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STRUCTURE, METAMORPHISM AND TECTONICS OF THE CENTRAL NEPAL HIMALAYAS

Volume I

(Text)

Thesis submitted by

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in the School of Earth and Environmental Sciences

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STATEMENT ON THE CONTRIBUTION OF OTHERS

Prof. Tim Bell developed the FIA technique central to this study. He helped me design this project and spent several hours working with me on a dual head microscope. He edited all drafts and co-authored Section C and D of this thesis. We both agree that each of us conceptually, literally and graphically contributed 50% for these two sections.

Dr. Ioan V. Sanislav helped me on data acquisition of the mineral compositions and application of THERMOCALC computer program used in Section B of this thesis. Accordingly, he will be added as a co-author when this section will be submitted for publication.

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Section B

Section C

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THESIS ABSTRACT

Analysis of mylonitic garnetiferous rocks within the Kathmandu Thrust Sheet, which overlies the Lesser Himalayas along the southern part of the Main Central Thrust (MCT) and constitutes a leading edge of the Higher Himalayas, reveals a complex tectonometamorphic history. This portion of the MCT in the Central Nepal Himalayas, which is folded by the Gorkha-Kathmandu fold couplet, contains tectonometamorphic signatures that were difficult to recognize because of formation of the MCT and subsequent deformations. These have been accessed quantitatively via inclusion trails preserved in garnet porphyroblasts, in spite of their truncation by all matrix foliations. They preserve structural and metamorphic history obliterated in the matrix accessed by methodologies including

- identification and measurement of various microfabrics preserved in the matrix and shear senses revealed by them,
- measurement of Foliation Intersection/Inflection Axes (FIAs) preserved in garnet porphyroblasts and shear sense interpretation from asymmetrically curved inclusion trails,
- measurement of pitches of internal foliations within garnet foliations in vertical thin sections cut at a high angle to the related FIA trend,
- modelling of PT pseudosections using bulk rock compositions analysed at XRF facilities,
- calculation of PT conditions of garnet core nucleation using Fe, Mn and Ca isopleths calculated from garnet core compositions analysed on electron microprobe and

- calculation of average PT conditions with various rim geothermobarometric methods from the compositions of garnet rims and surrounding biotite, muscovite and plagioclase grains.

Different generations of crenulated matrix foliations from various parts of the Gorkha-Kathmandu fold couplet constitute a comprehensive archive of structural history related to movement along the MCT, its folding by the couplet and subsequent deformation events. The oldest foliation preserved in the matrix formed sub-vertically as can be observed in strain shadows of some garnet porphyroblasts. Curvature of this foliation into the sub-horizontal foliation that formed subsequently indicates top to the south sense of movement in spite of different geometries preserved in parts of the central limb of the fold couplet. Antithetic reactivation of the central limb during folding has locally switched this shear sense to top to the north. A sub-vertical foliation that formed axial planar to the Gorkha-Kathmandu fold couplet exhibits a switch in shear sense across each of the hinges with a south side up shear sense on the external limbs and north side up on the central limbs. Moderately to steeply north dipping foliation observed in the Kalphu river section overprints the axial plane foliation with a top to the south sense of shear. The youngest foliation in the region is a sub-horizontal foliation that shows a top to the north sense of shear. This feature, observed close to the MCT in the Kathmandu Thrust Sheet, suggests that the shear sense reversed from top to the south to top to the north when these rocks were uplifted into a zone that was affected by gravitational collapse as India-Eurasia collision continued.

Inclusion trails preserved within garnet porphyroblasts contain a succession of five FIA sets trending SSE-NNW, ENE-WSW, NW-SE, E-W and NNE-SSW. These

FIA sets formed as a result of change in the direction of bulk horizontal shortening associated with India-Eurasia collision. The intersections of Fe, Ca and Mn isopleths for garnet cores in PT pseudosections modelled from bulk rock compositions reveal that FIAs 1-5 formed respectively at 6.2 kbar and 515°C, 6 to 7 kbar and 545 to 550°C, 6.6 kbar and 530°C, 5.6 to 6.2 kbar and 525 to 550°C and 6.8 to 6.9 kbar and 520 to 560°C. This data suggest that the PT conditions varied little during regional Barrovian metamorphism that commenced after India-Eurasia collision and stopped prior to development of the MCT. Pressures of about 11 kbar yielded by various rim geothermobarometric methods do not accord with those in the succession of garnet cores indicating that their rims are not in equilibrium with the surrounding silicates in the matrix. Pervasive matrix foliations in the rocks that overlie the MCT in the Kathmandu Thrust Sheet are mylonitic. The matrix grains deformed plastically during mylonitisation and did not equilibrate with garnet rims that probably underwent some dissolution as garnet porphyroblasts are competent and tend not to deform internally. Furthermore, the significantly higher pressures calculated using the rims do not accord with the development of all matrix foliations as the rocks were carried towards the surface along the developing MCT.

Multiple generations of internal foliations in garnet porphyroblasts developed sub-vertically and sub-horizontally. The preservation of these orientations in the porphyroblasts would not have been possible if they had rotated during their growth or subsequent deformations. A very small number of foliations that deviate from these orientations predated garnet growth and are present only in garnet cores. Some rocks belonging to each FIA set in the succession contain at least three and up to four foliations in garnet porphyroblasts. This suggests that Kathmandu Thrust Sheet rocks were affected by at least 15 events of horizontal crustal shortening and gravitational collapse, which occurred before mylonitic foliations related to the MCT truncated the internal foliations in garnet porphyroblasts.

The succession of five FIA sets exhibits a remarkable correlation with the motion of India between 50 and 29 Ma relative to Eurasia that was arbitrarily kept stationary in its present position. The direction of bulk horizontal shortening perpendicular to FIA 2 aligns with the appropriate segment of India's motion. If Eurasia moved along the trend perpendicular to FIA 2 but at different speeds to form the five FIA sets, then it should have moved NNW during FIAs 1, 3 and 4 and SSE during FIA 5 in order to produce the required resultant motion with the overall northward moving Indian plate.

Looking overall west, curvatures of steeply dipping foliations into gently dipping ones in garnet porphyroblasts are dominantly CW in FIAs 1, 3 and 4; coaxial in FIA 2; and dominantly anticlockwise in FIA 5. Therefore, the shear sense switched from being top towards north or coaxial during the development of the first four FIAs to being top towards south during the fifth. These developments occurred at a depth of at least 23 km as revealed by 6-7 kbar of pressures associated with all garnet nucleation. The presence of both asymmetries in each FIA with a dominance of clockwise asymmetry or coaxiality in FIAs 1 through 4 and an anticlockwise asymmetry in FIA 5 suggest that the central Nepal rocks migrated from north side of the orogen core to south side when FIA 5 developed. This occurred as India, lying some 7kms deeper, was displaced northwards below Eurasia during the 50 to 20 Ma period while FIAs 1 through 5 developed. It was accompanied by many phases of horizontal shortening and crustal thickening leading to periods of gravitational collapse and vertical shortening.

This eventually resulted in lateral southwards extrusion of the rocks towards the earth's surface as the MCT developed. The top to the south sense of shear in FIA 5 is similar to that recorded by mylonitic foliations, which truncate inclusion trails in garnet porphyroblasts and transported the Higher Himalayan rocks southwards by about 100 km on the MCT.

Keywords: Higher Himalayan crystallines, Kathmandu Thrust Sheet, MCT, FIAs, inclusion trail asymmetries, THERMOCALC, PT pseudosection, garnet core isopleths, subvertical and subhorizontal foliation development, orogen core

INTRODUCTION AND THESIS OUTLINE

Himalayan orogenesis began when northern margin of the Indian continental crust that was travelling passively on the Tethyan oceanic crust collided with the Eurasian Plate about 55 million years (Patriat and Achache, 1984; Searle et al., 2003) following the closure of the Tethys Ocean. The Himalayas have been broadly divided into four east-west trending tectonostratigraphic units by thrusts and normal faults. These bounding structures coalesce into a gently dipping decollement known as the Main Himalayan Thrust (Harrison et al., 1999; Upreti, 1999) and are progressively younger from north to south. The Main Central Thrust (MCT) placed high grade crystalline rocks of the Higher Himalayas over the Lesser Himalayas. The MCT initiated about 25 Ma (Johnson et al., 2001; Yin, 2006) and accommodated about 100 km of displacement (Hubbard and Harrison, 1989). The South Tibetan Detachment System separates the Higher Himalayan crystallines from the Tethys Himalayas and this normal fault has been interpreted to have developed roughly contemporaneously with the MCT (Searle et al., 2003). The Main Boundary Thrust (MBT) brought low-grade to unmetamorphosed Lesser Himalayan sediments over the Sub-Himalayas and folded the MCT at about 10 Ma (Meigs et al., 1995). The Sub-Himalayas consist of molassic sediments derived from the Himalayas itself and are thrust over the Quaternary Indo-Gangetic sediments along the Main Frontal Thrust.

The Higher Himalayas forms the metamorphic core of the Himalayas. However, metamorphic and structural conditions that predated the development of the MCT have been poorly understood (Guillot, 1999). That is, about 30 million years of Himalayan tectonic history are not distinguishable in the matrix of these rocks because of the intensity of deformation associated with the development of the MCT and subsequent structures. Consequently, porphyroblasts that predate the movement on the MCT constitute a potential source of information about tectono-metamorphic conditions that developed in the orogen core between the collision of the two plates and MCT development. This comprises more than half of the period of orogenesis.

Porphyroblasts were initially thought to rotate due to shear on an encompassing foliation as they grew resulting in inclusion trails with a double spiral shape (Rosenfeld, 1970; Schoneveld, 1977). Rather than rotating, Bell & Johnson (1989) suggested that such porphyroblasts overgrew successive crenulation hinges forming near orthogonal to one another to preserve spiral, staircase or sigmoidal shapes and argued that porphyroblasts overgrow sub-vertical and sub-horizontal foliations produced by the effects of bulk horizontal shortening and gravitational collapse that alternately occur during an orogenesis. The intersection of such two near-orthogonal foliations was referred to as a Foliation Intersection/Inflection Axis in porphyroblasts (FIA). Hayward (1990) and Bell et al. (1995) developed a method to quantitatively measure FIAs, which are essentially the axes of curvature of asymmetrically curving inclusion trails. Since then, asymmetrically curved inclusion trails preserved in porphyroblasts have been routinely used to unravel structural and metamorphic history destroyed in rock matrix as a result of deformation events that can occur after porphyroblast growth (Bell et al., 1995; Ham and Bell, 2004; Ali, 2010; Sanislav and Bell, 2011). Considering that FIAs should form perpendicular to the direction of bulk horizontal shortening, Bell et al. (1995) correlated FIAs with the relative motion between African and European plates.

Although FIAs have somewhat similar tectonic significance regardless of the process that produced them (Passchier et al., 1992; Aerden, 2004), rotation of porphyroblasts during subsequent events of deformation would redistribute pre-existing FIA trends relative to geographic coordinates. Similarly, inclusion trail asymmetries would indicate opposite shear senses depending on whether a rotation or non-rotation model is used to interpret porphyroblast growth mechanism. The non-rotation model considers asymmetrically curved inclusion trails as relics of crenulated foliations preserved within porphyroblasts and the shear sense is determined likewise. Thus, clockwise asymmetry indicates clockwise shear sense and anticlockwise asymmetry indicates anticlockwise shear sense according to this model. However, if a porphyroblast gradually overgrew adjacent matrix foliation and rotated during its development, the shear sense would be opposite to the asymmetry of inclusion trails. Therefore, whether porphyroblasts rotated or not must be affirmed before analysing inclusion trails contained in porphyroblasts for a wealth of tectonic and metamorphic information they preserve.

Some porphyroblasts contain different FIA trends in their cores and rims. A porphyroblastic mineral with a particular FIA trend can be overgrown by another porphyroblastic mineral or the same mineral phase with a different FIA trend. These relationships can be used to establish a relative timing succession between various FIA sets and group the porphyroblasts into different generations. Absolute timing of FIA sets can be calculated with in-situ dating techniques such as electron microprobe analysis of monazite inclusions. The intersection of X_{Fe}, X_{Mn} and X_{Ca} compositional isopleths from garnet core in PT space on a PT pseudosection represents the PT condition for garnet nucleation and thus for formation of the FIA set preserved in that particular core (Vance and Mahar, 1998; Evans, 2004). The PT pseudosection is modelled from effective bulk rock composition obtained from XRF analysis of rock samples. Commonly, these calculations are performed on a computer program THERMOCALC developed by Powell and Holland (1988).

This PhD Thesis examines complicated structural, metamorphic and tectonic history preserved in mylonitic garnetiferous rocks collected from the Kathmandu Thrust Sheet close to the MCT. The Thrust Sheet constitutes a leading edge of the Higher Himalayas in central

Nepal where the latter has extensively developed in the south and the MCT has almost reached the MBT. Stratigraphically, the KTS is divided into two groups, higher-grade Bhimphedi Group and weakly to unmetamorphosed Phulchauki Group (Stöcklin, 1980). The Kathmandu Thrust Sheet has been folded by the Gorkha-Kathmandu fold couplet.

This Thesis is comprised of four sections. Each section constitutes an independent paper intended for publication in a mainstream international journal. Sections C and D were co-authored by my supervisor Prof Tim H. Bell and myself. Dr. Ioan V. Sanislav helped me on pseudosection modelling and EPMA analysis. He will be a co-author with me when this section will be submitted for publication. Organisation of the four sections in this thesis maintain a logical flow. Volume I contains text and references list and volume II contains figures, tables and appendices.

Section A explains various generations of matrix foliations that can be observed on vertical thin sections striking 30° or less apart and discusses how they relate to the motion along the MCT, its folding by the Gorkha-Kathmandu fold couplet and more recent tectonic events that affected the KTS in the Central Nepal Himalayas. Pitches of these foliations were measured on about six variously striking vertical thin sections and plotted on an equal area stereonet with the computer program GEOrient v9.5.0 (http://www.holcombe.net.au/software/) to calculate their true orientation in three dimensions. Shear senses associated with these foliations provide important information on structural evolution of the Kathmandu Thrust Sheet since MCT development. Cross-cutting relationships between different matrix foliations and shear senses, particularly in the samples containing three or more foliations, provided a partial picture of the succession of matrix foliations. These overprinting relationships were combined with their position in the Gorkha-

Kathmandu fold couplet and the known deformation episodes to establish a complete succession of different foliations and shear senses. Mylonitic foliations related to the MCT and subsequently developed younger foliations always truncate internal foliations within garnet porphyroblasts. This demonstrates that garnet growth in the Kathmandu Thrust Sheet predated MCT development.

Section B focuses on metamorphic evolution of the garnetiferous mylonitic rocks lying adjacent to the MCT in the Kathmandu Thrust Sheet. The Higher Himalayan crystallines were affected by regional Barrovian metamorphism right after India collided with Eurasia and lasted until the motion on the MCT occurred. Monazite inclusions in garnet porphyroblasts above the MCT have been dated at 32 and 24 Ma in the Kathmandu Thrust Sheet (Gehrels et al., 2006) and at 45 Ma and between 28 and 19 Ma about 100 km to the east (Catlos et al., 2002). To comprehend the complexity of garnet growth in PTt space during the pre-MCT phase of Himalayan orogeny, porphyroblasts were grouped into five categories based on five FIA sets quantitatively measured from inclusion trails preserved therein. The porphyroblasts that preserved different FIA sets in their cores and rims helped establish the relative timing succession between the FIA sets. The bulk chemical composition for samples containing each FIA set was analysed using XRF facilities. Pseudosections showing stability of different mineral phases in the PT space were modelled on the computer program THERMOCALC. The content of major elements in garnet cores and rims and other major silicates were determined by their electron microprobe analysis. Core isopleths for almandine (Fe), spessartine (Mn) and grossular (Ca) end members were calculated for garnet porphyroblasts containing each FIA set. The intersection of these isopleths on PT pseudosections represent PT conditions of nucleation of related garnet porphyroblasts and development of the FIA sets preserved in their cores. Apparent equilibration PT conditions were calculated for eight samples using the composition of garnet rims and surrounding silicates. These calculations were performed on calcmode 2 of Thermocalc and on conventional geothermobarometric computer programs.

Section C describes the process of regular bulk horizontal shortening and gravitational collapse that alternately affected the Higher Himalayan crystallines prior to the development of the MCT. The occurrence of these near-orthogonal shortening events is demonstrated by the dominance of sub-vertically and sub-horizontally oriented foliations that are preserved within garnet porphyroblasts in the Kathmandu Thrust Sheet, which constitutes the southern proximal portion of the Higher Himalayas. Pitches of 287 internal foliations across garnet cores and rims were accurately measured on thin sections cut at a high angle to the related FIA trend and the results were plotted on vertical rose diagrams. A strong dominance of these sub-vertical and sub-horizontal orientations would not have occurred if the garnet porphyroblasts preserving them had rotated.

Section D discusses how repetitive gravitation collapse that occurred between the episodes of bulk horizontal shortening eventually brought the Higher Himalayan rocks that were metamorphosed at depths of more than 23 km towards the surface along what is now called the MCT. Shear senses indicated by asymmetrically curving inclusion trails belonging to each FIA set record the structural history that these rocks had been through between India-Eurasia collision and MCT development. The asymmetries were read on thin sections cut at a high angle to the related FIA trend and plotted on a histogram for each FIA set. Relative abundance of clockwise and anticlockwise asymmetries looking overall west for steep to gentle curving inclusion trails for each FIA set suggested where these rocks were located with respect to orogen core during the development of different FIA sets. Particularly important was the switch in dominant asymmetry from clockwise looking west in FIAs 1-4 to anticlockwise looking west in FIA 5 on gently dipping foliations, which exhibited that the shear sense reversed from being top to the north to top to the south towards the end of FIA development. The variation in direction of bulk horizontal shortening revealed by the succession of FIA sets, which can potentially result from changes in India's motion relative to Eurasia, were compared with India's overall northward path between 50 and 29 Ma.

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SECTION A

THE POST GARNET GROWTH HISTORY OF FOLIATION DEVELOPMENT ALONG THE MAIN CENTRAL THRUST

Section A

THE POST GARNET GROWTH HISTORY OF FOLIATION DEVELOPMENT ALONG THE MAIN CENTRAL THRUST

ABSTRACT

Garnet porphyroblasts predate all foliations preserved in rocks adjacent to the Main Central Thrust in the central Nepal Himalayas. The five foliations preserved in the matrix are not the remains of S/C foliations as there is no evidence for the synchronous development of any of them; they formed sequentially. The oldest foliation preserved in the matrix formed sub-vertically and relics of this orientation are preserved in the strain shadows of some garnet porphyroblasts. It was followed by the development of a gently dipping foliation that crenulated it anticlockwise looking west. This gently dipping structure was folded on a large scale to form the Gorkha-Kathmandu fold couplet at which time a sub-vertical axial plane foliation developed as the latter switches both its vergence and differentiation asymmetry across each fold hinge. In the Kalphu River section, the axial plane foliation is truncated by a moderately to steeply north dipping foliation with anticlockwise asymmetry looking west. This large-scale fold couplet was overprinted by a gently dipping foliation that curves the earlier formed steeply dipping foliation clockwise looking west. The shear senses indicated by the curvature of crenulation hinges into differentiated crenulation cleavage switched from the first to the second of the gently dipping foliations indicating that the direction of motion reversed from top to the south on the Main Central Thrust to top-to-the-north across the whole rock mass with time. This switch in shear sense suggests that these rocks have been moved upwards due to the continued effects of collision between India and Asia and are now undergoing the extensional effects of gravitational collapse.

Keywords: foliation, differentiation asymmetry, shear sense, reactivation of fold limb, MCT

1 INTRODUCTION

Folding is a complex structural process that apart from developing a new set of fabrics also potentially rotates and modifies pre-existing fabrics and can even reverse shear sense on them (Bell, 1986; Davis, 1995). Therefore, any interpretation of fabrics, particularly shear sense, in a complex fold-thrust belt such as the Himalayas must take the effects of folding into account. In the Central Nepal Himalayas, the MCT has been folded by a regional-scale Gorkha-Kathmandu fold couplet (Stöcklin, 1980; Johnson et al., 2001). No systematic attempt has been made to identify and classify the various foliations that can result from a the complicated structural history that this region has been through. This paper describes a succession of crenulated foliations and associated shear senses observed in thin sections cut from samples collected above the MCT that underlies the Kathmandu Thrust Sheet in the Central Nepal Himalayas. Structures that postdate the ones associated with folding provide an insight into the more recent history of the region that has not previously been documented. Multiple vertical thin sections striking 30° or less apart were used to identify and measure the pitches of different matrix foliations and determine their orientation and shear sense in 3-D. The terms such as antithetic shear sense, reactivation and differentiation asymmetry used in this paper are as in Davis (1995) and Bell et al. (2003).

2 REGIONAL GEOLOGY

The area contains two major stratigraphic units called the Nawakot and Kathmandu complexes that are separated by the Mahabharat Thrust (Stöcklin, 1980). The Mahabharat Thrust is considered to be the southern part of the MCT (Fig. 1). The Nawakot Complex consists of pelitic, psammitic and calcareous metasediments. Except for a few garnet porphyroblasts that appear close to the Main Central Thrust, metamorphism in this complex rarely exceeds sericite-chlorite grade. The overlying Kathmandu Complex is divided into two groups, the Bhimphedi Group consisting of relatively high-grade metasediments and the younger unmetamorphosed to weakly metamorphosed Phulchauki Group. Kathmandu Complex rocks increase in metamorphic grade towards the Main Central Thrust reaching garnet-grade (Stöcklin, 1980). The gneiss zone to the north of the Kathmandu Valley contains kyanite porphyroblasts and grains of sillimanite (Sapkota, 2005).

3 MATRIX FOLIATIONS AND DIFFERENTIATION ASYMMETRIES

Various generations of crenulated foliations can be recognised in the matrix. All these foliations truncate internal foliations preserved within garnet porphyroblasts in 3D and thus postdate them (Fig. 2). The orientations of the matrix foliations have been calculated from their apparent dips using 6 or more vertical thin sections striking 30°. Approximately, 3500 measurements were made from 170 thin sections. Commonly, 2-3 foliations can be recognized in each sample. The foliation numbers 1, 2, and 3 in Table 1 relate to individual samples. They are correlated later.

Ellipsoidal to sigmoidal quartz grains, elongate-shaped mica grains and mica fish are crenulated and curve into younger truncational foliations or differentiated crenulation cleavages. These truncational foliations contain thin layers (one or two grains thick) of mica and fine-grained quartz. Asymmetrical curvature of these crenulated foliations into crenulation cleavages has been termed as differentiation asymmetries and they are described as being clockwise or anticlockwise viewing towards a particular direction. Looking west, the foliations in the matrix display the following differentiation asymmetries (Fig. 3; Bell et al., 2003):

3.1 Gently-dipping foliations with anticlockwise differentiation asymmetry looking west

This asymmetry was observed at Melamchi, close to the hinge on the northern external limb of the Gorkha-Kathmandu fold couplet shown in Fig. 1. The crenulated foliations dip moderately north and bend anticlockwise into sub-horizontal to horizontal foliations (Fig. 3a, b).

3.2 Gently-dipping foliations with clockwise differentiation asymmetry looking west

This asymmetry is exhibited by moderately south dipping sigmoidal crenulated foliations that curve into weaker sub-horizontal to horizontal foliations (Fig. 3c, d). Elongate zoesite grains are aligned parallel to the crenulated foliations in sample S17. A few samples collected from the central limb of the fold couplet show this asymmetry.

3.3 Sub-vertical foliations with an anti or clockwise differentiation looking west

Moderately to steeply south dipping foliations on the central limb of the fold couplet are crenulated and bend into sub-vertical to vertical foliations, displaying an anticlockwise differentiation asymmetry (Fig. 4a, b). Crenulated foliations collected from the south limb of the fold couplet (Fig. 1b) dip moderately north and steepen into sub-vertical foliations with a clockwise differentiation asymmetry observed in a sample (H1; Figs. 4c). The angle between the intersecting foliations varies between 20° and 55°.

3.4 N/S-dipping foliations with anticlockwise differentiation asymmetry looking west

On the central limb of the Gorkha-Kathmandu fold couplet (Fig. 1), gently to moderately south dipping foliations formed by ellipsoidal and sigmoidal quartz and mica grains steepen and curve anticlockwise into steeper foliations dipping in the same direction (Fig. 4d, e). The angle between the two foliations varies between 15° and 25° in the schists collected around Galchhi and up to 40° in the Sheopuri gneisses. Locally along the Kalphu River, also on the central limb of the Gorkha-Kathmandu fold couplet (Fig. 1), overprinting foliations dip moderately towards the north and crenulate sub-vertical to vertical foliations with an anticlockwise differentiation asymmetry (Fig. 4f, g). On the southern limb of the fold couplet (Fig. 1), moderately north dipping sigmoidal crenulated foliations formed by mica fish and elongated quartz grains curve anticlockwise into more gently-dipping foliations that dip north (Fig. 5a).

3.5 S-dipping foliations with clockwise differentiation asymmetry looking west

In a few samples collected from the central limb of the fold couplet around Galchhi (Fig. 1), steeply south dipping foliations curve clockwise into moderately south dipping foliations (Fig. 5b, c). The latter are weakly developed and contain fine mica and quartz grains aligned along them. The two foliations are inclined to each other at 25°-30°.

4 INTERPRETATION AND DISCUSSION

4.1 Overprinting differentiation asymmetries looking west

Samples displaying three or more foliations and differentiation asymmetries can be used to determine an age succession for these fabrics. In samples T11, K9 and S13, moderately south-dipping foliations displaying clockwise differentiation asymmetry are themselves crenulated by sub-vertical to vertical foliations with anticlockwise differentiation asymmetry (Fig. 6a, b). Moderately south-dipping foliations in sample S7 curve with anticlockwise asymmetry into steeper south-dipping main matrix foliations. The latter are weakly crenulated by sub-vertical foliations with anticlockwise asymmetry (Fig. 6c, d). Moderately north-dipping foliations with an anticlockwise differentiation asymmetry bend clockwise into sub-vertical foliations in sample H1. Sub-vertical to vertical foliations in samples S10b, S14, S23, K2, K6, K7, K8, K10, K14, K19 and K23 with anticlockwise differentiation asymmetry curve anticlockwise into moderately north-dipping foliations (Fig. 6e). In sample S30, relics of moderately south-dipping foliations with an anticlockwise differentiation asymmetry curve clockwise into sub-horizontal to horizontal foliations (Fig. 6f).

These crosscutting relationships place the following constraints on the succession of the foliations and the asymmetries:

1. Sub-vertical foliations with anticlockwise differentiation asymmetry postdate moderately south-dipping foliations with anticlockwise differentiation asymmetry.
2. Sub-vertical foliations with anticlockwise differentiation asymmetry postdate moderately south-dipping foliations with clockwise and anticlockwise differentiation asymmetries.

3. Sub-vertical foliations with clockwise differentiation asymmetry postdate moderately north-dipping foliations with anticlockwise differentiation asymmetry.
4. Moderately north-dipping foliations with anticlockwise differentiation asymmetry postdate sub-vertical foliations with anticlockwise differentiation asymmetry.
5. Sub-horizontal foliations with clockwise differentiation asymmetry postdate moderately south-dipping foliations with anticlockwise differentiation asymmetry.

These overprinting relationships do not provide any evidence of how anticlockwise differentiation asymmetries along sub-horizontal to horizontal foliations relate to the other asymmetries or how clockwise and anticlockwise asymmetries on moderately south-dipping foliations relate to each other. However, the location of these fabrics in the Gorkha-Kathmandu fold couplet plus the deformation history of the region allow their relative timing to be interpreted (see below).

4.2 Shear senses and deformation episodes

4.2.1 Development of top-to-the-south fabric and its folding

Most of the differentiation asymmetries described above can either be related to movement along the MCT or the effects of development of the Gorkha-Kathmandu fold couplet (Fig. 7). Anticlockwise differentiated asymmetry into sub-horizontal to horizontal foliations looking west indicates a top-to-the-south shear sense (Figs. 3a, b and 7b). This top-to-the-south fabric has been associated with the motion on the MCT (Brunel, 1986; Harrison et al., 1997; Johnson et al., 2001). Samples collected around Melamchi (Fig. 1) that lie just north of the anitformal hinge of the fold couplet contain the fabric in its least rotated state (Fig. 7a).

The sub-vertical and vertical foliations described above accompanied development of the Gorkha-Kathmandu fold couplet. The sense of shearing along them indicated by the differentiation asymmetries was north side up on the central limb (Figs. 4a, b and 7c) and south side up on the external limbs to the north and south (Figs. 4c and 7c). During folding, synthetic shearing along developing axial plane foliations can switch to antithetic reactivational shearing along the fold limbs (Bell, 1986; Davis, 1995; Bell et al., 2003). Thus on the central limb of the Gorkha-Kathmandu fold couplet where shear on the axial plane was north side up, reactivation shearing operated top-to-the-north as the limb progressively steepened. The moderately south-dipping foliation defining the fold limb developed a clockwise differentiation asymmetry looking west as seen in Figs. 5b, c and 7c. Based on this top-to-the-north shear sense on moderately south-dipping foliation, Webb et al. (2011) delineated a ENE-striking shear zone, which they termed as Galchhi zone, and argued that the shear zone was equivalent to the South Tibetan Detachment System (STDS) in the north. However, moderately south-dipping foliation in a sample (S13, Fig. 1) collected north of their Galchhi shear zone immediately above the MCT preserves an indicator for a top-to-the-north sense of shear and contradicts their argument. Where shearing during reactivation was less intense or absent, remains of foliations oblique to the fold limb curve anticlockwise looking west into the foliation lying parallel to the fold limb preserving the south directed sense of shear (Fig. 4d, e and 7b) associated with Main Central Thrust movement. On the outer two limbs of the fold couplet, anticlockwise antithetic reactivation shearing along the steepening fold limb simply intensified Main Central Thrust formed shear indicators (Figs. 5a and 7c).

4.2.2 Post-folding top-to-the-south shearing

Anticlockwise differentiation asymmetry into moderately to steeply north-dipping foliations (Fig. 4f, g) observed on the central limb of the Gorkha-Kathmandu fold couplet suggests that the fold couplet was locally affected by north side up/top to the south shearing after its formation. The sub-vertical foliations crenulated by this north-dipping top-to-the-south shear preserve relics of north side up shear (Fig. 6e). This phenomenon was only observed in the samples collected along the Kalphu River (Fig. 1). The shear zone along the Kalphu River separates the Bhimphedi Group rocks in the south from the gneiss mass around Sheopuri (Sakai et al., 2006).

4.2.3 Late top-to-the-north shearing: evidence for vertical shortening?

Sub-horizontal foliations in several samples from the central limb of the fold couplet have a clockwise differentiation asymmetry looking west that indicates top-to-the-north directed shear (Fig. 3c, d). These were the youngest foliations to form as shown in Fig. 5e from sample S30. In this sample, moderately south-dipping foliations defining the central limb of the Gorkha-Kathmandu fold couplet contain relics of an earlier top-to-the-south shear. They are overprinted by sub-horizontal foliations preserving excellent criteria for top-to-the-north shearing. This overprinting relationship and the sub-horizontal orientation of this top-to-the-north fabric clearly indicate that the structure postdates folding of the MCT in the Central Nepal Himalayas. Therefore, the sub-horizontal top-to-the-north fabric observed in this study is not equivalent to the STDS in the north, which developed over the same time period as the MCT (Searle et al., 2003; Godin et al., 2006; Hodges, 2006). This late top-to-the-north motion could probably have developed in response to vertical shortening, which occurred after a period of horizontal shortening that folded the MCT and sheared the rocks along the north dipping planes with a top to the south sense of movement as discussed above.

4.3 Succession of the interpreted foliations in 3D

The differentiation asymmetries described above resulted from a succession of five generations of foliations that can be distinguished in thin sections from their orientation and asymmetry of curvature into cleavage seams. This succession of foliations is plotted in Fig. 9. Moderately north-dipping foliation (Fig. 9a) on the external limb of the fold couplet adjacent to its hinge is the least affected remains of the earliest formed matrix foliation recognizable in these rocks. This S_1 foliation curves anticlockwise looking west into sub-horizontal foliation, S_2, to display the top to the south shear sense associated with movement on the Main Central Thrust (Fig. 3a, b and 7b). Although this anticlockwise looking west shear sense remains the same on all limbs of the Gorkha-Kathmandu fold couplet, the geometry of these two foliations varies due to the variable partitioning effects of younger events. S_2 defines the limbs of the fold couplet and thus dips moderately north on the external limbs and south on the central limb. S_1 dips north on the external limbs but more steeply than S_2 (Fig. 5a and 7b). S_1 is gentler than S_2 on the central limb (Fig. 4d, e; 7b; and 9a, b). However, reactivation shearing that accompanied folding has locally made S_1 steeper than S_2. The curvature of S_1 in this case indicates a top-to-the-north shear sense (Fig. 5b, c and 7c). S_3 is a sub-vertical foliation (Fig. 9c) that crenulated S_2 with a south side up shear sense (Fig. 4c and 7c) on the external limbs and a north side up shear sense (Fig. 4a, b and 7c) on the central limb. It is axial planar to the fold couplet. S_4 is a north-dipping foliation (Fig. 9d) observed on the central limb of the fold couplet that crenulates sub-vertical S_3

foliations with a top-to-the-south sense of shear (Fig. 4f, g). S_5 is a sub-horizontal foliation (Fig. 9e) that has sheared S_2 with a top-to-the-north sense of movement (Fig. 3c, d).

4.4 S-C planes or crenulation cleavages

The morphological features suggested as characterizing S-C structures (Passchier and Trouw, 2005) are defined as having formed synchronously (Berthé et al., 1979; Simpson, 1986). Proving this is the case is difficult to impossible in most rocks. Identical structures result from the overprinting of foliations and thus the development of a crenulation cleavage (Bell and Hobbs, 2010). Synchronicity of development is not required in the latter case and the shear sense interpreted is the same.

Most of the foliations constituting the differentiation asymmetries discussed above formed sub-vertically and sub-horizontally. The oldest foliation S_1 preserved in the matrix formed sub-vertically and the relics of this orientation can be observed in low strain areas such as the strain shadows of garnet porphyroblasts (Fig. 8a, b). S_2 developed sub-horizontally and this orientation is well preserved in samples collected close to the anitformal hinge of the Gorkha-Kathmandu fold couplet although it is rotated in other parts of the fold couplet to define the fold limbs. S_3 that formed axial planar to the fold couplet and S_5 that postdates the couplet always occur sub-vertically and sub-horizontally, respectively. Consequently, the angle of less than 45^o that the crenulated foliations make with the truncating differentiation crenulated cleavages resulted from shearing of the former along the latter. These two foliations did not develop synchronously with the crenulated ones forming oblique to the direction of bulk shortening, which is an important genetic criteria required for a fabric to be termed as “S-C” (Passchier and Trouw, 2005).

5 CONCLUSIONS

Differentiation asymmetries present in high-grade rocks in the Central Nepal Himalayas allow shear senses for a series of deformation events to be recognised. Moderately north-dipping foliation that curves anticlockwise looking west into gently north-dipping foliation on the north external limb of the Gorkha-Kathmandu fold couplet has the expected shear sense for Main Central Thrust movement. The top-to-the-south shear sense indicated by these north-dipping foliations is the oldest that is currently preserved in the matrix. Where they dip south in the central limb and are least affected by reactivation they display the same shear sense. Locally, they have been rotated by antithetic reactivation shear that acted top-to-the-north along the south-dipping central limb during development of the fold couplet and now curve clockwise. Sub-vertical foliations axial planar to the fold couplet were the second generation of foliations to form. They are locally sheared north side up/top to the south along steeply north-dipping third generation foliations. Sub-horizontal foliations with clockwise differentiation asymmetry into them, i.e. top-to-the-north shear sense, are the most recent foliations, which suggest that the Main Central Thrust zone in the Kathmandu Thrust Sheet has lately been affected by vertical compression.

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SECTION B

PRESERVATION OF DEEP HIMALAYAN PT CONDITIONS THAT FORMED DURING MULTIPLE EVENTS IN GARNET CORES: MYLONITIZATION PRODUCES ERRONEOUS RESULTS FOR RIMS

Section B

PRESERVATION OF DEEP HIMALAYAN PT CONDITIONS THAT FORMED DURING MULTIPLE EVENTS IN GARNET CORES: MYLONITIZATION PRODUCES ERRONEOUS RESULTS FOR RIMS

ABSTRACT

The Kathmandu Thrust Sheet, which overlies the Lesser Himalayas along the southern part of the Main Central Thrust (MCT) and forms the leading edge of the Higher Himalayan crystalline rocks, is folded at a regional scale by the Gorkha-Kathmandu fold couplet in central Nepal. Garnet porphyroblasts lying close to the MCT within this thrust sheet preserve structural and metamorphic history that predates mylonitisation during thrust emplacement. The succession of five FIA sets preserved within these porphyroblasts formed due to changes in the direction of India's motion relative to Asia after they collided. The intersection of Fe, Ca and Mn isopleths for garnet cores reveal that FIA sets 1, 2, 3, 4 and 5 nucleated respectively at 6.2 kbar and 515^{o}C, 6 to 7 kbar and 545 to 550^{o}C, 6.6 kbar and 530^{o}C, 5.6 to 6.2 kbar and 525 to 550^{o}C and 6.8 to 6.9 kbar and 520 to 560^{o}C. The average PT mode of THERMOCALC, which relies on equilibrium being achieved between the garnet rims and the matrix, gives pressures around 11 kbar that do not accord with the lengthy succession of lower core pressures. The many foliations in the matrix, which formed during top-to-the-south thrusting plus subsequent deformations that eventually led to these rocks reaching the surface, truncate all foliations preserved within the porphyroblasts that are defined by inclusion trails. This has resulted in the garnet rims not being in equilibrium with the matrix and the anomalously high pressures. The garnet rims may have been affected by slow dissolution and solution transfer over the period of time that the matrix was deforming plastically at high strain rates as the rocks were uplifted. The assumption of equilibrium between garnet rims and surrounding silicates used by various rim geothermobarometric methods does not hold for these rocks.

Keywords: FIAs, MCT, PT pseudosection, garnet core isopleths, rim geothermobarometry

1 INTRODUCTION

The overprinting of earlier fabrics by younger ones and their obliteration in the rock matrix is common in rocks affected by multiple deformation (Bell, 1986; Davis, 1995; Worley and Wilson, 1996; Bell, 2010). However, porphyroblasts commonly preserve such early-formed matrix structures in the form of inclusion trails, shielding them from the effects of younger events. These structures, called FIAs (foliation inflection/intersection axes within porphyroblasts), can be quantitatively measured (Bell et al., 1995). They have been used since the early 1990s to distinguish a large range of structural, metamorphic and tectonic conditions and processes in rocks that predate development of the matrix foliation (Hayward, 1990; Bell et al., 1992; Bell et al., 1995). The shear sense indicated by asymmetrically curving inclusion trails differs depending on whether the porphyroblasts containing them have rotated or not (Bell, 1985). FIAs carry similar tectonic meaning irrespective of how they formed (Bell, 1985; Bell and Johnson, 1989; Passchier et al., 1992; Bell and Hickey, 1997; Aerden, 2004). However, rotation of porphyroblasts during later deformation events would redistribute the trend of these axes relative to geographic co-ordinates, reducing their tectonic significance. Therefore, whether or not rotation has occurred must be determined (Bell and Chen, 2002; Ham and Bell, 2004).

The Higher Himalayas, which form the core of the Himalayan orogen, have gone through several episodes of metamorphism and deformation since the Indian and Asian plates collided about 50 million years ago. Barrovian-type regional metamorphism resulting from crustal thickening and shortening commenced soon after the collision (Searle and Rex, 1989; Walker, 1999; Hodges, 2000; Simpson et al., 2000; Catlos et al., 2002). However, relatively little is understood about the conditions that predate the MCT (Guillot, 1999) although about 30 million years elapsed between the collision and the movement on the MCT.

This paper examines the metamorphic development of the mylonitic garnetiferous rocks collected adjacent to the MCT in the Kathmandu Thrust Sheet as it relates to the progressive structural development revealed by the measurement of FIAs and matrix structures. Different generations of crenulated matrix foliations record deformation events that both include and postdate MCT movement. The garnet porphyroblasts and inclusion trails preserved therein record pre-MCT tectonometamorphic history. FIA trends have been measured by analysis of these inclusion trails using differently oriented vertical thin sections. Pitches of inclusion trails on a section lying at high angle to the relevant FIA trend, plus core rim data that indicates a consistent FIA succession, affirm that the garnet porphyroblasts used in the study did not rotate. Intersection of Fe, Ca and Mn isopleths from garnet cores have been used to calculate the PT conditions that each FIA set developed at. Average or near peak metamorphic conditions attained by the rocks of the Kathmandu Thrust Sheet have been estimated for three different sections using average PT mode of THERMOCALC (Powell and Holland, 1994).

2 GEOLOGICAL SETTING

The central Nepal portion of the Himalayas consist of four east-west-trending tectono-stratigraphic units—the Sub-Himalayas, the Lesser Himalayas, the Higher Himalayas and the Tethys Himalayas (Fig. 1). These units are continuous along the entire length of the Himalayas and are bounded by fault systems. The Sub-Himalayas, also known as Siwaliks, are comprised of Neogene to Quaternary fossiliferous molassic rocks deposited in the Himalayan foreland basins (Upreti, 1999). This unit overrides recent Indo-Gangetic alluvial sediments along the Main Frontal Thrust. The Lesser Himalayas contain two stratigraphic units separated by a major unconformity. The lower part contains barely fossiliferous, weakly to unmetamorphosed Late Precambrian to Early Palaeozoic sediments and augen gneisses while the upper part is comprised of Late Carboniferous to Palaeocene Gondwana units and Eocene to Miocene Tertiary units (Upreti, 1999). These two upper units are restricted in occurrence in the Lesser Himalayan sequence and absent in the area mapped in Fig. 2. The Lesser Himalayas are bounded to the south by the Main Boundary Thrust and to the north by the Main Central Thrust (MCT). The Higher Himalayas constitute the metamorphic core of the Himalayas (Coleman, 1996) and are composed of Proterozoic to Ordovician high-grade gneisses with subordinate amounts of schists, quartzites and marbles. The Higher Himalayan crystallines exhibit an upward increase in metamorphic grade in the lower part and decrease in the upper part, passing gradually into fossiliferous Tethyan sediments that range in age between Cambrian and Lower Tertiary (Yin, 2006). A north dipping normal fault, known as the South Tibetan Detachment System, separates the Tethys Himalayas from the Higher Himalayas but unlike major Himalayan thrust systems it is not continuous along the entire length of the Himalayas (Vannay and Grasemann, 2001).

The Higher Himalayan crystallines are preserved further to the south in eastern and central Nepal, almost reaching the Main Boundary Thrust. This more extensive Higher Himalayan thrust sheet in the Central Nepal Himalayas is known as the Kathmandu Thrust Sheet and the part of the MCT that forms the base of this thrust sheet has been termed as the Mahabharat Thrust (Stöcklin, 1980). The Kathmandu Thrust

Sheet constitutes the southern proximal part of the Higher Himalayan thrust sheet and misses out the lower level rocks of the thrust sheet that exhibit inverted metamorphism in the north (Johnson et al., 2001; Searle et al., 2008). The Kathmandu Thrust Sheet and the Lesser Himalayas are regionally folded by an east-west-trending mega fold called the Gorkha-Kathmandu fold couplet. Stratigraphically, the Lesser Himalayan rocks have been grouped under the Nawakot Complex, which has been further divided into Lower and Upper Nawakot groups. The Nawakot Complex contains low metamorphic grade phyllites, slates, quartzites, metasandstones, stromatolitic dolomites and limestones. Kathmandu Thrust Sheet rocks are stratigraphically called the Kathmandu Complex and consist of the high- to medium-grade Bhimphedi Group and the weakly metamorphosed to unmetamorphosed fossiliferous Phulchauki Group. The Bhimphedi Group consists of schists, phyllites, quartzites and marbles. The metamorphic grade of this group decreases from kyanite-garnet at the bottom to biotite-chlorite towards the top. The overlying Phulchauki Group contains slates, siltstones, shales, sandstones, limestones and dolomites. Echinoderms, trilobites, brachiopods, crinoids and conodonts have been reported from the Phulchauki Group. Gneisses and Ordovician granites are also present in the Kathmandu Complex (Stöcklin, 1980; Johnson et al., 2001). The gneisses occupy the northern portion of the Kathmandu Thrust Sheet (Fig. 2).

3 SAMPLE DESCRIPTION

All of the samples were collected from the Kathmandu Thrust Sheet, which forms the hanging wall of the MCT in the Central Nepal Himalayas. They were taken from all three limbs (southern, northern and central) of the Gorkha-Kathmandu fold couplet. Major mineral phases in these samples are quartz, plagioclase, biotite, muscovite and garnet. Kyanite was only observed in samples from the central and the northern limb of the fold couplet and is more common in those collected around Melamchi (Fig. 2). Zoesite, tourmaline, ilmenite and zircon are present in these samples as accessory mineral phases and some of the samples contain retrograde chlorite. Garnet porphyroblasts range in shape from anhedral to euhedral but are usually subhedral and are up to 5 mm in size. Some of them have irregular boundaries while a few are rounded and elongate. Although quartz is the main constituent of inclusion trails in garnet porphyroblasts, biotite, muscovite, ilmenite, zoesite and zircon are also commonly present. Zoesite grains are usually found only towards garnet rims. Inclusion trails are sigmoidal to spiral in shape (Fig. 3) and are truncated by the matrix foliations. Matrix grains are always coarser than the grains forming inclusion trails. Biotite and muscovite grains are mostly aligned parallel to the matrix foliations. Biotite is more abundant than muscovite in most of the samples. Quartz inclusions are often sigmoidal and along with elongate mica grains and mica fish curve into younger truncational foliations that are differentiated crenulated cleavages. These truncational foliations contain thin layers (one or two grains thick) of mica and fine-grained quartz. Kyanite grains ranging in length from less than a millimetre to about 5 mm and are aligned parallel to the matrix foliations. Deformed and bent kyanite grains also occur. Porphyroblastic kyanites do not contain abundant inclusions.

4 MATRIX FOLIATIONS AND STRUCTURAL SUCCESSION

All foliations that were visible in the field were measured. However, other foliations that were visible using a microscope were measured as pitches in the 6 vertical thin sections with different trends that were cut per sample to determine the FIA trend (see below). About eight measurements were made for each identified foliation. Their apparent dips were plotted on stereonets with the computer program GEOrient v9.5.0 (http://www.holcombe.net.au/software/) to determine the true orientation of each of the different matrix foliations in three dimensions. Shear senses associated with these foliations are described in Section A.

5 FIA SUCCESSION

A FIA is the axis of the curvature of asymmetrically curved inclusion trails preserved in a porphyroblast (Fig. 4) and represents the intersection between a crenulated foliation overgrown by a porphyroblast and the developing differentiated crenulation cleavage. The FIAs were measured using the asymmetry technique described in detail by Bell et al. (1992) and Bell et al. (1995). Oriented samples were re-oriented to their field positions in a lab. A north-south-trending line were marked on each sample with arrows pointing north and horizontal lines were marked all the way around at 2.5 cm vertical intervals, which is the width of a thin section glass. Several horizontal slabs were cut along the marked horizontal lines. Six vertical blocks striking 0^o, 30^o, 60^o, 90^o, 120^o and 150^o were cut off the slabs. A vertical face of the block was glued on a thin-section glass. Strike lines and up direction that were drawn on the blocks were transferred to the glass by a single barbed arrow. The resulting thin sections were placed on a microscope in such a way that the single barbed arrows always pointed in the same direction. Asymmetries of inclusion trails from each thin section were then recorded as being clockwise or anticlockwise. The FIA trend lies in the sector between the two thin sections that display a switch in asymmetry from clockwise to anticlockwise or vice versa (Fig. 5). Two extra thin sections were cut 10^o apart between the sections that showed the asymmetry flip. This constrains the accuracy of determined FIAs to ±5°.

FIA trends measured in garnet porphyroblasts from 78 samples are presented in Table 1. On a rose diagram, these measurements display five distinct peaks with NNE-SSW, ENE-WSW, E-W, SW-NE and SSE-NNW trends (Fig. 6a). Samples exhibiting different FIA trends in garnet cores and rims (Fig. 6b) were used to determine relative timing between different FIA sets (Fig. 6c). In summary, the SSE-NNW trend is referred to as FIA 1 (peak at 165°) as it has been found in the cores of samples containing FIAs 2, 4 and 5 in their rims and FIA 3 has been found in the rim of a sample containing FIA 2 in its core. FIA 5 is placed at this location because it has a different asymmetry than the other FIAs (see Section D for more details).

Inclusion trails containing all FIA sets are truncated by all external foliations including S_1 and S_2, which are the oldest mylonitic foliations preserved in the matrix as shown in Figs. 3, 7, 8 and 9. A garnet porphyroblast in Figs. 8a and 8b consists of inclusion trails belonging to FIA 3 in its core and to FIA 4 in its rim. The smaller porphyroblast below it only contains FIA 4 inclusion trails (Fig. 8a and 8b). FIA 5 inclusion trails in the garnet core and rim in Figs. 8c and 8d exhibit the same asymmetry whereas in Figs. 9a and 9b, they show a change in asymmetry from an anticlockwise core to a clockwise rim (view towards ENE, i.e. N150° towards right) suggesting that shear sense reversed from top towards the north to top towards the south late during FIA development.

6 MINERAL CHEMISTRY

The JEOL SuperProbe housed at the Advanced Analytical Centre of James Cook University was used to determine the content of major elements in garnet, biotite, muscovite, plagioclase, K-feldspar, zoesite and chlorite. Several spots were analysed for each mineral grain and the average composition was used for geothermobarometric calculations. Operating conditions for spot analyses were 15 kV and 20 nA and a beam diameter of 1 µm. Natural silicates and oxides were used as standards.

6.1 Biotite

The number of Si and Al^{iv} atoms per formula unit (p.f.u.) does not vary significantly. Octahedral sites are filled mainly by Fe and Mg atoms, the former showing a slight dominance over the latter in some samples and vice versa. Fe/(Fe+Mg) ratio varies between 0.42 and 0.57. Ca is negligibly present in twelve-fold interlayer sites, which are filled almost exclusively by K atoms (Table 2).

6.2 Muscovite

As in biotite, the number of Si and Al^{iv} atoms p.f.u. is similar in all analysed samples. Al constitutes 75% to 87% of octahedral sites. The remainder of the sites is filled mainly by Fe and Mg. Fe varies significantly among the analysed samples, ranging between 4% and 15%. Mg comprises 5% to 8% of the octahedral sites. Twelve-fold interlayer sites are filled mainly by K atoms. Na/(Na+K) ratio p.f.u. varies between 0.03 and 0.13. Ca is absent in all the analysed samples (Table 3).

6.3 Plagioclase

Plagioclase in none of the analysed samples shows remarkable compositional variation from core to rim. Anorthite content is significantly low in the sample (H1, see Fig. 2) collected from close to the MCT on the southern limb of the Gorkha-Kathmandu fold couplet. This value in other samples range between 0.17 and 0.34 (Table 4).

6.4 Garnet

The almandine content (Fe/(Fe+Ca+Mg+Mn)) in most of the analysed samples is slightly higher in garnet rims than in their cores. It varies in cores between 0.42 and 0.74 and in rims between 0.47 and 0.77. The grossular content (Ca/(Fe+Ca+Mg+Mn)) decreases from core to rim in sample S24b but increases slightly in rims. Its value ranges from 0.12 to 0.28 in garnet cores and from 0.10 to 0.31 in garnet rims. Similarly, garnet rims have a slight higher concentration of pyrope (Mg/(Fe+Ca+Mg+Mn)) than their cores. The pyrope content ranges between 0.02 and 0.16 in garnet cores and between 0.03 and 0.16 in garnet rims. However, the spessartine content (Mn/(Fe+Ca+Mg+Mn)) decreases in garnet rims. It varies from 0.03 to 0.38 in garnet cores and from 0.01 to 0.25 in garnet rims. Samples S16, S30 and T14 show a negligible variation in the end member compositions in garnet cores and rims (Table 5).

7 PT PSEUDOSECTIONS

The bulk compositions of 8 rock samples were analysed for major silicates using the XRF facilities at the Advanced Analytical Centre, James Cook University. PT pseudosections were modelled in the Na_2O-CaO-MnO-K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O (NCMnKFMASH) system using the computer program THERMOCALC (Powell and

Holland, 1988) and the thermodynamic dataset of Holland and Powell (1998; with the update tcds55.txt produced at 19:29:59 on 22 November 2003) and mixing models for manganese-bearing phases as in Tinkham et al. (2001) and White et al. (2001). The activity model for white mica is as in Coggon & Holland (2002) and for feldspar is as in Holland & Powell (2003). Chlorite, zoesite, muscovite, plagioclase, biotite, garnet, staurolite, andalusite, sillimanite, kyanite, cordierite and H_20 were considered for these calculations. Fig. 10 shows a PT pseudosection modelled for sample K17 with equilibrium fields for the mineral phases that can potentially occur in a metapelite and includes chlorite, biotite, plagioclase, zoesite, garnet, andalusite, cordierite, staurolite, kyanite and sillimanite. All assemblages in the pseudosection contain muscovite, quartz, and water. Figs. 11 and 12 contain the pseudosections plus Mn, Fe and Ca isopleths in garnet cores (see below) for all samples analysed.

8 GEOTHERMOBAROMETRY

8.1 Garnet isopleths

Theoretically, the PT conditions of garnet nucleation can be determined if the composition of the garnet core and the mineral assemblage from where the garnet crystallised are known (Vance and Mahar, 1998; Evans, 2004; Cihan et al., 2006; Sayab, 2008; Ali, 2010; Sanislav and Bell, 2011). This is true only if the composition of the garnet core was not modified by subsequent events. The garnet core can be analysed by EPMA, from which compositional isopleths for almandine (X_{alm}), grossular (X_{gr}) and spessartine (X_{sp}) are calculated. The isopleths for these end members can be plotted on the stability field corresponding to the mineral assemblage from where the garnet crystallised. The intersection of all three isopleths in the PT space should reflect the PT conditions of garnet nucleation. Eight samples that contain garnet porphyroblasts with each of the FIA sets in the succession have been analysed and the PT conditions of garnet nucleation during each FIA set were determined. The garnet porphyroblasts containing the least inclusions were selected in order to avoid possible modifications of garnet composition by diffusion of components from the inclusions to the garnet or vice versa.

Inclusions in the garnet cores of the analysed samples consist mainly of quartz with subordinate amounts of muscovite, biotite, ilmenite and plagioclase. Probably, chlorite was completely consumed during garnet growth and thus do not appear in the inclusions. Prograde chlorite grains are absent in the matrix as well. The assemblage of chlorite, biotite, plagioclase and garnet was used to calculate X_{Fe}, X_{Ca} and X_{Mn} isopleths for garnet cores, and the intersections of these isopleths plot in chlorite-biotite-plagioclase-garnet quadrivariant fields. These three isopleths intersect either almost at a point or enclose a very small area in the PT field (Figs. 11 and 12). In sample M1 that preserves garnet porphyroblasts containing FIA 1, the core isopleths intersect at ~ 6.2 kbar and 515°C, with about 45°C of temperature overstepping (Fig. 11a). The core isopleths in sample S26 intersect at ~ 6 kbar and 545°C, suggestion about 45°C of temperature overstepping (Fig. 11b). Sample S26 contains garnet porphyroblasts representing FIA 2. The core isopleths for another sample (T14) with the garnet porphyroblasts representing the same FIA set intersect at ~6.7 kbar and 550°C (Fig. 11c). FIA 3 garnets in sample S16 have core isopleths intersecting at ~ 6.6 kbar and 530°C. Temperature overstepping for these garnets is about 55°C (Fig. 11d). Core isopleth intersection for sample K22 with garnet porphyroblasts belonging to the same FIA set occurs at ~ 6.2 kbar and 525°C (Fig. 12a). Similarly, sample K17 contains garnet porphyroblasts that preserve the same FIA set and core isopleths for this sample intersect at ~5.6 kbar and 550°C with about 25°C of temperature overstepping (Fig. 12b). In sample S13 that consists of garnet porphyroblasts representing FIA 5, the core isopleths intersect at ~6.9 kbar and 560°C (Fig. 12c). These isopleths intersect at ~6.8 kbar and 520°C in sample S13 that contains garnet porphyroblasts belonging to FIA 5. Temperature overstepping of about 70°C occurred during these garnets forming reactions (Fig. 12d).

8.2 Rim geothermobarometry

Average PT conditions were determined for eight samples by using the average PT mode (calcmode 2) of THERMOCALC (Holland and Powell, 1998). End member activities for the average PT determination were calculated on a computer program AX developed by Holland (http://rock.esc.cam.ac.uk/astaff/holland/ax.html). The compositions of the rims of garnet and other major silicates averaged from about four analyses obtained from the electron microprobe were used to determine the average PT conditions. Conventional geothermobarometric approaches of Ghent and Stout (1981) and Hoisch (1990) were also used to calculate the PT conditions. Intersections of Fe and Mg end member curves obtained by using compositions garnet rims and surrounding plagioclase, muscovite and biotite were used to estimate the PT conditions.

The average PT mode of Thermocalc yielded 11.8 ± 1.8 kbar of pressure and 700 ± 35 °C of temperature for sample M1 and 10 ± 1.3 kbar of pressure and 728 ± 29 °C of temperature for sample M16. These two samples were collected around Melamchi and lie in the eastern part of the gneiss zone that constitutes the northern portion of the Kathmandu Thrust Sheet (Fig. 1). Similarly, samples S30, S26 and S16 yielded an average metamorphic PT of 10.4 ± 1.8 kbar and 663 ± 52 ^{o}C, 12.6 ± 2.1 kbar and 717 ± 65 ^{o}C, and 11.6 ± 1.8 kbar and 659 ± 54 ^{o}C. These three samples are from the western part of the gneiss zone around Galchhi. An average metamorphic pressure of 12 ± 1.8 kbar and temperature of 717 ± 58 ^{o}C for a schist sample (K17, Fig. 1) belonging to the Raduwa Formation (the oldest formation of the Bhimphedi group; refer to Stöcklin, 1980 for details). Sample K22 from the same formation collected at Malekhu (Fig. 2) yielded an average metamorphic pressure of 11.3 ± 1.4 kbar and 678 ± 42^{o}C. An average PT of 7.4 ± 1.9 kbar and 534 ± 28 +C was calculated for sample H1 collected from the Raduwa Formation but from the south limb of the Gorkha-Kathmandu fold couplet near Hetauda (Fig. 2). The PT conditions calculated by Hoisch (1990) are similar to those calculated from the average PT mode of Thermocalc whereas the one by Ghent and Stout (1981) resulted in lower PT. The results obtained by the different methods are presented in Table 6.

9 INTERPRETATION AND DISCUSSION

9.1 Evidence for porphyroblast non-rotation

The striking distribution of FIAs on a rose diagram and the consistent succession of core rim changes for those samples that preserve differently trending FIAs strongly suggest that the garnet porphyroblasts did not rotate. The rotation of the porphyroblasts during the formation of each of the FIAs would have rotated all FIAs in previously formed garnets, producing an enormous spread of trends in a rose diagram and destroying the consistent timing relationships between different FIA sets (Bell et al., 1998; Bell and Chen, 2002; Bell et al., 2004; Bell et al., 2005). Furthermore, the measurement of the pitches for about 300 foliations preserved in garnet porphyroblasts in thin sections cut at high angle to the respective FIA trends and plotted on rose diagrams revealed that these foliations are dominantly sub-horizontal and sub-vertical (Fig. 13). The consistency of these orthogonal foliations from porphyroblast to porphyroblast confirms that the porphyroblasts did not rotate.

9.2 Garnet growth and FIA development

The PT conditions estimated from the intersection of X_{alm}, X_{gr} and X_{sp} isopleths for garnet cores belonging to each FIA in the succession indicate no significant variation from set to set. These garnet cores have preserved the signatures of regional metamorphism from the later effects of mylonitisation associated with the thrusting that finally brought the rocks to the surface. The garnet porphyroblasts containing these FIA sets nucleated with PTs between 5.6 and 7.0 kbar and 515 and 560^{o}C. Each FIA should form perpendicular to the direction of bulk horizontal compression with the FIA set 1 (NNW-SSE trending) forming when India was moving approximately towards east between anomalies 22 and 21, i.e. 50 and 48 million years (Fig. 14). This occurred around or soon after the collision between the Indian and Asian plates (Patriat and Achache, 1984; Windley, 1988; Klootwijk et al., 1992; Ratschbacher et al., 1994; Murphy and Yin, 2003). The Higher Himalayan crystallines are reported as having undergone regional Barrovian metamorphism at this time (Walker, 1999). A monazite inclusion within a garnet porphyroblast has been dated at 45 Ma in the Higher Himalayan crystallines in the eastern Nepal Himalayas. Barrovian metamorphism lasted for about 20 to 25 million years before the Higher Himalayan crystallines were subsequently exhumed (Simpson et al., 2000; Catlos et al., 2002). FIA sets 2, 3, 4 and 5 lie roughly perpendicular to the path of India's relative motion between anomalies 21 and 8 as depicted by Patriat and Achache (1984). Thus, the youngest NNE-SSW-trending FIA set could have developed between anomalies 13 and 8 (36 and 29 million years). The FIA data presented herein is consistent with FIAs measured in the NW Himalayas (Shah et al., 2011).

9.3 Rim geothermobarometry

The rim geothermobarometric methods used herein yield consistently much higher pressures of ~ 4 kbar more than those calculated using Mn, Fe and Ca isopleths for the garnet cores from each FIA set. Rim pressures were calculated for porphyroblasts containing all FIA sets. A 4 kbar or 12 km cycling in pressure is out of the question especially since porphyroblasts grew in both subvertical and subhorizontal events. For example, garnet isopleths used for isopleth calculation from samples S30 and T14 grew during subvertical events whereas the isopleths in sample S26 developed during subhorizontal event. The 12 km depth change required is so great that if it had occurred, some evidence would have been found for high pressures in at least one of the 8 samples where the core PT was determined using isopleths.

The Main Central Thrust is a zone of high shear strain that displaced the Higher Himalayan crystallines towards south by about 100 km (Johnson et al., 2001). The mylonitic matrix foliations of the MCT developed after garnet growth ceased as they truncate all foliations preserved as inclusion trails in the porphyroblasts for every FIA set (e.g. Figs. 3, 7, 8 and 9). The dissolution and solution transfer processes that dominate non-mylonitic foliations occur readily in slow strain rate environments. However, in high strain rate environments brittle deformation can only be prevented if plastic deformation is accommodated by recovery, subgrain formation, subgrain rotation and thus recrystallization (Bell and Cuff, 1989; Hickey and Bell, 1996).

Garnet porphyroblasts are very competent in comparison to the matrix and tend not to deform internally. However, their rims were sheared against the developing mylonitic matrix foliation as all internal foliations have been truncated. Such shearing might leave them unaffected, although it is more likely that some strain of their rims could result in some dissolution because they survived their mylonitic journey towards the surface (Bell and Cuff, 1989). However, it is unlikely that the plastically deforming matrix where the effects of dissolution and solution transfer are limited would ever reach equilibrium with the differently behaving garnet rim. This could lead to the anomalous relationship between core and rim determined pressures because the former remain unaffected. Therefore, PT values recorded by garnet cores, which are in the range of 5.6-6.9 kbar and 515-550°C, during the development of different FIA sets are interpreted to represent metamorphic conditions prevalent between India-Asia collision and initiation of movement along the MCT in the Central Nepal Himalayas.

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SECTION C

MULTIPLE ALTERNATIONS OF BULK HORIZONTAL SHORTENING AND GRAVITATIONAL COLLAPSE DURING HIMALAYAN OROGENESIS

Section C

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ABSTRACT

Multiple successions of sub-vertical and sub-horizontal foliation development are strikingly well preserved in garnet porphyroblasts that were carried to the Earth's surface within the mylonitic schists that overlie the Main Central Thrust. These porphyroblasts grew at depths ranging from 20 to 23 km within the core of the Himalayan orogen and the foliations preserved within them were truncated by subsequently formed mylonitic matrix foliations during uplift. A succession of 5 FIAs (foliation intersection/inflection axes preserved within porphyroblasts) trending 165°, 65°, 135°, 95° and 25° within garnet reveal that while this phase was growing there were 5 changes in the direction of bulk shortening and thus relative plate motion. Two foliations pitching dominantly within 20° of the vertical and one to two foliations pitching dominantly within 10° of the horizontal accompanied the development of each of the 5 FIAs. Far field bulk horizontal shortening, resulting from collision of the Indian and Eurasian plates developed the sub-vertical foliations. This thickened the crust, episodically leading to gravitational instability, collapse and sub-horizontal foliation development within the orogen core. By FIA 5 a switch in the dominant asymmetry of curving inclusion trails indicates that the component of overall shear on gently dipping foliations had shifted from top-to-the-north to top-to-the-south. Each of the many cycles of gravitational collapse recorded by garnet growth in these rocks creates a space problem that is resolved by the extrusion of rock from the orogen core towards to the surface. Zones of extrusion are soled by thrusts and switch to extensional geometries at higher structural levels. The mylonitic matrix foliations that resulted from this process contain the same top-to-the-south asymmetries on gently dipping foliation planes as those that first became dominant in FIA 5 garnets, and eventually led to the development of the Main Central Thrust.

Keywords: garnet porphyroblasts, inclusion trails pitches, FIAs, subvertical and subhorizontal foliation development, Main Central Thrust

1 INTRODUCTION

In 1986, top-to-the-north shear senses that oppose the top-to-the-south shear that occurred on the Main Boundary and Main Central thrusts were found in mylonitic rocks in the Higher Himalaya (Brunel, 1986). In 1989, successions of orthogonal foliations that appeared to have formed sub-horizontal and sub-vertical while spiral inclusions trails developed, were found in garnet porphyroblasts in several samples from around the world (e.g., Bell and Johnson, 1989); one of these samples was obtained from close to the Main Central Thrust. The model conceptualized to explain this relationship also explained the change in shear sense from the Lower to Higher Himalayas but was disregarded by those working in this region. In the subsequent decades much quantitative data has been gathered on foliation orientations preserved in porphyroblasts in many orogens. These data reveal a remarkable dominance of sub-horizontal and sub-vertical orientations (Hayward, 1992; Bell and Newman, 2006, Bell and Sanislav, 2011).

An opportunity arose in 2008 to collect numerous large oriented samples of garnet porphyroblast-bearing rocks from above the Main Central Thrust in the region of Nepal shown in Fig. 1. After reorienting these samples in the laboratory, horizontal slabs were prepared and marked up so that 6 vertical blocks could be cut every 30° around the compass for thin sectioning of a vertical face. The FIA (or foliation intersection axis preserved within porphyroblasts) was constrained within 30° from these by determining where the inclusion trail asymmetry flipped. It was then measured within 10° by cutting vertical blocks at 10° intervals using the technique described in detail in Hickey and Bell (1999). Where more than one FIA was found in a sample more blocks were cut to measure them within 10° as well.

2 FIA SUCCESSION AND INCLUSION TRAIL ASYMMETRIES

The 85 FIAs (measured from 78 samples) preserved by garnet cluster about a series of peaks on a rose diagram oriented clockwise around the compass at 165°, 25°, 65°, 95° and 135° (Fig. 2a). Core to rim changes in trends of FIAs are shown in Fig. 2b. The asymmetries of curvature of these inclusion trails moving outwards from the core were measured on sections lying near orthogonal to the FIA trend. They were recorded as changes in pitch from steep to gentle separately from gentle to steep because of the dominance of these 2 orientations (see below). Both are strongly clockwise (CW; Fig. 3) looking overall west for the FIAs trending 165°, 135° and 95° with the ratios of all those curving clockwise versus anticlockwise (ACW) being 5:1, 2.25:1 and 1.85:1, respectively. For the FIA trending at 65° (looking SW) the steep to gentle change in pitch is coaxial while the gentle to steep is strongly CW shifting the total CW to ACW ratio to 1.4:1. For the FIA trending at 25° (looking SW) the steep to gentle change in pitch is strongly ACW whereas the gentle to steep change is coaxial producing an overall ACW to CW ratio of 1.5:1. The inclusion trails in all samples are truncated by the mylonitic matrix foliations. This was determined using the 8 vertical thin sections cut per sample around the compass to measure the FIAs to eliminate strain shadow effects created by the porphyroblasts on exiting inclusion trails (Cihan, 2004).

3 FOLIATION ORIENTATIONS PRESERVED IN PORPHYROBLASTS

Measurement of the pitches of foliations across the centres and/or rims of garnet porphyroblasts using a microscope within a range of (±2º) was possible in 43 of the 78 samples because they contain numerous elongate quartz inclusion trails (e.g., Fig. 4a). The measurements were made using thin sections lying at a high angle to the appropriate FIA trend for the inclusion trails being measured in every porphyroblast present, as shown in Fig. 4a. The 287 measurements made from these 43 samples (Table 1), were plotted on a single vertical rose diagram with the horizontal running W-E across the page as shown in Fig. 4b. Figure 4c shows the first formed foliations that predate porphyroblast growth. Figure 4d shows truncational foliations that postdate growth of the porphyroblast cores and were then overgrown. Steep pitches (n= 153) averaging 71.8° dominate sub-horizontal pitches (n= 46) averaging 8.7° by 3.3 to 1 for foliations that predate any porphyroblast growth (Fig. 4c). There are 1.4 times more sub-horizontal pitches (n= 51) averaging 7.3° than sub-vertical pitches (n= 37) averaging 81.6° that formed after a first stage of porphyroblast growth (Fig. 4d). The latter pitches are ~10° closer to sub-vertical than those that predate but were preserved by the first phase of garnet growth (compare Figs. 4d and 4b).

4 PRESSURES PRESERVED IN GARNET CORES

FIAs allow porphyroblasts of different generations to be distinguished and the pressure of garnet core formation to be determined using a pseudosection in combination with the intersection of Ca, Fe and Mn core isopleths (e.g., Sanislav and Bell, 2011). The pseudosections and garnet core isopleths intersections for each FIA in the succession shown in Fig. 5 reveal that the pressures range from 5.6 to 7.0 kbar in 8 samples, averaging 6.41kb. The temperatures range from 515° to 560°C averaging 536.9°C.

5 INTERPRETATION

5.1 FIA succession

The changes in FIA trend from core to rim shown in Fig. 2b indicate a 165°, 65°, 135°, 95° succession in the changes of FIA trend with time as a porphyroblast core must form before its rim. Although a 25°-trending FIA occurs in the rim of a sample with a core at 165° (sample S30 in Fig. 2b) no relationship was found between this FIA and those at 65°, 135° and 95°. However, the inclusion trail asymmetry for the samples containing this FIA set differs from all the others. Figure 3 shows that looking west it is dominantly ACW, whereas those for the 165°, 65°, 135° and 95° trending FIAs are mainly CW. This switch from CW to ACW accords with the top-to-the-south motion required to form the porphyroblast inclusion-trail-truncating-mylonitic matrix foliations that helped these rocks to extrude from a depth of 23 kilometres to the surface along the MCT. Consequently, the 25° trending FIA is interpreted as the last to form in the succession of the five FIAs listed in Fig. 2c. This is strongly supported by similar data from the Western Himalayas of Northern Pakistan where the last 2 FIAs recorded in those rocks trend the same as FIAs 4 and 5 in Fig. 2c (Shah et al., 2011).

5.2 Changes in FIA trend and relative plate motion

Conceptually, FIAs should form perpendicular to the direction of relative plate motion as they are independent of the effects of motion on sub-horizontal planes such as thrusts. Consequently, they will not be affected by the topographic expression of the orogen as appears to be the case with other linear structures such as those that radiate around the Western arc of the Alps (Bell et al., 1995). Indeed, the only structures in the

Alps that show any relationship to the changes in relative plate motion between Africa and Europe are the FIAs preserved in garnet porphyroblasts. The 5 FIA trends recorded here formed over ~20 million years based on the range of ages obtained for monazite inclusions within garnet from the surrounding region. These have been dated from above the MCT, as well in the Central Nepal Himalayas between 32 and 24 Ma (Gehrels et al., 2006) and ~100 km to the east at 45 Ma and between 28 and 19 Ma (Catlos et al., 2002). The motion of India is obvious from magnetic striping of the sea floor, but that for Eurasia is not (Patriat and Achache, 1984). Slight changes in speed of one plate relative to another, where the motion is not parallel, changes the direction of relative plate motion. The 165°, 65°, 135°, 95° to 25° FIA succession potentially allows small changes in the rate and/or direction of motion of Asia relative to India to be back calculated relative to magnetic striping and is dealt with elsewhere (Bell and Sapkota, unpublished data).

5.3 Number of foliations versus FIAs

Generally, only 2 or 3 foliations oblique to bedding parallel schistosity are ever preserved within the rock matrix. Reactivation during the development of younger foliations decrenulates earlier formed one or rotates newly developing ones into parallelism with old ones (Bell et al., 2003). This process routinely destroys evidence for multiple deformations (Ham and Bell, 2004). The first of at least 2 deformations must generate a foliation for a FIA to be preserved within a porphyroblast (e.g., Fig. 4a; Bell and Sanislav, 2011); up to 7 foliations formed about each FIA trend in parts of the Appalachians (Bell and Newman, 2006). Since a FIA trend is controlled mainly by the strike of steeply dipping foliation events (Aerden, 2004; Bell and Bruce 2006) a minimum of 10 deformations are involved in the development of the 5 FIAs in the rocks described here. Indeed, in some rocks, at least 3 and locally 4 foliations were developed during the formation of each of the 5 FIA trends (Bell and Sapkota, unpublished data). Consequently, these rocks preserve evidence for at least 15 successively sub-vertical and sub-horizontal foliations forming at depths around 20 to 23 km prior to their transport to the surface along the MCT.

5.4 Pressure changes during garnet growth

The garnet porphyroblast cores grew at pressures ranging from 6 to 7 kbars during the development of each FIA in the succession (Fig. 5; FIA 1 @ 6.2 kbar, 2 @ 6 and 7 kbar, 3 @ 6.6 kbar, 4 @ 6.2 and 5.5 kbar, 5 @ 6.8 and 6.9 kbar). Growth of porphyroblasts is episodic occurring at the commencement of deformations and ceasing as foliations begin to form (e.g., Bell and Bruce, 2006; Sanislav and Bell, 2011). Porphyroblast rims likely formed at similar pressures to the cores containing the subsequently developed FIA set. Truncation of foliations defined by inclusion trails during the high strain rate mylonitisation that accompanied extrusion of these rocks towards the surface suggests the porphyroblast rims are not in equilibrium with the matrix. The average PT approach of Thermocalc (Sapkota and Sanislav, unpublished data) or other porphyroblast rim-matrix techniques published elsewhere (Rai et al., 1998; Johnson et al., 2001) therefore yield inappropriately high pressures.

5.5 Orientations of foliations preserved in porphyroblasts

Figure 4b shows that foliation pitches measured in thin sections near orthogonal to the FIA trend are pre-dominantly sub-vertical and sub-horizontal. Steep pitches (avg. 71.8°) dominate gentle ones (avg. 8.7°) by 3.3 to 1 for foliations that predate local porphyroblast growth (Fig. 4c). Gentle pitches (7.3°) dominate steep ones (81.6°) by 1.4 to 1 for foliations formed after a first stage of porphyroblast growth (Fig. 4d), being closer to horizontal and vertical respectively than foliations that predate porphyroblast growth (Fig. 4c). The latter feature has long been recognized as providing evidence for foliations forming sub-vertically and sub-horizontally within the metamorphic cores of orogens (e.g., Bell and Johnson, 1989; Hayward, 1992). Prior to porphyroblast growth, foliations that formed sub-vertically or sub-horizontally could have rotated away from these orientations due to reactivation or younger deformations. However, once a porphyroblast has formed, steep and/or gently dipping foliations that have formed against its rim are protected from such disturbance (e.g., Hickey and Bell, 1999). These data provide no evidence that the porphyroblasts containing FIA 1 rotated during the formation of those containing FIAs 2, 3 etc. This is so despite the minimum of 15 separate foliation-producing deformations that accompanied growth of garnet. Nor is there evidence that any porphyroblasts rotated during the many deformations that developed foliations after garnet growth ceased (Sapkota, unpublished data). This includes the deformations that took place during rock extrusion to the surface along the MCT or when the MCT was folded (Fig. 1).

5.6 Timing of porphyroblast growth relative to sub-vertical and sub-horizontal foliations

Porphyroblasts begin their growth (or nucleate) in the hinges of crenulations and cease to grow once a crenulation cleavage seam has begun to differentiate (Bell and Bruce, 2006). Consequently, they may not grow for millions of years despite T, P and bulk composition being appropriate through large bodies of rock, because crenulation hinges cannot develop or do not develop at an appropriate scale (Spiess and Bell, 1996; Sanislav and Bell, 2011). Figure 4c suggests that 3.3 times more porphyroblasts grow for the first time during a deformation that post dates the development of sub-vertical foliations. Figure 4d supports this because during a second phase of growth, 1.4 times more porphyroblasts grew during a deformation that postdated the development of sub-horizontal foliations. However, sub-horizontal foliations resulting from gravitational collapse are independent of the FIA trend, which is mainly controlled by the strike of steeply dipping foliations (e.g., Aerden and Sayab, 2008; Bell and Sanislav, 2011). Therefore, one could expect, for all FIA sets after the first that the first phase of porphyroblast growth in each would preserve more gently dipping foliations than steeply dipping ones in the cores. That is, sub-horizontal relics of foliation from earlier periods of orogeny would always be available for crenulation about the new FIA axis. Yet nearly 4 times more porphyroblasts formed during FIAs 2 through 5 with steep versus gentle pitching foliations in their cores than the 1.4 times in FIA 1. Such data suggest that when the direction of relative plate motion changes, there is an effective decrease in the rate of bulk shortening in the orogen core as the deformation re-partitions and spreads differently across the orogen. This would prevent portions of the orogen that were about to switch to gravitational collapse due to crustal thickening from reaching that tipping point. Sanislav and Bell (2011; their fig. 13) have suggested that deformation along an orogen core may be spatially partitioned at regional distances into zones of bulk shortening separated by zones of transform fault activity. With shifting directions of relative plate motion this would also cause vertical foliation to develop where less horizontal foliation was available for crenulation hinges to form and porphyroblasts grow.

6 CONCLUSION

At least 7 cycles of alternating sub-vertical and sub-horizontal foliation development were preserved by garnet porphyroblasts that grew ~23 km deep before they were extruded along the MCT. These cycles imply that episodes of gravitational collapse alternated with episodes of crustal shortening throughout Himalayan orogenesis. Similar relationships documented in other orogens suggest that this process is widespread.

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SECTION D

EPISODIC GRAVITATIONAL COLLAPSE AND MIGRATION OF THE MOUNTAIN CHAIN DURING OROGENIC ROLL-ON IN THE HIMALAYAS

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ABSTRACT

After collision, as India was displaced northwards beneath Eurasia, actively deforming and metamorphosing rocks below depths of ~30 km within the core of orogenic activity moved northwards relative to those above. Consequently, rocks metamorphosing at shallower crustal levels, but to depths of at least 23 km on the north side of this core, were displaced southwards across it rather than pushed further north as the Himalayan syntaxes began to form to the west and east. Garnet porphyroblast growth began and continued at these depths until movement towards the surface initiated. The latter motion occurred during numerous episodes of gravitational collapse with the rate of extrusional displacement increasing the further the rocks migrated from the orogen core. The mylonitic schists that host these garnet porphyroblasts formed during this extrusion and now overlie the Main Central Thrust (MCT).

This history resulted from the effects of metamorphosing crust at crustal levels shallower than ~30 km during multiple alternating episodes of bulk horizontal shortening and gravitational collapse. These emanated during roll-on of and from the northwards migrating orogen core throughout 5 extended periods of tectonism that are distinguished by changes in FIA trend (foliation inflection/intersection axes preserved within porphyroblasts). Each FIA involved the development of 3 or more sub-vertical and sub-horizontal foliations preserved within the many phases of growth of garnet porphyroblasts that took place at depths between 20 and 23 km. The first 4 periods of tectonism occurred on the north side of the orogen core with the 5th occurring on the south side. Long before these rocks reached the surface, all foliations that were preserved as inclusion trails within garnet porphyroblasts became truncated by the effects of mylonitisation. Indeed, these rocks were multiply deformed after mylonitisation began and prior to exposure above the MCT.

The 5 changes in FIA trend correlate markedly with changes in the motion of India relative to a constant Eurasia from 50 to 29 Ma. They reveal Eurasia moved NNW during FIAs 1, 3 and 4 and SSE during FIA 5. The switch in shear sense on gently dipping foliation planes that accompanied the latter movement eventually led to the development of the MCT.

Keywords: relative plate motion from FIAs, shear sense history, motion of Eurasia, tracking rocks across orogens, pressure history from core isopleths

1 INTRODUCTION

The Main Central Thrust (MCT) developed ~20 to 25 million years after the collision ~50 million years ago of India and Eurasia (Powell and Conaghan, 1973). This structure, which runs along the ~W-E trending portion of the Himalayan orogen, brought high metamorphic grade Higher Himalayan metasediments over low-grade Lesser Himalayan rocks in Nepal (Searle et al., 2008). The early structural history of the mylonitic rocks overlying the MCT in this region, prior to movement along it, was not previously distinguishable because of the intensity of deformation associated with the collision of India and Eurasia. However, quantitative data on inclusion trails and foliation intersection/inflection axes preserved in porphyroblasts (FIAs) can be used to resolve the tectonometamorphic history of rocks prior to the development a matrix foliation associated with intense shearing (e.g., Bell & Kim, 2004). Indeed, the relics of earlier foliations contained within porphyroblasts provide a wealth of valuable information that is commonly obliterated from the rock matrix by subsequent deformation events (e.g., Bell et al., 2004). Quantitative analysis of the inclusion trails preserved in garnet porphyroblasts in the hanging wall of the MCT in the Central Nepal Himalayas revealed significant information on the history of India-Eurasia collision prior to MCT movement.

2 STRUCTURAL SETTING AND MATRIX MICROSTRUCTURES

Within the central Nepal Himalayas the Kathmandu Thrust Sheet (which contains the Kathmandu Complex) and the Lesser Himalayas are separated by the MCT locally known as the Mahabharat Thrust. Both are regionally folded by the ~W-E-trending Gorkha-Kathmandu fold couplet (Fig. 1). The Kathmandu Thrust Sheet consists of the Bhimphedi Group, whose schists, phyllites, quartzites and marbles decrease from kyanite-garnet grade at the bottom to biotite-chlorite grade at the top, and the overlying Phulchauki Group whose slates, siltstones, shales, sandstones, limestones and dolomites contain Cambrian to Devonian aged fossils (Fig. 1; Stöcklin, 1980). Gneisses and Ordovician granites are present within the Kathmandu Complex. The low-grade Lesser Himalayan Nawakot Complex is composed of phyllites, slates, quartzites, meta-sandstones, stromatolitic dolomites and limestones.

At least 4 sets of matrix foliations in high-grade schists and gneisses, collected from the hanging wall of the MCT in the Central Nepal Himalayas (Fig. 1b), can be recognized in thin sections. The first formed, S_1 and S_2 have a mylonitic character associated with movement on the MCT and truncate foliations preserved as inclusion trails within garnet porphyroblasts (Figs 2 and 3a). In the northern hinge of the Gorkha-Kathmandu fold couplet (Fig. 1b), S_1 dips steeply north against garnet porphyroblasts (Fig. 3a) but moderately north away from them and curves into sub-horizontal S_2 with a top-to-the-south sense of shear. This fabric is locally preserved on all limbs of the fold couplet with the same shear sense. S_1 is steeper than S_2 on the external north-dipping external limbs of the fold couplet and both dip north (Fig. 3b). On the central south-dipping limb both foliations dip south with S_1 curving into steeper S_2 (Fig. 3c). A sub-vertical foliation S_3 formed axial plane to the Gorkha-Kathmandu fold couplet (Fig. 3d) because S_2 curves into S_3 with a north side up sense of shear on the central limb and a south side up sense of shear on the external limbs (e.g., Bell et al., 2003). Reactivation of the fold limbs, with shear antithetic to the bulk axial plane shear on S_3 during fold development (Davis, 1995; Ham and Bell, 2004), intensified $S_{1,2}$ on the north-dipping limbs of the fold couplet but locally rotated S_1 on the south dipping central limb to indicate a top-to-the-north sense of shear. Two younger foliations, in particular a sub-horizontal one that crenulates S_2 with a top to the north shear sense (S_h), are visible locally (Fig. 3e; Sapkota, unpublished data).

3 QUANTITATIVE MEASUREMENT OF INCLUSION TRAILS AND THEIR ASYMMETRIES IN PORPHYROBLASTS

Marking a N-S line across the top and down the sides of each re-oriented sample allows this direction to be accurately transferred onto the tops of 2.5-mm thick horizontal slabs prepared from it. Vertical blocks striking 0^o, 30^o, 60^o, 90^o, 120^o and 150^o cut from these slabs were thin sectioned and marked with a single barbed arrow showing strike and way up (e.g., Bell et al., 1995). Microscopic examination of these sections with the barb pointing up and in the same direction allows the asymmetry of curvature of the inclusion trails within garnet porphyroblasts to be recorded. A FIA lies between those thin sections where the asymmetry switches. Sections cut 10^o apart where such switches were found allow the trend of the FIA to be measured within a 10^o range (e.g., fig. 4h in Bell et al., 2003). Some samples can contain 2 or more such switches between the core and rim with differing trends. The inclusion trails have sigmoidal or spiral shapes and, in many samples, those in the core are truncated by those in the rim (Fig. 2). Peaks trending SSW-NNE, WSW-ENE, W-E, NW-SE and NNW-SSE occur in the distribution of the 85 FIA trends measured from 78 samples shown in Fig. 4a. Core to rim changes observed between them are shown in Fig. 4b. The orientation of the pitch of inclusion trails was measured in the core and truncational rims of porphyroblasts (Fig. 5a) using thin sections cut near orthogonal to the FIA trend for the 45 samples containing sufficiently elongate quartz inclusions in such section orientations. These data show that the inclusion trails in the core and rims predominantly pitch sub-vertically or sub-horizontally (Figs. 5b and 5c). Consequently, using thin sections near orthogonal to the FIA trend, inclusion trails were documented for all samples as changing in pitch clockwise or anticlockwise from gentle to steep and/or steep to gentle as they curve outwards from the core of a porphyroblast towards its rim. Figure 5d shows these asymmetries on a histogram combined as CW or ACW and separated into the FIA trends labelled 1 through 5 above looking NNW, WSW, NW, W and SSW so that the results could be related to a S-N cross-section through the W-E trending orogen. Samples K17 and T17 contain FIAs trending parallel to those labelled 4. Looking W they contain steep to flat portions of inclusion trails that switch on the porphyroblast rim from CW to ACW (Figs. 2c, 2d and 5d) suggesting top-to-the-south switched from top-to-the-north on gently dipping foliations towards the end of this period of FIA development if the porphyroblasts did rotate or vice versa if they did not. Garnet core isopleth compositions are shown in Fig. 6 on appropriate portions of a PT pseudosection obtained from THERMOCALC using the approach described by Sanislav & Bell (2011).

4 INTERPRETATION

4.1 FIA succession

The core to rim changes in FIA trend shown in Fig. 4b preserve a consistent pattern of relative timing for 4 of the 5 peaks shown in Fig. 4a with that trending NNW-SSE forming first, followed by WSW-ENE, NW-SE and then W-E. The SSW-NNE-trending peak postdates the NNW-SSE peak but no core to rim changes were found to indicate it’s timing relative to the other peaks. However, the inclusion trail asymmetry for this FIA set looking SSW is predominantly ACW whereas that for the others looking overall westwards is predominantly CW (Fig. 5d). As shown below, this change plus a flip in the asymmetry of the inclusion trails at the rim of some samples containing FIA 4 suggest that the SSW-NNE-trending FIA set was the last to form. This is strongly supported by similar data from the Western Himalayas of Northern Pakistan where the last 2 FIAs recorded in those rocks trend the same as FIAs 4 and 5 in Fig. 2c (Shah et al., 2011).

4.2 Inclusion trail asymmetries and the FIA succession

The sub-vertical and sub-horizontal nature of the core and rim inclusion trails shown in Fig. 5b,c, and the consistent succession of FIA peaks shown in Fig. 4b that are numbered 1 through 4 in Fig. 4c, could not develop if the porphyroblasts had rotated. Consequently, the inclusion trail asymmetries shown in Fig. 5d can be interpreted in terms of shear sense. They are all drawn looking overall westwards so that they coincide with how they appear projected onto a S-N cross-section through the central Himalayas. The inclusion trail asymmetries for the NNW-SSE, WSW-ENE, NW-SE and W-E FIA trends in Fig. 5d are dominantly CW where as those for the SSW-NNE-trending FIA are dominantly ACW. Furthermore, some CW-shaped inclusion trails for samples containing the W-E FIA (numbered 4 in Fig. 4c) show flips in the inclusion trail asymmetry at porphyroblast rims to ACW suggesting a change to ACW late in the development of this FIA set (Fig. 2b). ACW inclusion trails accord with top-to-the-south motion on the MCT whereas CW ones do not. Consequently, it is interpreted that the SSW-NNE FIA set was the last to form giving the NNW-SSE, WSW-ENE, NW-SE, W-E to SSW-NNE succession numbered 1 through 5 in Fig. 4c.

4.3 Sub-vertical to sub-horizontal foliation successions

Porphyroblast growth occurs early during the crenulation deformation of a pre-existing schistosity and ceases as crenulation cleavage begins to develop against its rim (e.g., Spiess & Bell, 1996; Bell and Bruce, 2007; Sanislav and Bell, 2011). Consequently, it commonly occurs prior to significant rotation by folding during a first phase of porphyroblast growth. If the foliation that forms against these porphyroblasts is crenulated by a deformation event that is accompanied by another phase of porphyroblast growth, it will be preserved in the orientation in which it formed. Only rotation of the porphyroblasts would disrupt this (Hickey and Bell, 1999). Figures 5b and 5c show that the foliations preserved as inclusion trails are dominantly sub-vertical and sub-horizontal according with the results obtained wherever this type of quantitative data has been collected (e.g., Hayward, 1992; Bell and Newman, 2006; Bell and Sanislav, 2011). They reveal that each foliation preserved by successive stages of porphyroblast growth formed with a sub-vertical or sub-horizontal orientation and that the porphyroblasts were not then rotated. They support the above history of porphyroblast growth relative to foliation development because Fig. 5c shows that foliations trapped by a second phase of growth have pitches closer to sub-vertical and sub-horizontal than those when a first phase of growth are included (Fig. 5b). They reveal that no rotation of porphyroblasts took place during the multitude of younger non-coaxial deformations that took place during the mylonitisation that accompanied development and uplift along the MCT.

The entrapped FIA that results from the intersection of orthogonal foliations has the same orientation as synchronously developing crenulation hinges or fold axes in that location and its trend is controlled by the strike of the sub-vertical foliation (Bell and Sanislav, 2011). Foliations, crenulation hinges and fold axes in the matrix may change in orientation as the deformation continues but this does not affect the orientation information preserved within the porphyroblasts (e.g., Bell & Bruce, 2006). Sub-vertical and sub-horizontal foliation successions develop as a result of bulk horizontal shortening causing crustal thickening through sub-vertical foliation development (e.g., Figs. 7a and & 7c). This cycles with gravitational collapse and spreading which generates sub-horizontal foliations (Figs. 7b and 7d). The relative plate motion driving bulk horizontal shortening within an orogen does not cease until plate boundaries shift elsewhere. Therefore, it is likely that sub-vertical foliations continue to develop below a deeper decollement, while episodically, phases of gravitational collapse take place above as shown in the series of sketches in Fig. 7 (e.g., Bell and Newman, 2006).

4.4 Shear sense on gently dipping foliations and motion relative to the orogen core

The spectacular Nanga Parbat and Namche Barwa syntaxes in the Himalayan Mountain chain, located in Pakistan and Tibet respectively, show that the core of Himalayan orogenesis has moved northwards as India pushed into Eurasia (schematically illustrated in Fig. 7). The data in Figs 5b and 5c allow the asymmetry of changes from steeply pitching inclusion trails towards gently pitching orientations shown in Fig. 5d to be used to determine the shear sense on gently dipping foliations. Looking west at a S-N cross-section through the Himalayas they indicate that the shear sense was dominantly CW in FIA 1, coaxial in FIA 2, CW in FIAs 3 & 4 but ACW in FIA 5. This indicates a reversal with time from top-to-the-north, or coaxial, to top-to-the-south. What do these data suggest has taken place tectonically? Figures 8a and 8b show very schematically a S-N cross-section through a vertical column of rock before and after the effects of gravitational collapse. To solve the space problems of vertical bulk shortening, rock must extrude to the surface. Consequently, the deformation has to involve bulk inhomogeneous shortening, anastomosing geometries and partitioning of progressive shearing and shortening during foliation development rather than the simple relationships in Fig. 8b (Bell and Bruce, 2007). Furthermore, there would be more vertical bulk shortening and spreading at depth. However, the problems of extrusion, coaxiality in the orogen core and the spectacular change in the rate of displacement towards the orogen extremities that gravitational collapse and spreading generate, are very similar as those illustrated by Fig. 8b. The thick vertical line in Fig. 8a remains undisplaced in Fig. 8b because at the orogen scale, this deformation was coaxial. However the outer thin lines in block Z are displaced dramatically more than those in blocks Y or X. Extreme non-coaxial deformation takes place during ductile deformation of rock close to the boundaries of these blocks because the transitions are gradational rather than knife sharp as drawn here (e.g., Bell and Johnson, 1989, 1992). Within these transitional zones, moving outwards from the thick central line along the upper and lower boundaries of block Z, the strain rate progressively increases. This occurs because of the differentially accumulative effects of bulk shortening across the boundaries of differentially shortened portions. Consequently, foliations forming along the transitional zones will change in character from non-mylonitic near the orogen core to mylonitic towards the extremities. Significantly, the shear sense on the upper boundary will be the reverse of that on the lower boundary. Furthermore, on both sides of the upper and lower boundaries, the shear sense switches across the central thick line. The shear senses below will be interpreted as resulting from thrusting and those above are commonly attributed to crustal extension, but both form at the same time from the same tectonic process. They produce, about a single FIA, spiral-shaped inclusion trails at depth and staircase-shaped trails at shallower crustal levels (Bell and Johnson, 1989). This switch from spiral to staircase shaped trails in single FIA samples takes place in an orogen core at ~5 kbar in garnet porphyroblasts (Bell and Johnson, 1992).

Examining the steep to gentle versus gentle to steep inclusion trail asymmetries recorded by these porphyroblasts in the context of Fig. 8b allows us to track where the rocks are located and have potentially moved within the orogen during the development of each FIA. The pressures of garnet core formation for each of the 5 FIAs in the succession vary little (Fig. 6) and suggest that the rocks lay between 20 and 23 km deep while garnet was growing. Both shear senses are present for changes in inclusion trail curvature from steep to gentle (Fig. 5d) that define the shear sense on gently dipping foliations for FIAs 1 through 4, but most are CW (1, 3 and 4) with some coaxial (2). The inclusion trails are also spiral shaped which indicates that they lay in the lower half of the portion of the orogen affected by gravitational collapse. This suggests that they lay near the bottom of block Z, close to but on the right (N) side of the thick vertical line in Fig. 8b (see Bell and Johnson, 1989 for details on inclusion trails versus location in the orogen). Both shear senses are present for steep to gentle changes in inclusion trail curvature for FIA 5 but most are ACW and the inclusion trails are still spiral shaped. This suggests the rocks still lay in the lower half of the portion of the orogen affected by gravitational collapse but were displaced southwards just across (to the left of) the thick vertical line in Fig. 8b. Figures 8c, 8d, 8e and 8f show schematically, but in more orogen recognizable terms, only collapse stages of orogenesis. Between each of these 4 figures are many intervening stages of both horizontal crustal shortening and gravitational collapse, such as shown in Fig. 7. The other difference between these and Figs 8a and 8b are the effects of roll-on. These effects, which are also shown in Fig. 7, result from India being pushed northwards into and under Eurasia as suggested by the Nanga Parbat and Namche Barwa syntaxes. The basal decollement to the zone affected by gravitational collapse in Figs. 7 and 8, is located ~30 km deep in the orogen core. Displacement of the hot zone of most affected by bulk horizontal shortening below this decollement to the north due to roll-on truncated through the central core of orogenesis that lay above during garnet growth. This eventually resulted in rocks, which at one stage lay in the core, being extruded towards the surface as shown in Figs. 8d, 8e and 8f. It is noteworthy that the orogenic pile is progressively lifted across this basal decollement as bulk horizontal shortening proceeds. Consequently, roll-on will continuously tend to move rocks metamorphosing close to core and a little above the decollement, southwards as occurred for the samples described herein. After FIA 5, the dramatic increase extrusion effects, as the rocks move towards the orogen extremities, due to the space constraints of bulk shortening shown for block Z in Fig. 8b, come onto play. These extrude rocks towards the Earth’s surface during phases of gravitational collapse at greater and greater speeds as indicated by the change in time versus distortion of the heavy black line from Figs. 8d to 8e to 8f. The MCT is the product of such a transition. The opposite shear senses recorded by Brunel (1986) in the higher Himalayas to the north, that lie structurally above the rocks described herein, result from those rocks lying on the upper side of a block such as Z in Fig. 8b. Rocks that formed at higher pressures during earlier collisions are now exposed, e.g., near the syntaxes (Searle and Treloar, 2010), or will one day be exposed a long way to the north (e.g., fig. 1b in Harrison et al., 1997).

4.5 Length and timing of orogenesis

These porphyroblasts preserve a lengthy record of orogenesis during which 5 FIA sets developed that involved the development of more than 15 foliations at depths between 20 and 23 km; all of this occurred prior to the 4 or 5 foliations that are preserved in the matrix. Collisional orogenesis started in the Himalayas around 55 Ma (Searle et al., 1997 and references therein). Monazite inclusions in garnet dated from above the MCT, as well in the Central Nepal Himalayas between 32 and 24 Ma (Gehrels et al., 2006) and ~100 km to the east at 45 Ma and between 28 and 19 Ma (Catlos et al., 2002). The changes in direction of bulk shortening revealed by the FIAs most likely resulted from a succession of changes in the direction of relative plate motion between India and Eurasia (e.g., Bell and Newman, 2006). The garnet porphyroblasts in Central Nepal appear to contain ~ 20 million years of Himalayan orogenic history with periods of unchanging motion ranging from 2 to 7 million years between 50 and 29 Ma (see below). The matrix foliations preserve some of the foliation development history that occurred as these porphyroblast bearing rocks were uplifted towards the surface along the MCT.

4.6 FIA succession and the motion of India relative to Eurasia

FIAs lie parallel to the intersection between alternating steeply and gently dipping foliations. Therefore, their trend is controlled by the strike of foliations that are near-vertical (Fig. 9; Bell and Sanislav, 2011). Consequently, the FIA trend for each of the 5 sets that developed in these garnet porphyroblasts, now located as shown in Fig. 1b, is controlled by the strike of the sub-vertical foliations (Fig. 5b,c). Their orientation is independent of the direction of motion on gently dipping foliations, as shown in Fig. 9, depending only on the changes in direction of bulk horizontal shortening that developed the steeply dipping foliation. Consequently, *FIAs should form perpendicular to the direction of relative plate motion* and indeed are the only structures along the Alps that show any relationship to the known directions of relative motion between the African and European plates for the past 115 million years (Bell et al., 1995). This, plus the consistency of successive FIA trends for distances greater than 300 km along orogens, suggests that these structures can routinely be used to track the directions of relative plate motion that took place during orogenesis (e.g., Bell and Newman, 2006). Applying this approach using the FIAs from Nepal described herein, the direction of relative plate motion between India and Eurasia shifted with time from WSW-ENE to NNW-SSE to SW-NE to N-S to WNW-ESE.

Patriat & Achache (1984), using magnetic anomalies in the central Indian Ocean, showed that India’s motion relative to a stationary Eurasia changed after collision 5 times from 50 to 29 million years ago (highlighted with a heavy black line in Fig. 10a and enlarged in Fig. 10b). Figure 10c shows the succession of FIA trends and the changes in the direction of bulk shortening and thus the direction of relative plate motion that they reflect. Although the directions in Fig. 10c are not the same as those shown in Fig. 10b, with the exception of that for FIA 2, the *succession* of changes in direction that they reveal is remarkably similar to that which occurred between 50 and 29 Ma. This strongly suggests that the deformation and metamorphic history preserved by these garnet porphyroblasts took place during this time period. Monazite inclusions in garnet from near the MCT, as well in the Central Nepal Himalayas have been dated between 32 and 24 Ma (Gehrels et al., 2006) and ~100 km to the east at 45 Ma and between 28 and 19 Ma (Catlos et al., 2002). If the FIA sets had been determined from their rocks before dating was attempted the monazite inclusions could have been grouped and dated to test the time succession revealed by such an approach (e.g., Cao, 2009; Sanislav, 2011). Consequently, the lengths of the lines showing the relative direction of bulk shortening were drawn identical to similar portions of the succession shown in Fig. 10b.

4.7 Motion of Eurasia

The differences between the directions of relative plate motion indicated in Figs. 10b and 10c may have resulted from the fact that Patriat & Achache (1984) were unable to take into account any change in motion of Eurasia and assumed it was stationary. A comparison of Figs. 10c and 10b. shows that only during FIA 2 was the direction of motion coincident with the equivalent portion of the path between 50 and 29 Ma calculated by Patriat & Achache (1984). The directions of relative plate motion of India and Eurasia using the magnetic striping (Fig. 10b) and the FIA approach (Fig. 10c) do not align for any of the other 4 trends. If variation in the speed rather than trend of motion of Eurasia caused the latter variation, then the alignment for FIA 2 but not FIAs 1, 3, 4 and 5 would only occur if the trend of motion of Eurasia was parallel to FIA 2. This approach was used to determine the vector of movement of the Eurasian plate required to produce the other FIA trends to see if it provided information that provided insight into other tectonic data. Figure 10d plots the vector for 4 of the periods of motion in the 50 to 29 Ma succession shown in Fig. 10b, the equivalent direction of motion indicated by the FIA trend, plus the direction of motion from 48 to 44 Ma. This gives a vector of motion of Eurasia for each of these 4 periods that shows it moving NNW *away* from India during FIAs 1, 3 and 4 and SSE *towards* India during FIA 5. The motion was 1.32°/Ma during FIA 1, 0.36°/Ma during FIA 3, 0.72°/Ma during FIA 4 (averaging 0.80°/Ma to the NNW) and 0.41°/Ma to the SSE during FIA 5. This switch in the direction of motion of Eurasia coincides with the switch in shear sense recorded by garnet porphyroblasts from top-to-the-north to top-to-the-south during the development of gently dipping foliations that took place around the transition from FIA 4 to FIA 5 (Fig. 5d). Tectonically this may have led to the southward surge in the motion of Eurasia that eventually led to the breakout of the decollement horizon shown in Fig. 8e at the earth's surface that became the MCT. Intriguingly, when the motion of India and Eurasia were parallel during FIA 2, the shear sense on gently dipping foliations was coaxial. We do not know whether Eurasia was moving NNW or SSE at this time. For compressional orogenesis to occur it would have to be moving either SSE or slower NNW than India. If Eurasia switched to moving SSE, the directly opposed motions might mean that the deformation became more coaxial and even explain why there was one more sample containing a top to the SSE shear sense than top to the NNW!

4.8 Tectonic setting of the MCT prior to exposure at the earth's surface

Thrust motion ceased on the MCT some million of years ago and is currently occurring at lower levels that surface to the south along structures such as the Main Boundary Thrust. The locally developed sub-horizontal crenulation foliation that crenulates S_2 and S_3 with a top-to-the-north shear sense formed after development of the

Kathmandu-Gorkha fold couplet. This crenulation formed within the ductile deformation environment presumably just prior to exposure of these Central Nepal rocks as they rode upwards on younger thrusts. These relationships, in the context of the FIA and asymmetry data present herein, suggest that the MCT was uplifted during the development of S_3 across the boundary where the shear sense reverses during gravitational collapse producing thrust geometries below and extensional geometries above (Figs. 7 & 8). This ductile reversal in shear sense occurred at cooler temperatures much closer to the earth's surface than those that produced the South Tibetan Detachment System to the north because of the roll-on effects of orogenesis as India pushed northwards below Eurasia.

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CONCLUSIONS

Tectono-metamorphic events that occurred in the core of the Himalayan orogen between India-Eurasia collision and the development of the Main Central Thrust (MCT) have been elusive for many years. The effects of the collision that led to the development of the MCT and subsequent exhumation of the Higher Himalayan crystallines obliterated evidence for earlier structural and metamorphic history in the matrix of these rocks. However, garnet porphyroblasts lying close to the MCT in the Kathmandu Thrust Sheet, which constitutes the southern extension of the Higher Himalayas in central Nepal, predate MCT related mylonitic and subsequently developed foliations. They necessarily truncate inclusion trails preserved in the porphyroblasts. Quantitative measurement of Foliation Intersection/Inflection Axes in porphyroblasts (FIAs) contained in these inclusion trails and careful examination of their asymmetrical curvatures for shear sense interpretation allowed changes in the direction of bulk horizontal shortening and motion of what are now Kathmandu Thrust Sheet rocks relative to the core of the Himalayan orogen to be determined. Modelling of phase diagrams combined with analysis of Fe, Mn and Ca end member isopleths from garnet core compositions revealed the PT conditions over which each of the FIA set developed. However, anomalously high equilibration pressures calculated from the composition of garnet cores and surrounding silicates raise questions as to whether the matrix grains ever attained equilibrium with garnet rims during mylonitisation. The following paragraphs summarise the key conclusions for each section.

Section A

Five generation of foliations preserved in the matrix and shear senses associated with them formed as a result of the motion on the MCT, followed by folding at a regional scale by the Gorkha-Kathmandu fold couplet plus other deformation events. Correlation of overprinting relationships between different foliations and shear senses from sample to sample and their position in the fold couplet helped establish a complete structural succession of these matrix foliations. Deformation of the first foliation that can be recognized in the matrix by the originally gently dipping second reveal the shear sense for motion along the MCT and are present with different geometries in various parts of the fold couplet. The MCT related fabric can be observed close to its initial geometry near the hinges of the fold couplet, where S_1 dips moderately north and curves into gently dipping S_2 with a top-to-the-south sense of shear. In the external limbs of the fold couplet, S_1 dips steeply north and curves into moderately north dipping S_2 where as in the central limb of the fold couplet, S_1 assumes a gentle dip and its curvature into moderately south dipping S_2 indicates a top-to-the-south sense of shear. S_1 formed sub-vertically as the relics of this orientation are preserved close to the hinge of the fold couplet within low strain zones such as pressure shadows of garnet porphyroblasts. Therefore, S_1 and S_2 did not develop synchronously but rather formed during near-orthogonal events and do not constitute an S-C fabric. The angle of 45^o that can now be observed between S_1 and S_2 in high-strain zones resulted from progressive shearing of S_1 during the motion along the MCT that resulted in the displacement in an order of 100 km.

The folding of the Kathmandu Thrust Sheet by the Gorkha-Kathmandu fold couplet crenulated S_2 and formed a sub-vertical axial planar foliation S_3. The curvature of S_2 into S_3 exhibits a south side up shear sense in the external limbs and north side shear sense in the central limb of the fold couplet. Reactivational shearing on fold limbs operates antithetic to the shearing occurring on axial plane as the limbs are progressively steepened during folding. Therefore, reactivational shearing that acted top-to-the-south on the external limbs of the fold couplet intensified the $S_{1\text{-}2}$ MCT fabric but locally rotated it in the central limb where the shearing was top-to-the-north.

Sub-vertical S_3 is locally crenulated by north-dipping S_4 in the central limb of the fold couplet with a top-to-the-south sense of shear. Relics of S_2 within S_3 indicate a north side up sense of shear. This post-folding top-to-the-south phenomenon was observed in the shear zone along the Kalphu River, which separates Bhimphedi Group rocks from the gneisses in the north. The youngest foliation formed in the region was a sub-horizontal S_5 with a top-to-the-north sense of motion on it. The samples exhibiting this late north-directed shear also contain relics of an earlier top-to-the-south motion. The sub-horizontal S_5 could have formed as a result of vertical shortening that occurred after a period of sub-horizontal shortening that folded the MCT and sheared the rocks top-to-the-south along the north-dipping S_4. Top-to-the-north shearing on S_5 is not equivalent to normal motion on the South Tibetan Detachment System in the north as the latter developed roughly contemporaneously with the MCT.

Section B

The Higher Himalayan crystallines were affected by regional Barrovian metamorphism after India collided with Eurasia. This metamorphism occurred for about 21 million years until the Higher Himalayan rocks began to be brought towards the surface along the MCT around 25 Ma. Inclusion trails that were preserved by garnet porphyroblasts during this period record five FIA sets. The NNW-SSE-trending peak was the earliest FIA to form, followed by WSW-ENE, NW-SE, N-E and SSW-NNE trends. This relative timing succession for the first four peaks was determined mainly on the basis truncational relationships between various FIA trends occurring in garnet cores and rims. These five FIA sets nucleated at 6.2 kbar and 515^{o}C, 6 to 7 kbar and 545 to 550^{o}C, 6.6 kbar and 530^{o}C, 5.6 to 6.2 kbar and 525 to 550^{o}C and 6.8 to 6.9 kbar and 520 to 560^{o}C, respectively. Nucleation PT conditions for the FIA sets are represented by the intersection of Fe, Mn and Ca end member garnet core isopleths.

Various rim geothermobarometric methods yield more than 4 kbar higher pressures than those calculated by isopleth intersections. This would require about 12 km recycling of depth during metamorphism, and if this was the case, some evidence for it would have been preserved in at least one garnet core out of the eight analysed. Moreover, all matrix foliations that truncate inclusion trails preserved in garnet porphyroblasts are MCT-related mylonitic or developed during subsequent deformation events that brought the rocks towards the surface. Consequently, rim pressures calculated from various geothermobarometric methods should have recorded the exhumation process, which is not the case.

Garnet porphyroblasts are much more competent that the surrounding matrix and tend not to deform internally. Therefore, they underwent slow dissolution and solution transfer during high strain rate environment associated with the movement on the MCT. However, matrix grains were affected by plastic deformation, sub-grain formation, sub-grain rotation and recrystallization. Thus, garnet rims and surrounding silicates behaved differently during mylonitisation and the assumption of equilibrium between them held by rim geothermobarometric methods does not apply for these rocks. Anomalously high rim pressures could be a result of this non-equilibrium.

Section C

Internal foliations preserved within garnet porphyroblasts in the Kathmandu Thrust Sheet are dominantly sub-horizontal and sub-vertical. Small amounts of moderately-dipping foliations are the first foliations preserved in porphyroblasts. Such first foliations overgrown by porphyroblasts during their early stages of growth are relics of pre-existing fabrics in the matrix such as fold limbs and can lie in any orientation. Excluding the first foliations, the remaining later foliations preserved in the porphyroblasts are exclusively sub-horizontal and sub-vertical. Pitches of 287 foliations preserved in garnet porphyroblasts were measured in thin sections cut at high angle to the related FIA trends and plotted on vertical rose diagrams to examine the orientation distribution of the internal foliations.

Steep pitches (avg. 71.8^o) dominate gentle ones (avg. 8.7^o) by 3.3 to 1 for foliations that predate local porphyroblast growth, i.e. the first foliations preserved by the porphyroblasts. Gentle pitches (avg. 7.3^o) dominate steep ones (avg. 81.6^o) for the foliations that formed after a first stage of porphyroblast growth. These data strongly suggest that the foliations formed sub-vertically and sub-vertically within the metamorphic core of the Himalayan orogen at pressures between 6 and 7 kbar and demonstrate that the porphyroblasts did not rotate during their growth or during subsequent deformation events that produced younger FIAs and eventually led these rocks reaching the surface.

A FIA results from the intersection of two near-orthogonal foliations and its trend is controlled mainly by the strike of steeply dipping foliations. Thus, the preservation of five FIA sets in the rocks described here suggests that a minimum of 10 deformations are involved in the formation of these sets. Some porphyroblasts containing each FIA set contain at least 3 foliations and thus provide evidence for at least 15 successively sub-vertical and sub-horizontal foliation forming events occurring at depths around 20 to 23 km prior to their exposure at the surface along the MCT.

The pitch distribution data suggest that 3.3 times more porphyroblasts grew for the first time during a deformation that post-dated the development of sub-vertical foliations. This is supported by a fact that during a second phase of growth, 1.4 times more porphyroblasts grew during a deformation that post dated the development of sub-horizontal foliations. However, sub-horizontal foliations resulting from gravitational collapse are independent of the FIA trend. Thus, for all FIA sets that formed after the first, i.e. for FIAs 2-5, the first phase of porphyroblast growth would preserve more gently dipping foliations than steeply dipping ones. However, the ratio of steeply vs. gently dipping foliations in FIA 1 is 1.4:1 whereas in FIAs 2-5, it is about 4:1. This suggests that any change in the direction of relative plate motion can be accompanied by an effective decrease in the rate of bulk horizontal shortening, which can prevent portions of the orogen core that were about to undergo gravitational collapse as a result of crustal shortening from reaching that threshold point.

Section D

The succession of NNW-SSE-, WSW-ENE-, NW-SE-, W-E and SSW-NNE-trending FIA sets formed in response to changes in the direction of bulk horizontal shortening that could have resulted from variations in India's motion relative to Eurasia during the growth of garnet porphyroblasts that contain these different FIA trends. These trends were recorded by garnet porphyroblasts after the collision of the two plates when regional Barrovian metamorphism commenced in the Higher Himalayas and before the motion on the MCT took place. The direction of bulk horizontal shortening (which lies perpendicular to a related FIA trend) for the FIAs 1, 3, 4 and 5 show a remarkable match with India's motion between 50 and 29 Ma as calculated by Patriat and Achache (1984), whereas that for FIA 2 aligns with the equivalent portion of the path between 50 and 29 Ma.

Patriat and Achache (1984) were, however, unable to take into account Eurasia's motion and assumed that it was stationary at its present position when India has been moving overall north since 70 Ma. This could have resulted in small differences between the direction of bulk horizontal shortening determined from the FIA trends, which is controlled by relative motion between two colliding plates, and the portions of India's motion correlated for FIAs 1, 3, 4 and 5. If Eurasia was moving along the same trend but with different speeds, then the alignment for FIA 2 but not the rest would only occur if Eurasia's trend of movement was parallel to FIA 2. The vector of Eurasia's motion during the formation of the remaining four FIAs was therefore determined by keeping its trend as it was in FIA 2. This approach suggests that India was moving NNW away from India during FIAs 1, 3 and 4 and SSE towards India during FIA 5.

Asymmetries of inclusion trail curvatures were recorded for each FIA trend looking overall west so that they could be related to a S-N cross section, which is perpendicular to the trend of the Himalayan orogen. These asymmetries into gently dipping foliations, i.e. for steep to gentle curving inclusion trails, was dominantly CW in FIA 1, coaxial in FIA 2, CW in FIAs 3 & 4 but ACW in FIA 5. This indicates that the shear sense switched from top to the north or coaxial to top to the south during FIA 5.

The pressures of garnet nucleation for each of the FIAs in the succession vary little and suggest that all FIA sets were nucleated at depths between 20 and 23 km. The spiral shape of inclusion trails indicates that they formed in the lower half of the orogen. The presence of both CW and ACW asymmetries but a dominance of CW asymmetries in FIAs 1, 3 and 4 and coaxial in FIA 2 for steep to gentle changes in inclusion trail curvatures suggest that the first four FIAs developed at the lower half of the orogen but close to the core on its northern side. The dominance of anticlockwise asymmetries for steep to gentle curving inclusion trials in FIA 5, i.e. top-to-the-south sense of shear, indicates that this FIA developed on the southern side of the orogen core but still on the lower half and close to the core. Repeated gravitational collapse that occurred between the episodes of bulk horizontal shortening displaced the rocks described herein across the orogen core during the development of FIA 5 as India continued to move northwards. These rocks were eventually extruded at greater and greater speeds southwards towards the surface on what is called the MCT now.

Recommendations for future investigations

Detailed examination of microstructures preserved in garnet porphyroblasts and the matrix of rocks collected from the Kathmandu Thrust Sheet close to the MCT and calculation of PT conditions over which garnet porphyroblasts nucleated have provided a comprehensive picture of tectonometamorphic evolution of the Himalayan metamorphic core since the Indian and Eurasian plates collided about 50 million years ago. A similar FIA-based approach to identify changes in the direction of bulk horizontal shortening has been carried out in the NW Himalayas in Pakistan. The FIA data presented herein is similar to the FIAs measured in the NW Himalayas. Similar studies can be carried out in other parts of the Himalayas and more interestingly in the rocks now exposed north of the Indus Tsangpo Suture Zone for comparison. Garnets containing different FIA trends could not be dated during this study because monazite grains large enough were not found in any of the several polished thin sections. Dating of monazite inclusions in the garnet porphyroblasts would have helped to group garnet ages based on the FIA succession and provided more detailed information on tectonic evolution of the region.