression in the distribution of various index mineral phases (garnet, staurolite, andalusite and cordierite). The area described herein forms part of a Proterozoic orogenic belt in the southwestern United States and provides a classic example of a large high-T-low-P terrane and the problems associated with the tectonic interpretation of such regimes (Williams and Karlstrom, 1996).

Methods

1. FIAs measurement

The measurement of a FIA is achieved by cutting a minimum of eight vertically oriented thin sections around the compass from each rock sample to locate the switch in inclusion trail asymmetry (clockwise or anticlockwise) within the porphyroblasts (Fig. 1a and b). Where the FIA trends vary from the core to the rim of the porphyroblasts, a relative timing and thus a FIA succession can be established (e.g. Fig. 5a,b; Bell et al., 1998). A total of 67 oriented samples were collected that contained inclusion trails well enough developed for FIA measurement. 800 oriented thin sections were prepared from these samples. A total of 134 FIA and pseudo-FIA trends were determined and are shown as trends on a map for each sample location in Fig. 2.

2. P-T pseudosection, garnet isopleth thermobarometry and average P-T calculations

Three samples were selected containing growth-zoned garnets that could be used to construct isopleths, one for each of the 4 FIA sets distinguished (Shah, 2009A and B). Polished thin sections made from these samples were analysed for garnet on the JEOL JXA-8300 Superprobe housed in the Advanced Analytical Centre of James Cook University. A representative portion of each of these samples was crushed to obtain 50-100mg of powder for XRF analysis. Pseudosections were then calculated ((Table 2), in the MnNCKFMASH system using THERMOCALC 3.2.1 (Holland and Powell, 1985; 1990), the dataset of Holland and Powell (1990) and the mixing models of Tinkham et al. (2001). Plagioclase and quartz were assumed to be in excess and kyanite was omitted, as no sample enclosed this mineral. In all calculations water activity was assumed to be 1. The limitations of these procedures have been published in several articles (e.g. Tinkham et al., 2001). The P-T conditions of nucleation of garnet cores can be estimated using the intersection of XMn (spessartine), XCa (grossular), and XFe (almandine) isopleths (e.g., Vance and Mahar, 1998). These three isopleths (Table 3) for the core should intersect tightly in PT space for this approach to work (e.g. Evans, 2004; Sayab, 2005; Cihan et al., 2006). The X-ray maps for all these samples were examined for apparent zoning in the elemental concentration of Mg, Fe, Mn and Ca (Shah, 2009B). All samples preserve normal growth zoning.

Garnet rim and matrix mineral compositions were used to calculate P-T conditions of the matrix using the average P-T mode in THERMOCALC (Powell et al. 1998). Isopleths from the rim regions of garnet do not provide constructive estimation of P-T conditions due to preferential fractionation of some elements into garnet cores (Cihan et al., 2006).

3. Dating of FIA sets

Monazite grains were dated within the foliations defining each FIA set (Shah, 2009B) with FIAs set 1, 2 and 3 forming from around 1760 to 1670Ma (Shah, 2009B).

Examples

Accurate measurement of the foliation inflection/intersection axes preserved within different porphyroblastic phases (FIAs) has made it possible to decode lengthy and complex histories of deformation and metamorphism in orogens around the world (e.g. Bell et al., 1998; Bell and Newman, 2006; Cihan et al., 2006). More than ten years of research and data have already been published using this technique from tectonically complex regions around the world (e.g. Bell and Mares, 1989; Bell et al., 1998; Sayab, 2005).

Conclusions

The FIA succession and the inclusion trail/matrix microstructural relationships suggest that the pelitic rocks in the Colorado Frontal region have experienced multistage porphyroblastic development. The sequential order of porphyroblast growth was commonly garnet, staurolite, andalusite and finally cordierite. Garnet grew early during each deformation that affected this region. Staurolite growth commenced after garnet and grew during each stage of FIA development. Staurolite normally grows at higher temperatures that could be related to granitic intrusion or some cause of crustal heat flux. Such sequential growth of index minerals in pelites has been investigated in many magmatically heated LPHT terrains around the globe (e.g., Bell and Rubenach, 1983; Sayab, 2005).

Metamorphic/tectonic relationships

~1700Ma orogeny

The FIA age data correlates well with previous assessments of the age of Colorado Orogeny in this region that range from 1780 to 1700 Ma (Sims and Peterman, 1986). A ~1760 Ma age for FIA set 1 is consistent with deformation accompanying initial accretion (Sim et al., 2003; Bickford et al., 1993). The SW-NE trend of FIA set 1 would have formed during NW-SE directed shortening and accords well with the present orientation of the Cheyenne Belt which is regarded as a suture zone. The presence of different shear zones with the same trend as of FIA set 1 suggests, these might have been formed very earlier during the initial accretion processes. The nucleation PT conditions obtained from the garnet core preserving this FIA set are 3.5-4Kbars and 540-550°C. Slightly higher-grade metamorphism occurred during the development of FIA set 2 trends. Garnet development was relatively smaller during this event and was followed by staurolite formation. Neither cordierite not andalusite has grown during this event (c.f., Selverstone, 1997). An age range of ~1721±6.4Ma was measured for this FIA set using monazite inclusions within garnet and staurolite porphyroblasts. Garnet nucleated at a temperature and pressure range of 450-550°C and 3.4-3.65Kbars during this event. The W-E trend of FIA set 2 would have been formed during N-S directed shortening and accords well with the W-E trending axial traces of folds in the region. Growth of garnet and staurolite during this FIA set, with a monazite inclusion age around ~1721±6.4Ma, overlaps the intrusion of 1726±15, trondhjemites in the area. The trondhjemite intrusions lie sub-parallel to bedding and may have been emplaced during compressional or gravitational collapse phases during FIA set 2.

During the formation of FIA set 3, garnet, staurolite, cordierite and andalusite porphyroblasts were produced in these rocks. Dating of monazite within inclusion trails defining this FIA set gives an age of 1674±16Ma. Garnet nucleated at a temperature and pressure range of 525-535°C and 3.3-3.6Kbars during this event. The NW-SE trend of FIA set 3 would have been formed during SW-NE directed shortening and accords well with the NW-SE trending axial traces of folds in the region. This event was the last thing that happened during the regional ~1700Ma orogeny, in this area. The progressive formation of garnet-staurolite-andalusite-cordierite mineral assemblages at ~3-6kbars of pressure and at varying temperatures of ~420-620°C suggests a LPHT metamorphic assemblage during this orogeny. The complete absence of a high pressure mineral phase such as kyanite, further illustrated the LPHT tectonic setting.
After the end of the last phase of Colorado orogeny, rocks have remained at the same depth till the arrival of ~1400 orogeny, suggested by nucleation PT conditions of garnet cores, preserving FIA set 4 trends.

Pressure-Temperature-time-Deformation (PTtD) path

Based on the mineral assemblages, garnet core isopleths, average PT conditions and pseudosection information, a slightly clockwise PTtD path is suggested for ~1700 orogeny.

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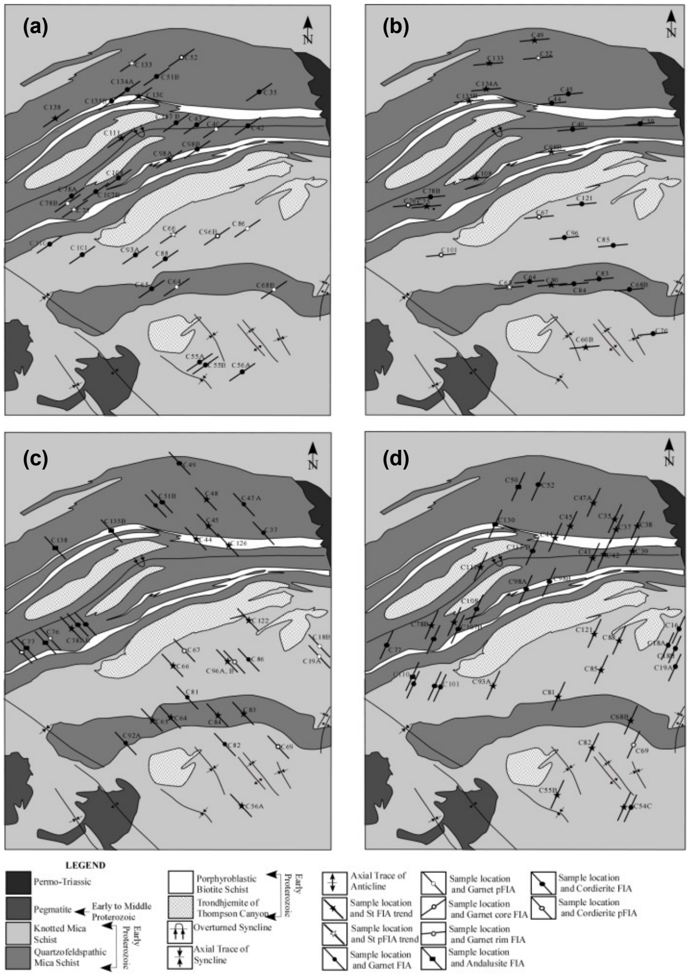

Fig. 1

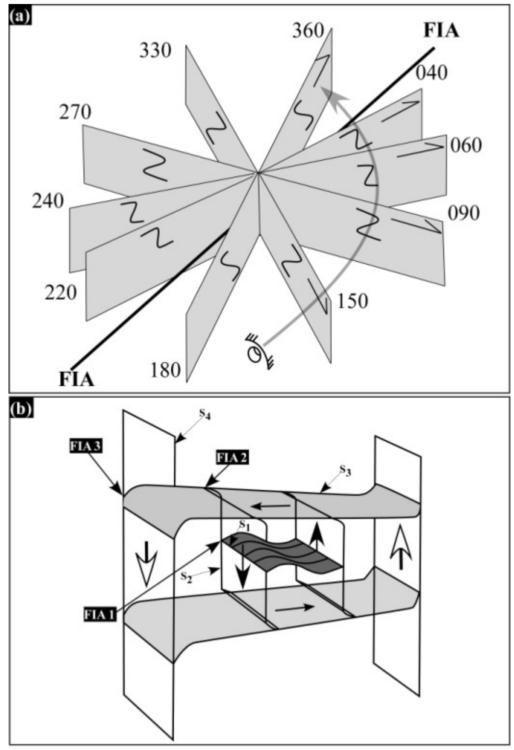

Fig. 2

Figure 1. FIA trends for successive FIA sets in the Big Thompson region of Colorado Rockies. (a) Shows the geological map, location and the FIA trends of all samples which preserve inclusions trails of FIA set 1. This FIA set is preserved within garnet and staurolite porphyroblast. In (b) the geological map, location and the FIA trends of all samples which preserve inclusions trails of FIA set 2 are shown. Only garnet and staurolite porphyroblast contains this FIA set. (c) Shows the geological map, location and the FIA trends of all samples which preserve inclusions trails of FIA set 3. This FIA is preserved within garnet, staurolite, andalusite and cordierite porphyroblasts. In (d) the geological map, location and the FIA trends of all samples which preserve inclusions trails of FIA set 4 are shown. This FIA is preserved within garnet, staurolite, andalusite and cordierite porphyroblasts.

Figure. 2. (a) Sketch illustrating the method developed by Bell et al. (1995, 1998) by which the trends of FIA are measured. This technique uses changes in asymmetries of inclusion trails in a porphyroblast, when viewed in a consistent direction for successive striking vertical thin sections. The range of inclusion trail geometries expected in thin sections of varying orientation along a single FIA, which is between 0 and 40 in this case, is shown. The inclusion surfaces marked on thin sections represent the geometry of the inclusion trails within the porphyroblast. Thin section orientation is marked as barbed arrow. The position of eye ball indicates that the geometry is viewed from that direction. (b) The 3-D sketch illustrates a change in FIA sets.