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Mineralogical and Geochemical Evidence of Fluid-rock Interaction at the Shallow Crustal Level in Koyna Seismogenic Region, Maharashtra, India: Impact and Implications

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The Koyna region of Maharashtra located in the western part of the ~65 Myr old Deccan traps province, overlying the Neoarchean cratonic granitoid basement of peninsular India, has been experiencing recurring seismicity since 1962 after the impoundment of the Shivajisagar Reservoir behind the Koyna Dam. The establishment of the Warna Reservoir at a later stage has amplified the seismicity in this region. So, the Koyna-Warna region has evidenced more than 1,000,000 earthquakes in the last five decades. Several geophysical studies have proved that the seismicity in this region is somehow related to the water level in the reservoirs (Rastogi et al., 1995). Talwani (1997) has recognized several seismotectonic features in this intraplate seismogenic region such as Koyna River Fault Zone trending N-S, Patan Fault trending NE-SW and NW-SE trending fractures extending from near-surface to hypocentral zones. Few small-scale faults have also accompanied these major faults in this area. So, seismicity triggering structural elements were already present in this region, where construction of the dams and/or reservoirs has acted as the catalysts for reactivation of those faults. It has also been noticed from the previous monitoring that the seismic activity is increased during the post-monsoonal period when water is discharged from the dam and/or reservoirs. It implies that the huge water content of both the water bodies accumulates huge stress along the pre-existing faults of the region. Hence the discharge of water after the rainy season creates instability in the entire system and the accumulated stress is released in form of seismic energy causing several earthquakes in this seismogenic zone.

Recently, a geophysical investigation conducted in the Borehole KFD1, drilled up to 3000 m depth near Gothane (17°17'57"N, 73°44'19"E), has found seven anomalous zones in the granitoid basement based on the low resistivity (R1: 51–2,610 Ωm and R5: 228–7,613 Ωm), low density (1.9 to 2.4 g/cm^3), low P wave velocity (as low as 4.8 km/s), low S wave velocity (as low as 2.2 km/s), low Young's modulus (41–53 GPa), high neutron porosity (10% to 33%), and high Poisson's ratio (as high as 0.40) (Goswami et al., 2019). In support of this geophysical study and few other earlier geophysical observations (Gupta, 1992, 2002, 2011; Gupta et al., 2015, 2016), we have initiated an extensive geological especially geochemical research as a part of the Continental Deep Drilling Programme in this small 600 km^2 seismogenic area, which primarily deals with the different aspects of fluid-rock interaction at shallow crustal depth. Here the fluid-rock interaction has given rise to several mineralogical changes in the granite gneiss basement. The present work deals with those mineralogical and/or geochemical alterations recorded in the microscopic observations and FESEM-EDAX data of the core samples collected from the borehole KBH1 drilled up to 1522 m depth near Rasati location (17°22'38.5"N, 73°44'27.8"E) in this region. Besides, we also have attempted to explain the probable geophysical aspects of those mineralogical and/or geochemical alterations due to fluid-rock interaction. In addition, this study has also given an insight into a probable mechanism of generation of the slip surface and reactivation of pre-existing faults as a result of fluid infiltration and subsequent alterations.

Fluid-rock interaction is a complex thermodynamic process in which usually aqueous solutions chemically react with the rock bodies through the exchange of elements and/or their isotopes to attain the equilibrium (Hurai et al., 2015; Glassley et al., 2016). The rate of obtaining equilibrium is controlled by the reaction kinetics and is exhibited by the development of assemblages of co-existing minerals and dissolved aqueous species which owe the lowest free energy for the chemical components in the total system (Glassley et al., 2016). Fluid-rock interaction can occur in presence of aqueous fluid where temperatures vary from 0°C to ~800°C and pressures are between 0.1 MPa and ~3 GPa (Glassley et al., 2016).

In our study, we have carried out mesoscopic observations and identified the most prominent areas of fluid-rock interaction in the granitoid basement. Detailed optical microscopy using an advanced petrological microscope (Leica DM 2700 P) has been carried out to

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identify the host minerals along with the newly formed and transformed mineral phases. We have also separated the highly altered parts of the core samples and analysed them with the help of the Field Emission Scanning Electron Microscope (JEOL JSM 7610f -FESEM) and Energy Dispersive X-Ray Spectroscopy (EDAX).

The mesoscopic observations conducted in the Borehole KBH1 reveal occurrences of several phyllosilicates, carbonates and highly oxidized minerals at altered and fractured zones in the pre-Deccan granite gneiss basement along with other primary minerals such as quartz, alkali feldspar, plagioclase feldspar and biotite. The extremely friable nature of the massive granitoid at several depths, the mineralised network of fractures (Fig. 1a) and dominant calcification (Fig. 1b) indicates the fluid-induced alteration and subsequent precipitation in the granitoid basement. Besides, prominent greenish tint or precipitation of green-coloured minerals (Fig. 1d) has also been noticed, which has been identified as chlorite and epidote (Fig. 1e) during optical microscopy. Chlorite has been distinguished from Epidote with the help of ultra-blue or anomalous blue interference colour and extinction angle around 0°–10°, whereas epidote shows variegated interference colour and extinction angle of 25°–40° (with respect to the basal cleavage). In few places, Chlorite and epidote both are observed together, however, the abundance of chlorite is relatively greater than epidote. Similarly, calcite has been found in a high proportion along with other major constituting minerals (Fig. 1c). The Field Emission Scanning Electron Microscopy (FE-SEM) data also reveals the presence of chlorite (Fig. 2a) and calcite (Fig. 2b) as secondary minerals at several depths. Besides, point mode analysis of the highly altered samples (identified by mesoscopic observation) conducted through Energy Dispersive X-ray spectroscopy (EDAX) shows the presence of, Mg, Fe, Al etc. along with Si and O (Fig. 2c, Table 1) probably corresponding to the occurrences of other clay minerals, which have been identified by X-Ray Diffraction analysis (XRD) during the further study.

Based on these observations, an outline has been drawn to explain the event of subsurface fluid-rock interaction, subsequent mineralogical and/or geochemical changes and their geophysical aspect. Physiographically, Koyna Seismogenic Region is located on the eastern side of the Western Ghats escarpment and experiences high rainfall allowing infilling of the reservoirs during the monsoon season. This meteoric water percolates with time through the vesicular part of the basalt up to the granitoid basement and dissolves several elements causing the transformation of the composition of the infiltrated meteoric water and gives rise to the fluid suitable for geochemical alterations. Then this reactive fluid starts moving through the network of pre-existing fractures of the granitoid basement with increasing temperature which may be caused due to radioactive decay of the elements as well as the friction along several major and minor faults. During the passage of this infiltrated fluid through the fractures, it deposits or precipitates some elements or mineral phases that were already dissolved into it and also cause dissolution of primary mineral phases of the precipitating sites. As a result, carbonates are precipitated and some mafic minerals such as feldspar, biotite etc. are

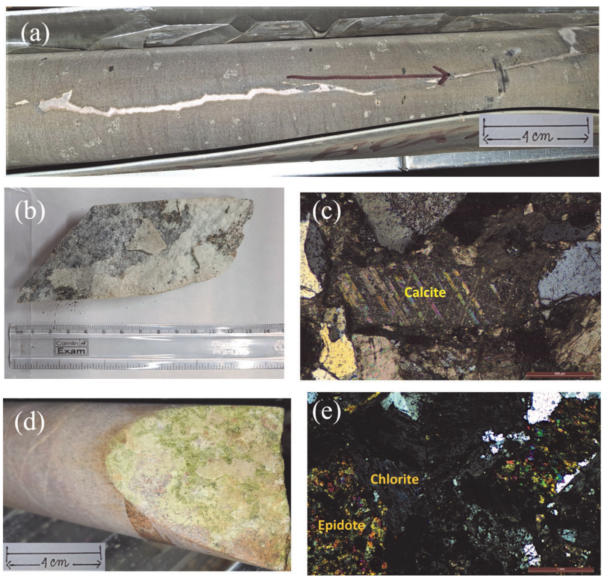

Fig. 1. (a) Mineralised Network of fracture; (b) mesoscopic Evidence of incipient calcification at around 1153.78 m depth; (c) microscopic evidence of the presence of calcite at around 1073.75 m depth; (d) greenish tint of Secondary mineralisation at 1027.81 m depth; (e) microscopic evidence of occurrences of chlorite and epidote at 1027.81 m depth.

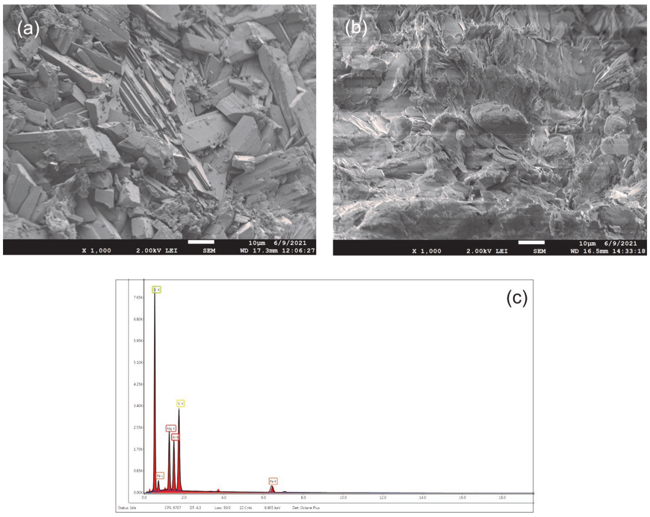

Fig. 2. (a) FE-SEM image of calcite (Sample depth-1286.04 m); (b) FE-SEM image of the greenish tint revealing the presence of Chlorite (Sample depth-1073.75 m); (c) corresponding EDAX graph of the same greenish part of the sample of 1073.75 m depth showing occurrences of Mg, Fe, Al along with Si and O.

Table 1 Analysis result of energy dispersive X-ray spectroscopy (EDAX)

Element	Weight (%)	Atomic (%)
O	57.94	70.97
Mg	11.55	9.31
Al	9.82	7.13
Si	15.38	10.73
Fe	5.32	1.87

transformed into clay minerals. Consequently, these chemical changes in the host rock bring about some sort of geophysical anomalies (Allis, 1990) due to the generation of new mineral phases mainly pervasive clay minerals, which are generally associated with argillic-propylitic type of hydrothermal alteration. Actually, the newly formed clay minerals have the potentiality to adsorb as well as absorb significant volumes of water, various cations and/or organic matters because of their thin sheet silicate structure, extremely fine particle size and charged surfaces. This change in their crystal lattice leads to relatively rare mechanical and hydrologic properties of clay minerals. The plasticity during shear in clay minerals also allows them to deform by sliding or dislocation gliding along the surface at temperatures relatively lower than that for common rock-forming primary minerals (Maltman, 1987; Shea and Kronenberg, 1992). Hence, a strong anisotropy is developed by particle reorientation during progressive shear as critical states are attained for laminar flow (Warr and Cox, 2015). These diverse behaviours of clay minerals are also recorded in the geophysical logs. Earlier geophysical investigations on the clay minerals have already revealed that homogeneous clay is characterized by low electrical resistivity, increased conductivity (up to 400 milli siemens), positive SP anomaly and sometimes high radioactivity (Allis, 1990). That is why, in areas of advanced argillic alteration resistivity values decrease to less than 10 Ohm-m although it should be in the range 10–30 Ohm-m (Allis, 1990). This extremely low value of resistivity is probably due to the reaction of extremely hot acidic waters with the rock bodies. In addition to this, most of the hydrothermal fluids, including relatively cool CO_2-bearing waters, dissolve magnetite and cause demagnetization anomalies (Allis, 1990).

On the other hand, successive growth of clay minerals decreases shear strength, modify porosity and permeability and induce fluid pressure variations by storing or releasing water by hydration-dehydration reactions (Bruce 1985; Vrolijk 1990). So, clay minerals play an important mechanical role in active faults, as they are frictionally weak and their presence affects permeability with consequences for shear strength and fluid pressure evolution (e.g., Wu et al., 1975; Saffer and Marone, 2003; Collettini et al., 2009). Thus, the formation of clay minerals in subsurface rock bodies due to the infiltration of aqueous fluids not only brings about the changes in the mechanical behaviour of rocks or subsequent geophysical anomalies but also plays a role of natural lubricant, causes the generation of slip surface and accelerates fault weakening process (Ben van der Pluijm, 2011). Thus, the interplay between faulting, fluid migration, and conversion of hydrous clay mineral leads to weakening within the upper section of this crustal discontinuity (Warr and Cox, 2015) and cause artificial-water-reservoir-triggered recurring seismicity in the Koyna Seismogenic Region in the Western Part of the Indian Subcontinent.

Key words: Continental Deep Drilling Programme, artificial reservoir triggered seismicity, fluid-rock interaction, shallow crustal level, geophysical anomaly, clay mineral, hydrothermal alteration

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