Origin of 'Millipede' and 'Rotational' Inclusion-Trail Microstructures in the NW Himalaya and their Tectonic Significance

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Conflicting kinematic models have been postulated for the development of 'millipede' and 'rotational' microstructures preserved in porphyroblasts involving porphyroblast rotation (e.g. Jiang and Williams, 2004; Jessell and others, 2009), non-rotation (e.g. Aerden and Sayab, 2008; Bell and Hobbs, 2010) or little relative rotation (e.g. Johnson, 2009). These different interpretations of porphyroblast microstructures have important implications for the tectono-metamorphic growth of orogenic terrains. For this study, we applied advanced 3D microstructural techniques to examine the orientation of inclusion trail patterns preserved in porphyroblasts in medium- to high-grade rocks of the Swat region of the NW Himalaya in Pakistan. This area represents Indian-plate rocks that were deformed and metamorphosed during the Himalayan orogeny.

Previous workers in the Swat area and adjacent regions assumed 'rotational' porphyroblast models to calculate shear strain and kinematics of the thrust sheets. However, the timing of porphyroblasts preserving different types of inclusion trail patterns with respect to successive deformation regimes that affected the study area have remained poorly constrained. In order to investigate the growth sequence of porphyroblasts and their relationship with the orogenic evolution of the NW Himalaya, we applied two independent techniques for determining the orientation of inclusion trails in 3D developed by Hayward (1990) and Aerden, (2003). Both techniques are based on the measurements of porphyroblast inclusion-trail microstructures from multiple, differently-oriented thin sections of single samples. Axes of relative porphyroblast–matrix rotation (FIA: Foliation Intersection/Inflection Axes) previously determined via these methods in other orogens have systematically revealed regionally consistent orientations of these microstructures that appear to relate to (successive) crustal shortening directions that can, commonly, no longer be deduced from the study of matrix microstructures alone (e.g. Bell and others, 1995).

Fifty-five samples analyzed using both techniques yield coherent single- and multi-FIA results that demonstrate the existence of three principal sets of FIA in the study area. These FIA sets can be distinguished based on their specific relative timing, and geographic trends (Figure 1a). The FIA-trend succession, from old to young, is SE-NW (FIA set 1), E-W (FIA set 2) and NNE-SSW (FIA set 3). FIA set 2 can be further subdivided into set 2a (ESE-WNW) and set 2b (ENE-WSW). The FIA succession suggests an anticlockwise rotation of the bulk shortening directions through time, consistent with the collision history of the Indian plate, Kohistan-Ladakh Island Arc (KLIA) and the Eurasian plate since 55 Ma (Figure 1b-d). The orientation of FIA set 2 can be correlated with early-formed E-W trending thrust-related structures, whereas the trend of FIA set 3 is consistent with the younger regional-scale NNE-SSW trending folds and shear zones. FIA set 1 reflects the orientation of primitive structures that mark the trend of initial collision of the Indian plate with the KLIA. Regionally, relics of these primitive structures are barely preserved due to transposition by later deformation that caused for FIA sets 2 and 3.

The relative timing of E-W versus NNE-SSW trending regional structures in the Swat region was controversial (cf. Coward and others, 1988; Treloar and others, 1989; DiPietro and others, 2008), but is now resolved by the succession of FIA data and crustal shortening directions recorded by these microstructures (Figure 1d). In addition, two separate kyanite-grade metamorphic cycles have been identified associated with N-S (FIA set 2) and E-W (FIA set 3) shortening. Our combined data for both 'millipede' and 'rotational' types of inclusion trails indicate that all developed during a polyphase deformation history without having experienced significant relative rotations between them.

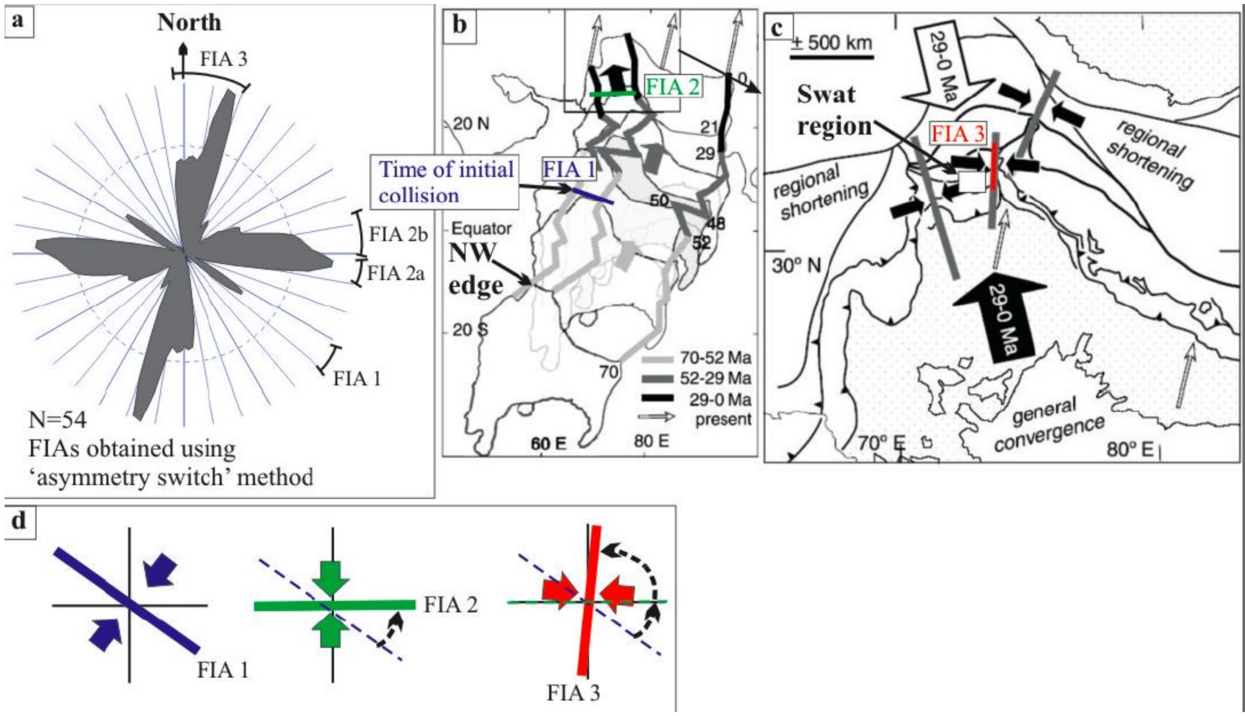

Figure 1. (a) Rose diagram showing FIA sets obtained with the 'asymmetry switch' method of Hayward (1990). (b) Movement trail of the Indian plate towards Eurasia after Patriat and Achache (1984). (c) Regional shortening directions inferred from fold orientations and plate convergence in the NW Himalaya (after Llana-Funez et al., and others, 2006). (d) Interpretation of the FIA sets (mean trends) with respect to the Indian plate (this study) convergence with the KLIA and Eurasian plate.

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