21 Application of SEM-EBSD Analysis of Deformed rocks in the Indian Context

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The measurement of texture using Scanning Electron Microscope (SEM) based Backscatter Diffraction (EBSD) is one of the most powerful techniques that is being used in a large number of geological investigations that involve evaluation of grain size, shape, grain boundaries, deformation mechanisms, kinematics and related aspects. All the above microstructural/textural information has direct relevance to the conditions of regional deformation and tectonics, which in turn can be linked to larger scale processes such as evolution of continents, and supercontinent assembly/cycles. Although SEM-EBSD studies have been in vogue in earth sciences since the last century, the use of this technique in the Indian context has been rather limited. India, with its vast expanse of deformed rocks viz. the Himalaya, several mineralized shear zones (e.g. Singhbhum), accretionary zones (e.g., in central India, Dharwar, SGT etc.), mobile belts (e.g., Eastern Ghats), provides earth scientists with an opportunity to understand geological deformation in a variety of tectonic settings using SEM-EBSD data. The objective of this writeup is to provide the reader with an insight about the various possibilities that this method offers to Indian earth scientists, particularly in structural geological/tectonic investigations.

A beam of high energy electrons is incident at an area of interest on a superpolished sample, which is placed at 70° tilt angle inside an SEM. This produces scattered electrons that travel in all directions. The backscattered electrons that satisfy Bragg's law for a specific crystallographic plane get diffracted and travel with a cone geometry. A set of cones is produced from each crystallographic plane, and the

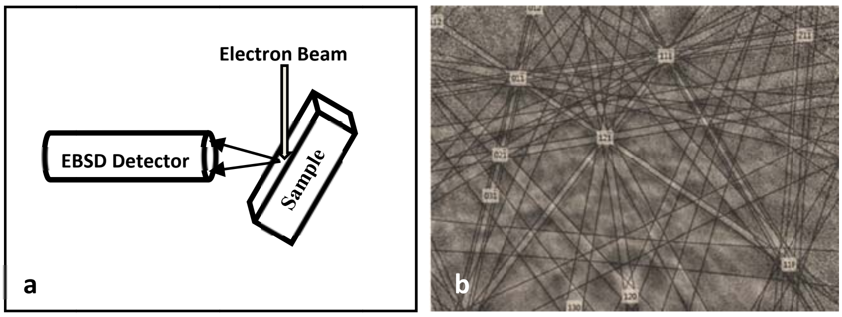

Figure-1: (a) Schematic diagram showing the sample geometry for EBSD analysis inside an SEM chamber. The sample is tilted by 70°. (b) Example of indexed EBSD pattern of quartz.

intersection of these cones with the phosphor screen gives rise to a band referred to as Kikuchi band. Depending on orientations of various crystallographic planes of the area analyzed, several such cones are produced, which produce a pattern of Kikuchi bands on the phosphor screen (EBSP - electron backscatter diffraction pattern). The points of intersection of different bands can be indexed, which provides all the crystallographic information about the mineral/s present in the area. (Schwartz et al. 2009). For the past two years, the author and his team have been carrying out extensive EBSD data acquisition using Nordlys Max2 detector (Oxford Instruments, UK) fitted in Carl Zeiss Auriga Compact FEG-SEM housed in Central Research Facility (CRF, IIT Kharagpur, India). Data acquisition and indexing of EBSD patterns is done using Aztec software (Oxford Instruments, UK), and processing of acquired data is done with HKL CHANNEL 5 software (Oxford Instruments, UK). The graphical output includes stereographic projections, pole figures, inverse pole figure maps, grain boundary maps, grain size and orientation information, orientation contrast images etc. all of which make EBSD a major tool in quantitative texture analysis of rocks, which can be subsequently interpreted in the regional tectonic context. Following are some of the investigations in deformed rocks that can be effectively done using EBSD.

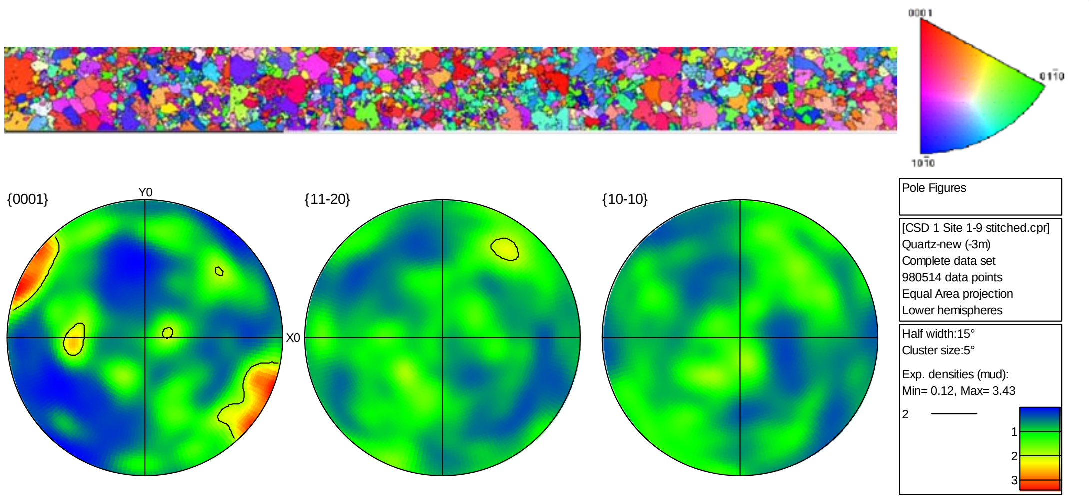

Figure-2: EBSD data of quartz from 9 different areas analyzed in quartzite of the Lunavada Group. Top row shows inverse pole figure (IPF) maps (9 stitched images; length ~1.5 cm). Bottow row shows the lower hemisphere equal area projections of quartz crystallographic data. Analysis are done using Carl Zeiss Auriga Compact FEG-SEM fitted with Nordlys Max^2 EBSD detector (Oxford instruments, UK) housed in Central Research Facility (CRF, IIT Kharagpur, INDIA).

(a) Complete crystallographic information can be obtained from EBSD studies. The obtained graphical data (such as lower hemisphere equal area projections of *c*- and *a*- axes of quartz) can be used for interpreting kinematics, temperature of deformation and slip systems. An example is presented in Fig. 1, where quartz crystallographic data from quartzites of the Lunavada Group of rocks collected from the vicinity of Godhra Granite(India) are presented. Systematic EBSD studies on quartzites taken at varying distance from the granite margin can provide vital information about texture evolution during syntectonic granite emplacement.

(b) EBSD data can also be effectively used to evaluate shear zones and mineralization. Field studies of deformed rocks provide geoscientists with very interesting structures such as folds, faults and shear zones. Working out the kinematics of development of such structures is an important objective of geological investigations (e.g. Passchier and Trouw, 2005; Mamtani, 2014). Majority of deformation in nature occurs by combination of simple and pure shear. EBSD data from deformed rocks can provide useful information about kinematics, enable vorticity quantification, thus providing geoscientists with the possibility of better understanding of tectonic evolution of a region. Often fluid activity associated with deformation influences rheology, thus leading to

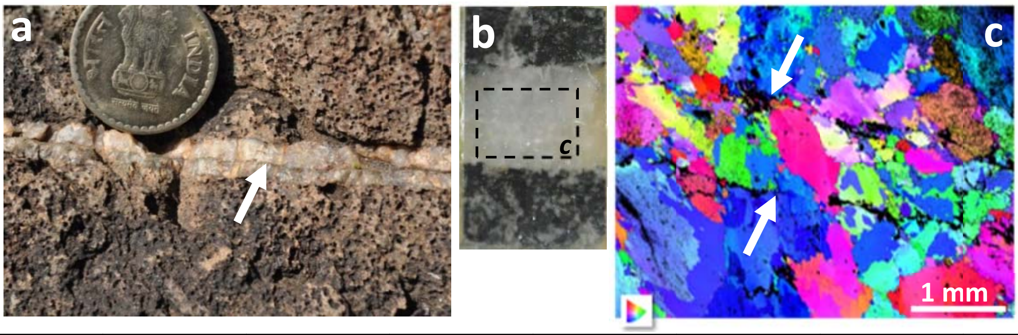

Figure-2: (a) Field photograph of quartz vein in Gadag region, Dharwar craton, southern India (after Mondal and Mamtani, 2013). White arrow points to the growth surface. (b) Photograph of polished quartz vein from Gadag. The area enclosed in the dashed-box (marked c) is the region of interest within the quartz vein that was mapped using SEM-EBSD at IIT Kharagpur. The IPF map of the analyzed area is shown in (c); white arrows point to the growth surfaces in quartz vein.

emplacement of veins. An example of quartz vein in Gadag (Dharwar craton, southern India) is presented in Fig. 2a (after Mondal and Mamtani, 2013). Such veins become locales for mineralization (e.g., gold in Gadag and uranium in Jaduguda). The present authors research team is carrying out EBSD analysis of such quartz veins in Gadag (Fig. 2b,c). This provides information about kinematics of vein development, which also controlled gold mineralization.

(c) Deformation mechanism of minerals in a rock can be efficiently inferred from EBSD data, as well as with the help of Orientation Contrast Imaging done using forescatter detectors. For e.g., Mamtani et al. (2011) were able to demonstrate with EBSD data that in the Godhra Granite (Gujarat, western India), magnetite was rigid, while the surrounding minerals (quartz, feldspar and ilmenite) underwent intracrystalline deformation, thus developing subgrains. Such information helps in better investigation of rheological response of different minerals in the same rock and provides possibilities to refine existing deformation mechanism maps of minerals (e.g., see Mamtani, 2012).

(d) Deformation of rocks often leads to development of shape preferred orientation (SPO) as well as crystallographic preferred orientation (CPO). Since most rocks are polymineralic, deformation and rheological response of one mineral in a rock influences that of adjacent minerals. In this process, minerals within the same rock influence the SPO and/or CPO of one another. Often, in rocks such as quartzites, minor amount of mica is common. This minor phase can influence the fabric evolution of the major phase (quartz). EBSD studies help better understand this (e.g., Renjith and Mamtani, 2014).

The above discussion presents a few cases, based on the authors experience, where EBSD studies of deformed rocks can be useful in earth sciences. According to the author, an integration of EBSD data with field data, magnetic fabric (from anisotropy of magnetic susceptibility, AMS, studies), and petrographic information helps better understand structural/tectonic evolution of an area. With the setting up of several SEM-EBSD facilities in recent times within India, the awareness about the wide-ranging applications of EBSD research in rocks is increasing. The present author hopes that this short write-up is another step in this direction to highlight the robustness of carrying out EBSD studies of deformed rocks.

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