**Abstract**

The use of porphyroclasts analysis for vorticity estimates is limited by the extrapolation to three dimensions of the two dimensional thin-section analysis of rigid clasts. We propose an alternative approach based on the use of X-ray micro computed tomography that offers a 3D view and thus considerably decreases the limitations of the method. Two mylonitic orthogneisses from the Munsiari Thrust, the lower boundary of the top-to-the-SW km-thick Main Central Thrust zone in the Indian Himalaya, containing K-feldspar porphyroclasts yield a kinematic vorticity ranging between 0.49 and 0.57. 40Ar/39Ar dating constrains the biotite growth on the main foliation at 4.8 ± 0.02 Ma.

Adding as much information as possible to a shear zone and relating them to different pressure and temperature conditions of shear episodes recorded besides by age variations of micas is a key point to keep in mind when debating the non-cylindrical nature of Himalayan orogen.

**Keywords:**

microCT, kinematic vorticity, stable porphyroclasts method, Himalaya, Main Central Thrust zone, Munsiari Thrust, 40Ar/39Ar geochronology

1. **Introduction**

The Himalayan belt is commonly regarded as a cylindrical structure from west to east due to the impressive lateral continuity of litho-tectonic units and shear zones, which is a peculiar feature of this mountain range. Nevertheless, differences in geological structures, topography, convergence rates and chronological ages have to be expected, and are confirmed by literature data, along strike in such large and complex orogenic belt. The regional occurrence of shear zones makes the Himalaya the right place to deduce large-scale tectonics of these structures regarding both their kinematics and the age of their timing, especially in the frame of exhumation of the Greater Himalayan Sequence (GHS), the metamorphic core of the orogenic belt. All along the belt, regional scale discontinuities accommodate the deformation *via* thrust-sense shear zones propagation in time and space towards the foreland (Montomoli *et al*., 2013; Carosi *et al*., 2018). The most studied and certainly the most discussed shear zone of the Himalaya is the Main Central Thrust zone (MCTz) a km-thick zone of intensively sheared rocks at the base of the GHS. Different criteria have been proposed for the definition and location of the MCT (Martin, 2017; Carosi *et al*., 2018 for updated reviews), nevertheless, an unique consensus lacks in the Himalayan community especially regarding its time of activity and precise location. This complex structure gives rise to different geological map localization (Carosi *et al*., 2018) and, as a consequence, to the comparison between different episodes of the deformation history comparing, for example, kinematic vorticity estimates that record different time of deformation in different areas/portions/parts of the structure.

The aim of this paper is to constrain the kinematic and temporal evolution of the lower boundary of the MCTz, the Munsiari Thrust, in the Bhagirathi valley (NW India) presenting a new three-dimensional approach that can aid to minimize the restrictions that arise in the estimate of kinematic vorticity using the stable porphyroclasts method.

1. **Geological Framework**

The Himalaya (Fig. 1a) developed as result of the India – Asia collision at 59 ± 1 Ma during the middle Paleocene (Hu *et al*., 2015), is approximately a 2400 km length NW – SE mountain range characterized by continuous litho-tectonic units delimited by regional scale discontinuities (Hodges, 2000; Carosi *et al*., 2018). Among these, the Lesser Himalayan Sequence (LHS), made by quartzite, schist, orthogneiss and marble of low- to medium-grade metamorphism (Arita, 1983), is divided by the GHS, the metamorphic core of the belt of medium- to high-grade gneiss, schist, migmatite, calc-silicate and the High Himalayan Leucogranites (HHL, Visonà *et al*., 2012), *via* MCTz, a zone of strongly sheared rocks.

In the study area, the Bhagirathi valley in the Indian Himalaya, the MCTz is bounded by two discrete faults and shear zones, the Munsiari Thrust at the bottom and the Vaikrita Thrust at the top. According to Metcalfe (1993), the deformation towards the structurally upper part of the MCTz (i.e. the Vaikrita Thrust) is completely ductile, whereas near the Munsari Thrust fabrics related to ductile-brittle transition occur. Within the MCTz the metamorphic grade increases structurally upward from the Munsiari Thrust to the Vaikrita Thrust (Metcalfe, 1993; Searle *et al*., 1993), increasing in temperature from 500 to 770 °C and in pressure from 6 to 12 kbar (Metcalfe, 1993). The main shear fabric in the MCTz is related to D2 (Metcalfe, 1993) and a variety of top-to-the-south kinematic indicators show a simple shear flow during this event.

1. **MicroCT on Munsiari Thrust orthogneisses**

Samples

Two samples from the Munsiari Thrust (UT15-5; UT15-6) have been selected for *Electron Probe Micro Analysis* (EPMA), vorticity analysis and 40Ar/39Ar step-heating dating.

Sample UT15-5 (Fig. 2a-d) contains quartz, K-feldspar, biotite, rare muscovite, monazite, allanite and zircon. The main foliation (S2) is defined by shape preferred orientation of biotite and rarely muscovite, and can be defined a disjunctive schistosity due to the alternation of granoblastic quartzo-feldspathic layers and lepidoblastic ones (Fig. 2a). Monazites with a symplectitic halo of allanite and apatite occur enveloped by the S2(Fig. 2b). Pre/inter-kinematic K-feldspar porphyroclasts are sericitized, being fractured or replaced by quartz, which also recrystallized in the strain shadows. In one case, a porphyroclast is bounded by a symplectitic structure at the contact with biotite. Quartz recrystallization mechanisms are represented by *Grain Boundary Migration* (GBM; Passchier & Trouw, 2005) recrystallization in sigmoid aggregates and ribbons in which quartz is coarse-grained and pinning structure and over-pinning of micas occur (Fig. 2c). Quartz is also characterized by straight grain boundaries in fine-grained domains. Kinematic indicators such SCC’ fabric, group 1 (and minor group 5) biotite fish, asymmetrical strain shadows around K-feldspar porphyroclasts, σ-porphyroclasts and quarter mats (Fig. 2d; Passchier & Trouw, 2005) show a top-to-the-S/SW sense of shear.

UT15-6 (Fig. 2e-f) contains quartz, K-feldspar, biotite, rare muscovite, titanite and zircon. As in the companion sample UT15-5, the SCC’ fabric is ubiquitous and S2 is defined by shape preferred orientation of biotite. Some sporadic static biotite overgrows the foliation. In this sample, biotite contains numerous titanite needles, suggesting unmixing of these two phases. K-feldspar porphyroclasts still preserve their habits and twinning, but someone is sericitizated and fractured (Fig. 2e). SCC’ fabric, δ-type porphyroclasts, quarter mats, asymmetrical strain shadows around K-feldspar porphyroclasts and group 4 biotite fish (Fig. 2f) all point to a top-to-the-S/SW shear sense.

EPMA on biotite reveal that although similar, biotites from the two samples have different XMg (Fig. 3a). The chemical variability of biotite trioctahedral sheet (Fig. 3b,c) is maily driven by the “dioctahedral” substitution 3Me2+ <> 2VIAl + □, with minor insertion of Tschermakitic substitution Me2+ + Si4+ <> IVAl + VIAl (CITARE) and Ti by the exchange vector: Ti4+ + 2O2– <> VIMe2+ + 2OH–. The age of biotite growth along the main foliation has been constrained at 4.81 ± 0.02 Ma and 4.78 ± 0.02 Ma for UT15-5 and UT15-6 respectively (Fig. 3 d-f) by 40Ar/39Ar step-heating technique.

Method and results

The theory of the stable porphyroclasts method is based on the fact that for a general shear, two fields exist distinguishing a population of porphyroclasts rotating continuously and therefore do not developing a preferred orientation, and a population that reaches a stable sink position (Jessup *et al*., 2007). Thus, in last decades the stable orientation analysis has been a proxy for vorticity estimates (Xypolias, 2010 and references therein) to deduce large-scale tectonics of shear zones (Li & Jiang, 2011 and references therein) from different tectonic settings (Xypolias, 2010; Fossen & Cavalcante, 2017). Nevertheless, severe limitations arise because of the extrapolation in two dimensions of motion of rigid clasts that is a complex three-dimensional problem (Li & Jiang, 2011; Mancktelow, 2013). We faced this problem using a X-ray micro computed tomography (microCT), a non-destructive technique used since 90s in different fields of geological sciences (Denison *et al*. 1997, Cnudde *et al*., 2006 and references therein), as paleontology (Fourie, 1974; Haubitz *et al*., 1988), soil and petroleum research (Pierret *et al*., 2002; Wellington and Vinegar, 1987; Géraud *et al*., 2003), fractures and rock porosity investigation (Carlson *et al*., 1999; Landis *et al*., 2000; Allan *et al*., 2002) and 3D visualization of petrography (Carlson & Denison 1992; Van Geet *et al*., 2001; Zanchetta *et al*., 2011).

MicroCT analyses were performed with a BIR Actis 130/150 Desktop Micro-focus CT/DR system hosted at Dipartimento di Scienze dell’Ambiente e della Terra, Università degli Studi di Milano – Bicocca. The samples were attached to a plastic sample holder with their maximum axis in a vertical position. The X-ray tube was provided with an energy of 100 keV and a current of 80 mA. The dimensions of the voxel (3D pixel, i.e. the resolution of the images) of the obtained images are: x, y, z = 0.0019 mm. The obtained 3D microCT image stacks were processed with the software AvizoTM.

X-ray microCT produces stacks of 2D grey-scale value images (referred to as “slices”) that allow observing the internal structure of a scanned object. As exhaustively reported in Denison *et al*. (1997), the contrast in an X-ray CT image is mainly caused by differences in X-ray absorption within the object due to variation in density and chemical composition. K-feldspar porphyroclasts and the matrix dominated by quartz appear generally lighter in color than biotite and rare muscovite sheets, which define the main foliation. Mineral phases were identified by comparing grey-scale colored slices with grey values of the Back Scattered Electrons (BSE) images of controfaccia as well as thin section observations: the comparison between SEM images and corresponding microCT slices allowed a reliable identification of mineral phases. To process the image automatically, we applied a threshold value to the main foliation to highlight wrapped porphyroclasts (Fig. 8a). In order to apply the stable porphyroclasts method, the slices representative of the XZ plane of the strain ellipsoid were processed (Fig. 8a), but factors such as the isolation factor and the slipping effect (Passchier *et al*., 1987; Iacopini *et al*., 2011) were evaluated also on the other planes (XY and YZ).

152 and 32 porphyroclasts have been analysed for the vorticity estimates from UT15-5 and UT15-6, respectively (Fig. 8). We adopt the plot proposed by Wallis *et al*. (1993) and the Rigid Grain Net (RGN) plot suggested by Jessup *et al*. (2007).

Vorticity number ranges between 0.53-0.58 (Fig. 8b) and 0.49-0.57 (Fig. 8c-d) for UT15-6 and UT15-5, respectively.

1. **Discussion and conclusions**

In the frame of exhumation models proposed for the GHS, adding as much information as possible to our knowledge about the bounding shear zones of the GHS itself, is a crucial and often a difficult challenge. Quantitative estimates of kinematic of the flow have been increasingly used to deduce large scale tectonic from a variety of geodynamic settings (Xypolias, 2010; Xypolias *et al*., 2010, Fossen & Cavalcante, 2017 and references therein). In the Himalaya, several studies have been carried out to infer the kinematic vorticity of the STDS, especially in the Eastern Himalaya (Law *et al*., 2004, 2011; Jessup *et al*., 2006; Carosi *et al*., 2006, 2007). Studies also exist on the vorticity of flow of the MCTz from NW India (Grasemann *et al*., 1999; Law *et al*., 2013), central Nepal (Larson & Godin, 2009; Larson *et al*., 2010), eastern Nepal (Jessup *et al*., 2006) and Bhutan (Long *et al*., 2011).

Our stable porphyroclasts analysis results (Wm = 0.49-0.57) on two mylonitic orthogneisses from the Munsiari Thrust reveal a strong pure shear component (65-60%). In the Sutlej valley (NW India, approximately 300 km to the west from our study area), Grasemann *et al*. (1999) support a strong pure shear component throughout the entire MCTz from ductile to late stage of ductile-brittle transition. They analysed mylonitic orthogneisses overprinted by fringe folds from the lower part of the MCTz and suggest that the pronounced pure shear component in the late stage of ductile flow is probably due to a decelerating strain path from a simple shear dominated flow to a pure shear dominated flow. In the same area, Law *et al*. (2013) combining stable porphyroclasts and quartz *c*-axis methods, obtain a vorticity number of 0.75-0.82 (Sutlej valley) and 0.90-0.95 (Shimla klippe transect), suggesting a dominated simple shear flow with a minor component of pure shear. In central Nepal, both Larson & Godin (2009) and Larson *et al*. (2010) obtain a strong pure shear component (66-41%, Larson & Godin, 2009) that decreases with structural distance from the MCTz (Wm from 0.50-0.68 to 0.78-87; Larson *et al*., 2010). In eastern Nepal, Jessup *et al*. (2006) find a Wm = 0.63-0.77, testifying a pure shear percentage of 44 – 58%; and also in Bhutan, Long *et al*. (2011) find a large component of pure shear.

As highlighted by Iacopini *et al*. (2011) the occurrence of thin rims of micas or fine-grained quartz around clasts could impede their rotational behaviour resulting in underestimated simple shear component in favor of higher pure shear component. This implies that strain localization may for example occur at the clast boundaries, which could compromise the estimation of real vorticity number. Nevertheless, our results are in agreement with the aforementioned for the MCT along the belt, and suggest a strong pure shear component (65-60%).

As stated by Tikoff and Fossen (1995), Li & Jiang (2011), Iacopini *et al*. (2011) and Mancktelow (2013) the reduction in 2D of motion of rigid clasts that is a 3D problem generates several limitations.

The first and foremost consideration is that the use of microCT certainly increases the number of investigated clasts because hand samples are scanned. MicroCT restricts the problems due to the isolation factor, we selected only the clasts that observe such parameter and do not interact each other, indeed. Moreover, observation in three dimensions allows correctly evaluating the aspect ratio and radii of clasts whose erroneous measurements generate systematic errors in the vorticity valuation (Iacopini *et al*., 2011).

The microCT that has been widely used in geological studies may represent a suitable tool in the acquirement of data for vorticity estimates using rigid porphyroclasts embedded in a matrix, because of the high resolution, the high number of investigated clasts and the possibility to inspect the third dimension and therefore limit the restrictions of the method.

**Acknowledgements**

We thank A. Risplendente (Università degli Studi di Milano) for his support during the electron microprobe analyses, V. Barberini (Università degli Studi di Milano Bicocca) for her assistance during 40Ar/39Ar dating and N.C. Fusi (Università degli Studi di Milano Bicocca) for the work session at the microCT. This research was financially supported by PRIN 2015EC9PJ5 (to C. Montomoli and R. Carosi) and by funds from Dipartimento di Scienze dell’Ambiente e della Terra, Università degli Studi di Milano Bicocca.