Trabajos de Geología, Universidad de Oviedo, 30 : 208-213 (2010)

Porphyroblast inclusion trails: a new reference frame for correlating orogenic terrains

M. SAYAB[1*] AND D. AERDEN[2]

[1]*National Centre of Excellence in Geology, University of Peshawar, Peshawar-25120, NWFP, Pakistan.*

[2]*Departamento de Geodinámica, Universidad de Granada, Fuentenueva s/n, 18002 Granada, Spain.*

[*]*e-mail: msayab@upesh.edu.pk*

Abstract: Tectonic and metamorphic correlation in ancient (Proterozoic) orogenic terrains has always been problematic. This is because of the lack of a suitable reference frame to correlate deformation and metamorphic events from one orogenic terrain to another. Measurement of porphyroblast inclusion trails as Foliation Intersection/Inflection Axes (FIA) allows the chronological and kinematic linking of deformation as well as metamorphism. FIA measurements in the Mesoproterozoic Mount Isa and Georgetown inliers of the North Australian Craton have revealed two separate orogenic events (O1 and O2), which not only correlate better within the orogen but also between the two terrains. Microstructural corelations have also been made with the Mesoproterozoic rocks of the SW USA. Hence, porphyroblast inclusion trails as FIA provide a new reference frame to help correlate orogenic terrains.

Keywords: Mount Isa, FIAs, porphyroblasts, inclusion trails, orogenesis.

Tectonic and metamorphic correlation of Proterozoic Rodinian terranes has proved problematic, partly because of incomplete understanding of the global distribution of pre-Gondwanaland fragments (Karlstrom *et al.*, 2001; Wingate *et al.*, 2002). Several mutually exclusive Rodinia models have been proposed to reconcile paleomagnetic, geochronological, metamorphic and structural data for different basement provinces, continental rifts and passive margins (e.g. the Missing-Link, SWEAT, AUSWUS and AUSMEX; Li *et al.*, 2008). An added problem concerning Rodinian terranes is their long-lived deformation histories (Page and Sun, 1998; Karlstrom *et al.*, 2001; Williams and Jercinovic, 2002) and high-grade polymetamorphism (Williams and Karlstrom, 1996; Sayab, 2008).

Research during the past two decades has demonstrated the merits of a new methodology for unravelling and correlating complex tectono-metamorphic histories based on the collection of orientation data for porphyroblast inclusion trails (Aerden, 2004; Sayab, 2008, and references therein). In particular, the orientation of "Foliation Intersection Axes" (FIA; Bell *et al.*, 1995) defined by polyphase inclusion trails has been found to be remarkably consistent across large metamorphic regions. In both the Mesoproterozoic Mount Isa and Georgetown inliers of the North Australia Craton, two age sets of FIA have been found with similar geographic trends (E-W and N-S, respectively), suggesting that both regions formed part of a continuous orogenic belt. Additionally, a tentative correlation can be proposed with Mesoproterozoic rocks exposed in the Grand Canyon of the southwestern United States, based on limited inclusion trail data also available for this third region (Ilg and Karlstrom, 2000). Thus, the microstructural "fingerprints" of two distinct tectonometamorphic cycles potentially recognized in different continents provide interesting constraints on various earlier paleogeographic reconstructions of Rodinia.

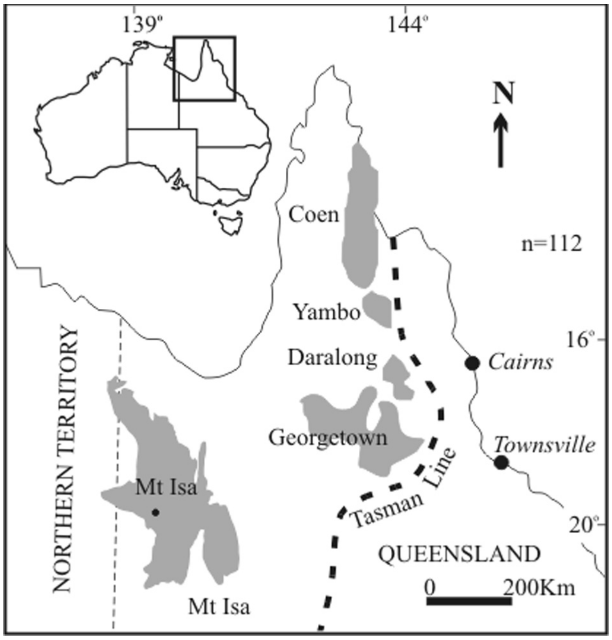

Figure 1. General map of the North Australian Craton showing the Mount Isa and Georgetown inliers.

Geological setting

The Mount Isa and the Georgetown inliers of NE Australia are Mesoproterozoic (Withnall, 1996; Page and Sun, 1998), multiple deformed and polymetamorphosed terranes with extensive bimodal intrusive and extrusive complexes (Fig. 1). The Mount Isa inlier is divided into three N-S-oriented tectono-stratigraphic belts (Blake, 1987), from east to west: the Eastern Fold Belt (EFB), Kalkadoon-Leichhardt Belt and Western Fold Belt, separated by late major reverse and/or strike-slip faults (Blake, 1987). The Isan orogenic event (1610-1510 Ma) was responsible for multiple deformation events (D1 to D4) with an anticlockwise P-T path (Bell and Hickey, 1998). Two major tectonothermal events are proposed for the Georgetown inlier. These were dated as D1 1570±20 Ma and D2 1553±3 Ma (Black *et al.*, 1998).

Method for determining FIA

The 'asymmetry switch' technique (Bell *et al.*, 1995) involves recording the asymmetry ('S' or 'Z') of curved inclusion trails preserved in porphyroblasts in a series of vertical thin sections with different strikes from the same samples. An opposite asymmetry will be noticed in sections whose strike lies on opposite sides of the FIA trend (Fig. 2). FIA are measured with respect to geographic coordinates and record the inflection/intersection lineations defined by inclusion trails in porphyroblasts. After FIA determination, their relative timing is based on three basic criteria: (1) multiple FIA preserved in core vs. rims of porphyroblasts (Bell *et al.*, 1995), (2) continuity of inclusion trails with respect to surrounding matrix foliation (Adshead-Bell and Bell, 1999), and (3) FIA trends parallel or at a high angle to matrix microstructures (Sayab, 2005). A complete description and methodology for measuring FIAs and their implications for tectonic processes can be found in Bell *et al.* (1995).

FIA succession in the NW Australia craton

An older group of E-W-trending FIA and a younger group of N-S-trending FIA were recognized in different parts of the EFB of the Mount Isa inlier based on the method described above. Both groups can be further subdivided into five sub-sets, which show basically the same time sequence in the White Blow formation (Sayab, 2005), Snake Creek anticline, Gilded Rose, Tommy Creek block and southern Selwyn

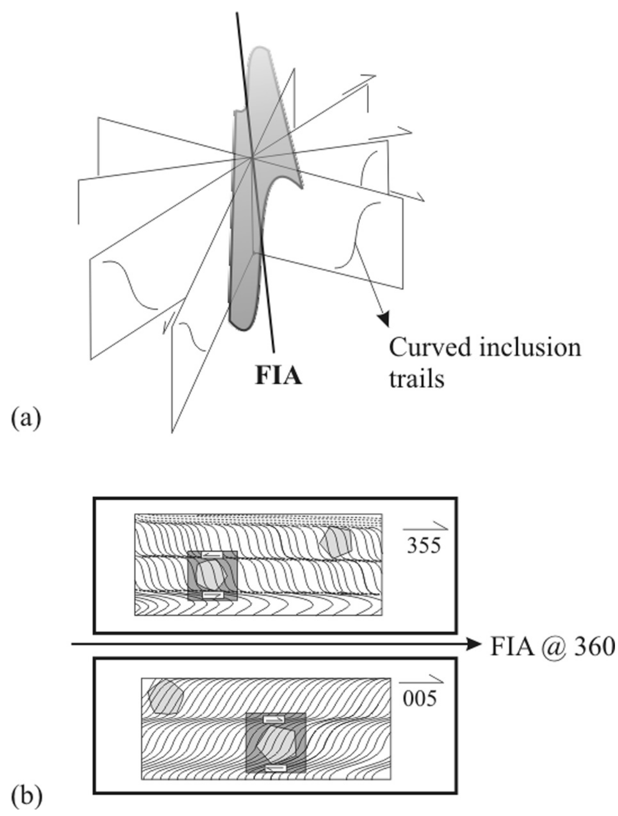

Figure 2. Diagrams illustrating the method by which porphyroblast FIA can be measured (Bell *et al.*, 1995). a) The asymmetry of inclusion-trails ('S' vs. 'Z') observed in a series of vertical thin sections with different strikes allows us to constrain the FIA trend in a sample (N-S in this case), (b) hypothetical microstructures in vertical thin sections striking N005 and N355.

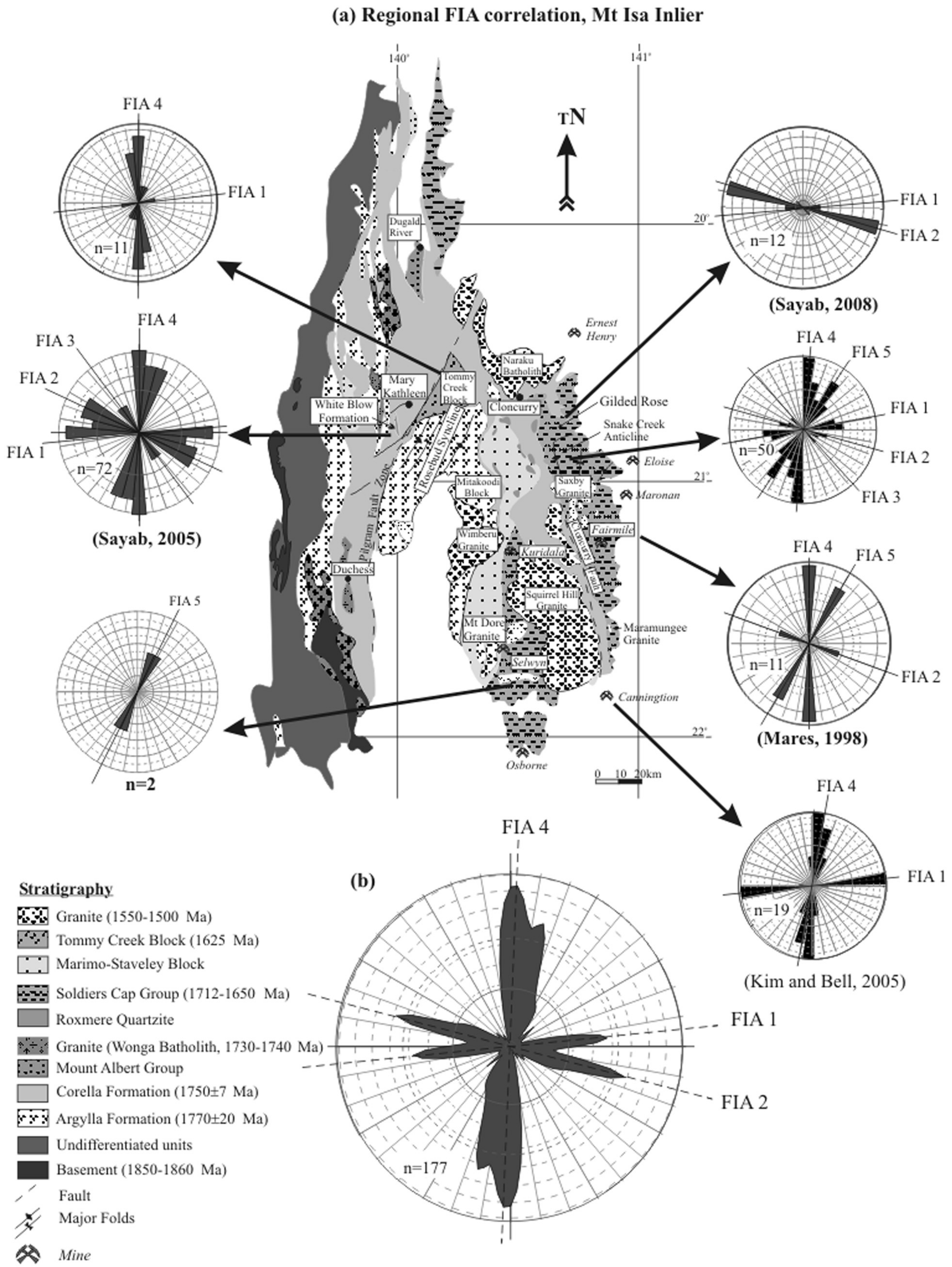

Figure 3. (a) Equal area rose diagrams for successive FIA sets and their proposed correlation across the Eastern Fold Belt of the Mount Isa inlier. E-W FIAs are consistently older than N-S FIAs, (b) total FIA measurements from the Mount Isa inlier at 1° interval.

Range (Sayab, 2008), Cannington (Kim and Bell, 2005) and Fairmile-Partridge areas (Mares, 1998) of the EFB (Fig. 3). The oldest sub-set (FIA 1) has an average WSW-ENE trend and was followed by the development of a younger WNW-ESE-trending FIA (FIA 2), locally by NW-SE FIA (FIA 3), NNE-SSW (FIA 4) and, finally, NE- SW (FIA 5). Figure 3 presents a graphical correlation chart summarizing the FIA succession deduced for the EFB of the Mount Isa inlier. It is interpreted that an initial N-S shortening event was responsible for the roughly E-W-trending FIA (sub-sets FIA 1 plus FIA 2) and that it was followed by E-W crustal shortening responsible for N-S-trending FIA (sub-sets FIA 4 and FIA 5).

FIA trends and microtextural relationships in the Robertson River Metamorphics of the Mesoproterozoic (1650 to 1500 Ma) Georgetown inlier are remarkably similar to those obtained from the Mount Isa inlier (Cihan *et al.*, 2006; Fig. 4). This strongly suggests that both regions formed part of a continuous orogenic belt and were affected by the same polyphase deformation history.

Correlating multiple stages of metamorphism based on FIA

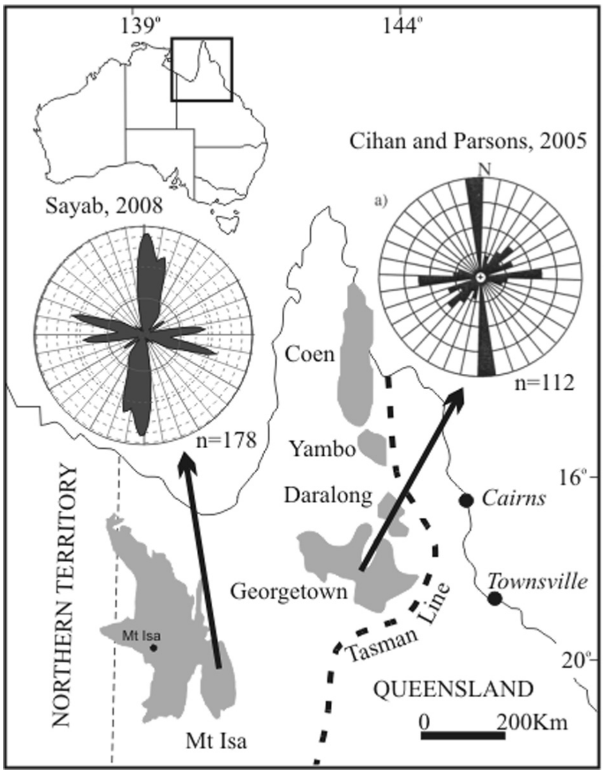

Figure 4. Rose diagrams showing correlation of FIA trends in the Mount Isa and Georgetown inliers of the North Australian Craton.

It is commonly assumed that porphyroblast growth occurs broadly synchronously with syn-metamorphic-tectonic processes affecting a homogenous matrix (Florence *et al.*, 1993; Zeh *et al.*, 2004). However, in recent years, detailed microstructural work has demonstrated that porphyroblast growth occurs in an episodic, highly heterogeneous manner in different samples and is punctuated by discrete deformation phases (Aerden, 2004). Consequently, P-T paths derived from a few samples without tight constraints on the timing of porphyroblast growth relative to a multiple foliation development history may be deceptive. Such constraints can be potentially obtained by *in situ* mineral dating, but much more easily by determining FIA orientations preserved in the porphyroblasts. Indeed, garnets from the EFB preserving the oldest recognized FIA sub-set have higher pressure cores (6.0±1.0 kbar; M1 of Sayab, 2008) than garnets hosting N-S-oriented FIA (3±1.0 kbar; M2 of Sayab, 2008). The two stages of porphyroblast growth and the associated large-scale kinematics deduced in the Mount Isa inlier are similar to those reported by Cihan *et al.* (2006) in the Georgetown inlier, 300 km further east.

Implications for Rodinia

Strike measurements of porphyroblast inclusion trails as observed on horizontal oriented thin sections by Ilg and Karlstrom (2000) led to the identification of two near-orthogonal sets in the Mesoproterozoic (1700-1600 Ma) supracrustal rocks of the Grand Canyon, Arizona. The regional "tectonic grain" in their study area is constituted by a pervasive NE-SW-striking subvertical foliation, partially included in porphyroblast rims. However, garnet cores consistently preserve NW-SE-trending inclusion trails, near-orthogonal to the younger trend. The positions of the southwestern United States and western Australia in the AUS-WUS reconstruction of Karlstrom *et al.* (2001) allows tentative correlation of the NW-SE and NE-SW-trending microstructures in the former with E-W and N-S-trending ones in the latter, respectively (Fig. 5).

Discussion and conclusion

Correlating tectonometamorphic events within or between ancient orogenic terranes has been traditionally hampered by the lack of a suitable reference frame or (micro) structural 'fingerprints'. This situation has dramatically changed since the discovery, in many orogens, of consistent orientation patterns defined by multiple generations of porphyroblast inclusion trails. In particular, regionally consistent trends

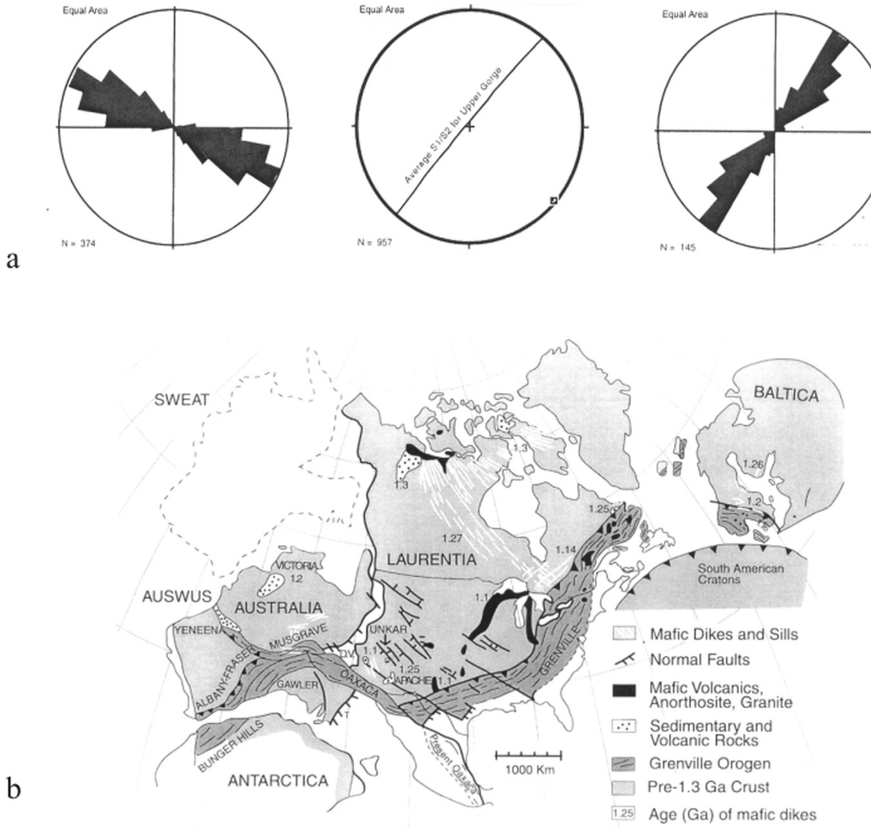

Figure 5. (a) Pitches of inclusion trails measured on horizontal thin sections from Mesoproterozoic rocks of the Grand Canyon, SW United States (Ilg and Karlstrom, 2000). The near-orthogonal bimodal trends are remarkably similar to those of the North Australian Craton (see Fig. 4), (b) AUSWUS reconstruction of Rodinia proposed by Karlstrom *et al.* (2001).

of foliation intersection axes (FIA) defined by polyphase inclusion trails have been shown to provide an effective framework for correlating heterogeneously developed larger-scale structures. Two FIA age-sets with almost identical orientations have been demonstrated in the Mesoproterozoic Mount Isa and Georgetown inliers of the North Australian Craton and suggest that both regions experienced the same two-stage orogenic history. A tentative correlation has been further established with Mesoproterozoic rocks currently exposed in the Grand Canyon of the SW United States exhibiting remarkably similar inclusion-trail patterns. The occurrence of two sets of orthogonal FIA in all three regions (Mount Isa inlier, Georgetown inlier, Grand Canyon) allows us to suggest that these regions formed part of a single continuous orogenic system, consistent with the proposed Rodinia reconstruction of Karlstrom *et al.* (2001). Thus, the inclusion trail signature of metamorphic rocks can potentially be used not just for correlating tectonometamorphic events between isolated metamorphic terranes but also for paleogeographic reconstructions as complementary information alongside geochemical and paleomagnetic data.

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