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Fluid–rock interaction in the basement granitoids: A plausible answer to recurring seismicity

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ABSTRACT

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The Koyna–Warna Seismogenic Region in the western part of the Indian Subcontinent has been recognized as one of the most significant sites of Reservoir–Triggered–Seismicity (RTS) during the last five decades. The basement granitoids, overlain by the porous and vesicular Deccan Trap basalt, contain numerous interconnecting fractures which act as the ascending and descending pathways of fluid flow. As a result of this fluid flow along fractures, the host rock has been subjected to significant chemical alteration along with the subsequent formation of some new minerals at the expense of a few other pre–existing mineral phases. Mesoscopic observations followed by Optical microscopy in the core samples of the basement rocks upto 1.5 km depth retrieved from the borehole KBH1 near Rasati (about 4.7 km from the Koyna Dam) have revealed the presence of chlorite and the precipitation of calcite, whereas the bulk mineralogical XRD has reaffirmed the presence of chlorite, calcite along with illite at a certain depth. This entire secondary mineral assemblage resembles the propylitic kind of hydrothermal alteration at temperatures < 350°C under acid–to–neutral solution conditions and also indicates water channelization up to the deeper level in the basement granitoids (>1.5 km). In addition, the presence of the hydrophilic clay minerals along fault and fracture zones may be responsible for triggering the seismicity in the Koyna Seismogenic Region as their absorption of water reduces the shear strength of faults and their low frictional strength accelerates the fault weakening process causing the generation of slip surfaces. Thus, in addition to several seismotectonic features, fault geometry and existing stress pattern, the clay mineralisation along the pre–existing faults and fractures of the basement rocks may also be a factor behind the recurring seismicity in this region.

Key–words—Fluid–rock interaction, Clay minerals, Propylitic alteration, Reservoir–Triggered–Seismicity (RTS), Borehole core.

INTRODUCTION

FLUID or any aqueous solution when comes into contact with the rock–forming primary mineral constituents may cause reactions involving elemental and/or isotopic exchange to achieve the thermodynamic equilibrium. Such fluid–rock interaction brings about weakness within the crystal lattice and produces relatively stable secondary minerals such as clay minerals, hydroxides and oxides. Chemical weathering is one of the dominant processes for the formation of these secondary minerals in igneous and metamorphic rocks. Besides, fluid percolation through fractures and faults is another key process in which secondary mineralization can occur even within the subsurface or buried rock bodies. So, the formation of secondary minerals due to interaction of the fluid with rock bodies can take place over a range of temperatures (0°C to ~800°C) and pressures (0.1 MPa to ~3 GPa) (Glassley *et al.*, 2016).

Subsurface secondary mineralization due to fluid–rock interaction has drawn much attention for the last few decades, especially in the case of geothermal energy, hydrothermal ore deposits, etc. Our current study, as a part of the MoES–sponsored project, has mainly dealt with mineralogical aspects of fluid–rock interaction as evidenced in the granitoid basement rocks up to 1500 m depth in the Koyna–Warna Seismogenic Region of western India. This region is an upland plateau that lies close to the crestline of the Western Ghat areas of the southwestern Deccan Volcanic Province (DVP). This region was considered the stable intracontinental region till 1967. In 1962, Shivajisagar Reservoir behind the Koyna Dam was impounded in the region, and on 11th December, 1967, the area experienced a massive earthquake that took almost 200 lives. But without considering such consequences, another Reservoir Warna was impounded there as a result of which the seismicity increases in terms of number and magnitude. More than ~1,00,000 earthquakes have been recorded in the area during the last five decades (Gupta, 2002). The annual loading and unloading cycles of the artificial water reservoirs (Koyna and Warna) influence reservoir–triggered seismicity (RTS) in the area (Gupta *et al*., 2016). The seismicity in the region is confined to a 600 Km^2 area which extends to a depth of ~10 km, located to the south of the Koyna Dam. Ministry of Earth Sciences (MoES), Government of India, has initiated a scientific deep drilling program followed by the establishment of a deep borehole observatory to study critical parameters in the proximity of earthquakes regularly occurring in this tectonically stable region. The current article has accounted for the preliminary findings that came out from the meso– and micro–scopic observations followed by the bulk mineralogical as well as elemental analysis carried out in the core samples of the pre–Deccan basement rocks of this area upto 1.5 km depth, retrieved during the Scientific Deep Drilling Program.

GEOLOGICAL SETTING AND SAMPLING

The Precambrian basement rocks in the study area are composed mainly of granite, granite gneiss and migmatitic gneiss, overall granitoid in nature, which are overlain by

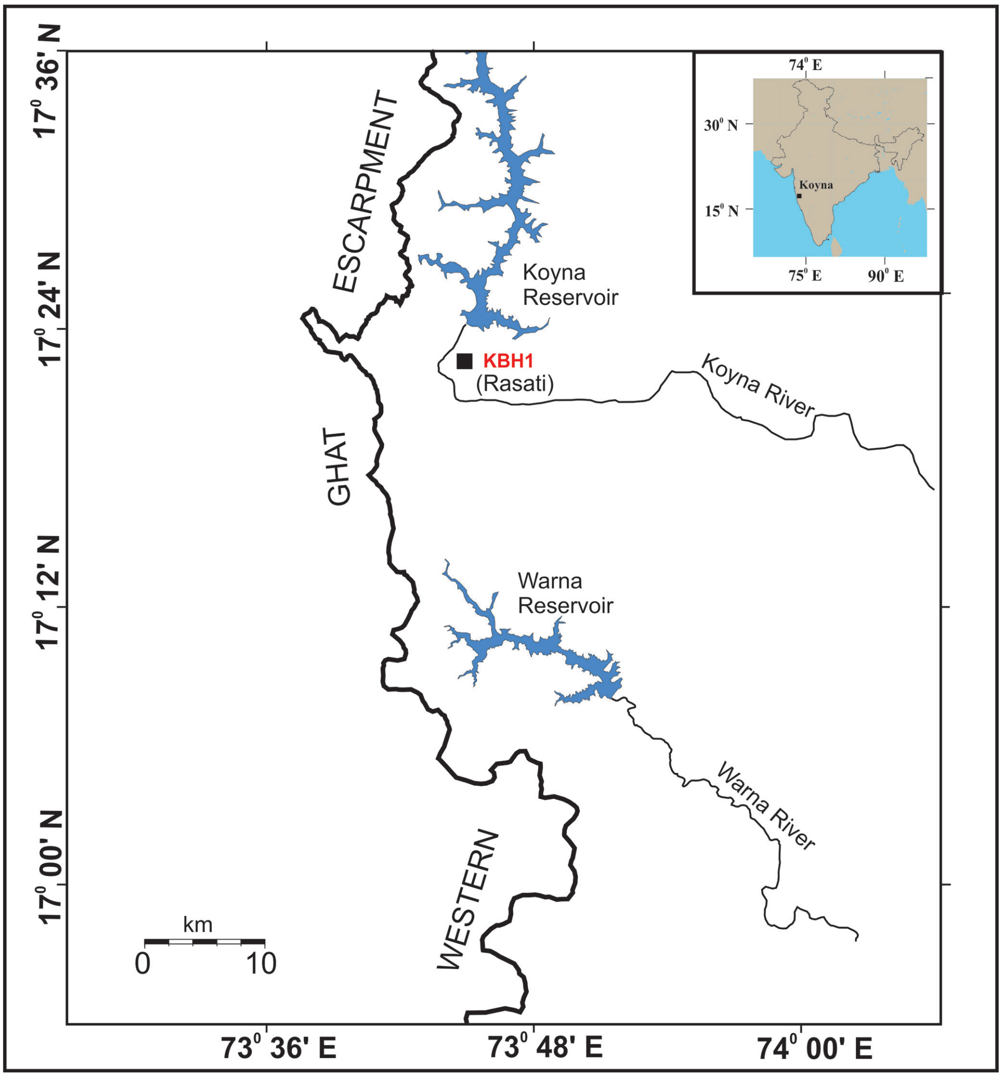


Fig. 1—Physiographic map of the Koyna–Warna Region showing the location of studied borehole KBH1 in the vicinity of the seismogenic zone. Inset shows the location of Koyna on the outline map of India.

several layers of basaltic lava flows of the Deccan traps with massive as well as vesicular and/or amygdaloidal characters (Misra *et al*., 2017a; Shukla *et al*., 2022). The vesicular basalt containing columnar joints along with a dense network of fractures and minor faults may act here as the medium for infiltration of reservoir water, and subsequently responsible for chemical alteration of primary minerals in the basement granitoids. The basement rocks containing quartz, feldspar, and hornblende as the major constituents, are peraluminous in nature and show the predominance of sodium over potassium, also they are lithologically heterogeneous and genetically related by fractional crystallization (Shukla *et al*., 2022).

Structurally, Koyna–Warna Seismogenic Region is bounded to the west by the Koyna River fault zone (along the N–S portion of the Koyna River) and to the east by NE–SW trending Patan fault (Talwani, 1997). A surface rupture zone comprising multiple numbers of en–echelon type fractures, near vertical fissures and oblique or diagonal tensional cracks is extended from 905 m hill near Kadoli Village (Misra *et al*., 2017b). These fissures have been interpreted as the surface expression of underlying active faults (Misra *et al*., 2017b).

In this study, the representative core samples have been collected from the KBH1 borehole at Rasati (17.377 N, 73.741 E; Fig. 1). The total drill depth of the KBH1 borehole is 1522 m of which 932 m is Deccan basalt and below this 590 m thick basement core of granitic composition is explored. The entire borehole cores are preserved at the newly constructed state–of–the–art core repository of MoES–BGRL in the Karad region of the Maharashtra State of India.

METHODS AND INFERENCES

The meso– and micro–scopic studies have been carried out on the core samples of the basement section of the KBH1 borehole. Fractures filled up with secondary minerals have been found at a depth of 1168 m, whereas at the depths of 1153.78 m and 1286.04 m (Fig. 3a), prominent zones of alteration have been identified which show incipient carbonate formation/ calcification (Figs 2, 3b and 3c). The optical microscopic investigation has also confirmed the neoformation of secondary minerals like chlorite at various depths, especially along the fractures and fault slip surfaces (Fig. 3d). Besides these, the extremely friable nature of the granitoids at several depths, e.g. 936.76 m, 1073.75 m, 1145.61 m, 1201.3 m, and 1308.61 m have also been inferred indicating long–term interaction of fluid entered into the subsurface and causes the generation of secondary minerals. Scanning Electron Microscopic (SEM) analyses (model: JEOL JSM 7610f) have been performed on six representative core samples collected from altered zones of the basement rocks, using the laboratory facilities at Birbal Sahni Institute of Palaeosciences, Lucknow. Secondary electron (SE) images are showing evidence of chemical alteration and precipitation of phyllosilicates along with weathered and hydrothermally altered surface morphology defined by the chemical transformation of mineral assemblages and a few elements, such as Ca, Mg, Al behaviour was also observed. In order to roughly estimate the elemental characteristics of the altered samples, Energy Dispersive Spectroscopic (EDS) analysis has also been carried out in three modes (i.e. point, line and area). Two prominent intensity peaks (~50k) of Ca with 10.12 wt. % has been noticed (Fig. 4) during EDS analysis at two spots, which reveals incipient carbonate formation/calcification in the form of calcite ($CaCO_3$) occurring in the altered zone of the basement at 1153.78 m depth (Fig. 5). Bulk mineralogical X–ray diffraction (XRD) analyses (model: X'PERT^3 powder; PANalytical) have been carried out on a few selected samples for the characterisation of mineral phases of those altered samples. Secondary minerals like clinochlore and calcite along with albite have been found at around 1073 m depth (Fig. 6) whereas illite has been characterized at 1145 m depth (Fig. 7).

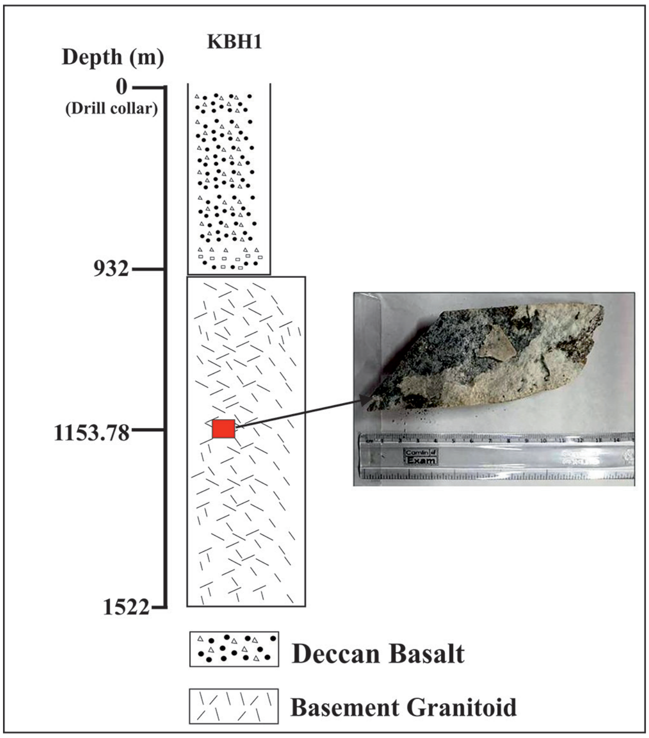


Fig. 2—Generalised litholog of the area with the hand specimen (sample ID–KBH1_381) showing incipient carbonate formation/ calcification in the altered zone of basement at 1153.78 m depth.

DISCUSSION

Fluid–rock interaction at shallow subsurface depth brings significant changes in mineralogy in certain geological setups. So, the neoformed clay minerals may be the key to identifying the alteration zones as well as the characterization of alteration facies (e.g. Argillic, Phyllic, Propylitic, etc.). It also helps in

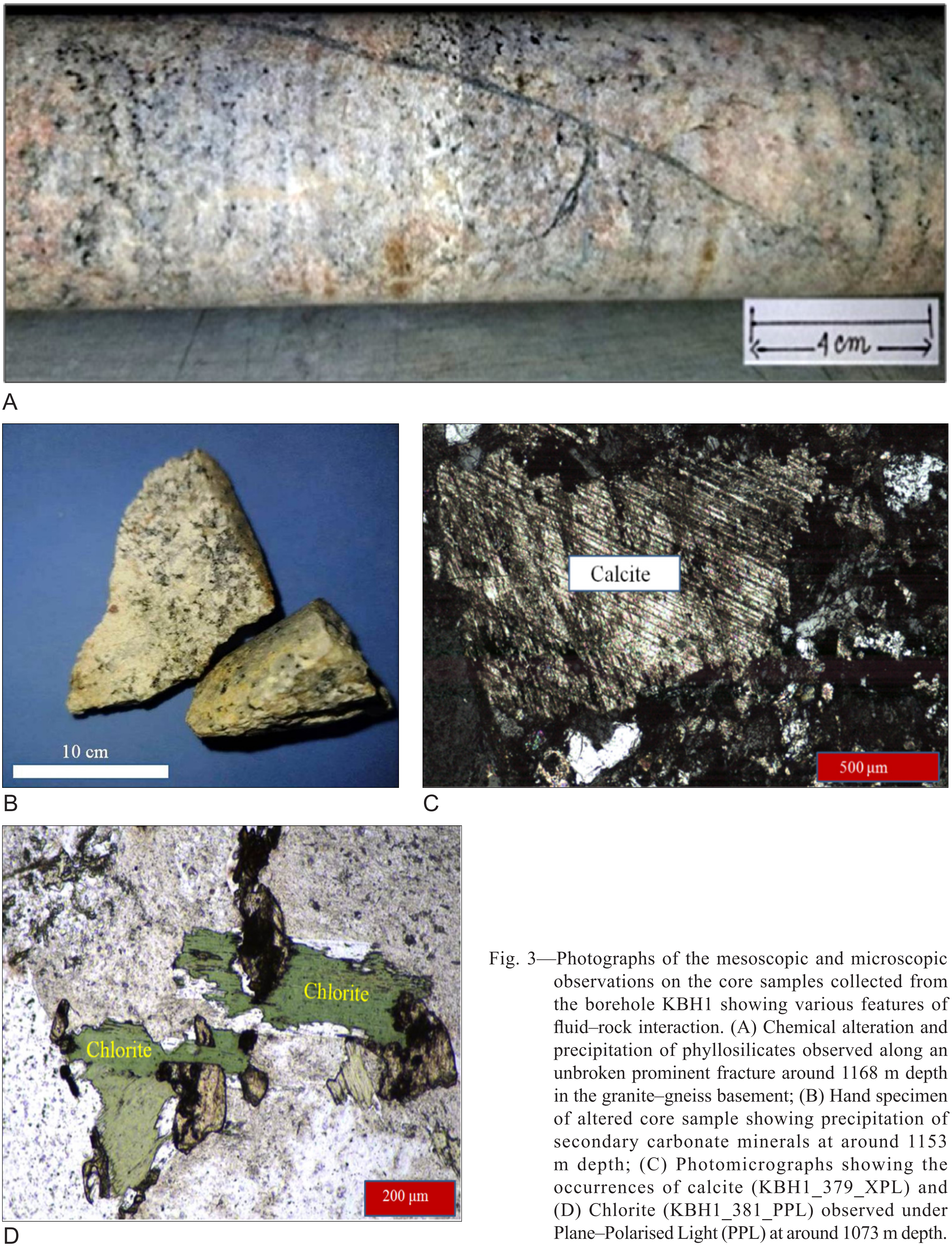
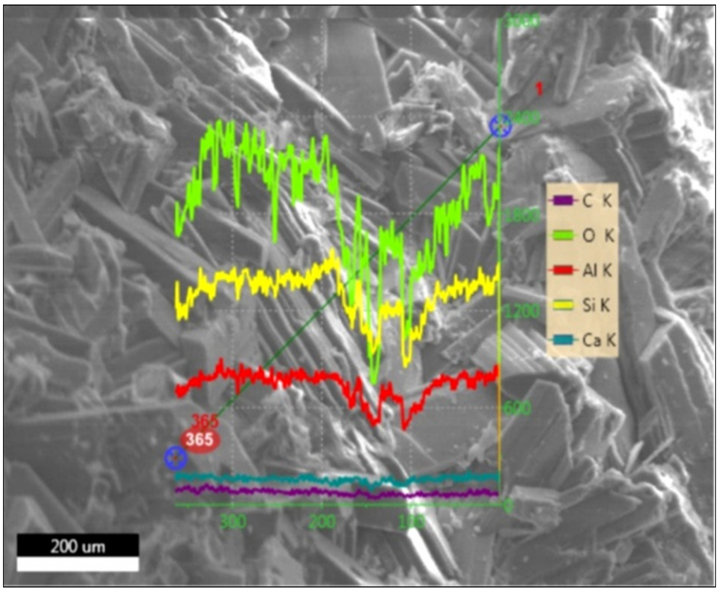


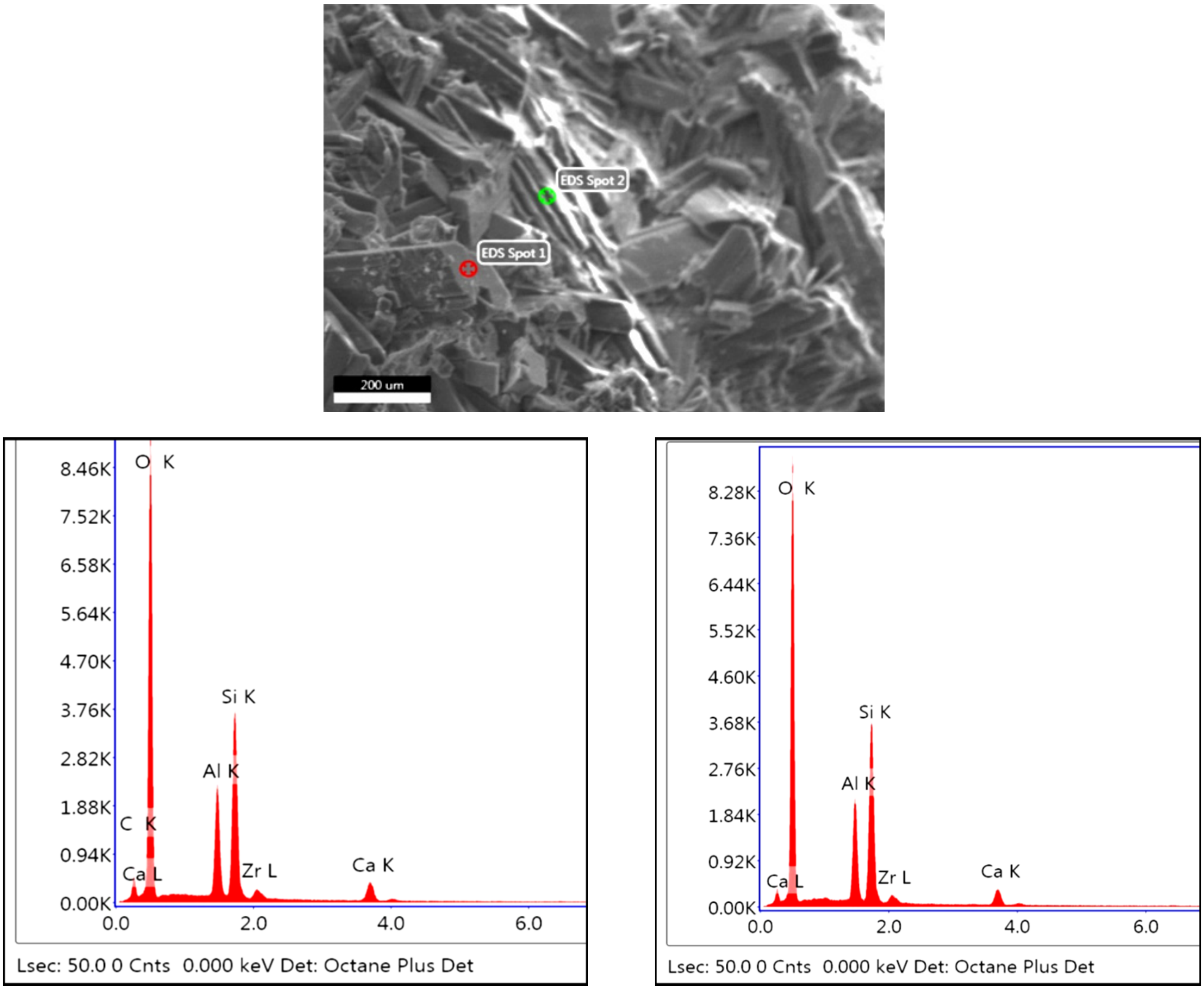
Fig. 3—Photographs of the mesoscopic and microscopic observations on the core samples collected from the borehole KBH1 showing various features of fluid–rock interaction. (A) Chemical alteration and precipitation of phyllosilicates observed along an unbroken prominent fracture around 1168 m depth in the granite–gneiss basement; (B) Hand specimen of altered core sample showing precipitation of secondary carbonate minerals at around 1153 m depth; (C) Photomicrographs showing the occurrences of calcite (KBH1_379_XPL) and (D) Chlorite (KBH1_381_PPL) observed under Plane–Polarised Light (PPL) at around 1073 m depth.



Element	Weight (%)	Atomic (%)	Error (%)	Net Int.
C K	10.35	15.70	12.08	47.19
O K	56.66	64.53	8.99	730.28
Mg K	1.39	1.04	10.63	60.68
Al K	6.91	4.67	5.69	377.35
Si K	14.58	9.46	4.57	863.76
Ca K	10.12	4.60	2.66	407.37

Fig. 4—Elemental variation obtained through Energy Dispersive Spectroscopy (EDS) in the core sample (sample ID–KBH1_383) collected from 1286 m depth of borehole KBH1, image showing elemental variation in line analysis mode with corresponding table of elemental concentration.

estimating the physicochemical conditions responsible for such alteration such as–fluid temperature and pH conditions (Cathelineau & Nieva, 1985; Vidal *et al*., 2001 and references therein). The presence of chlorite, illite and calcite in the altered zones represent propylitic facies of hydrothermal alteration and also indicate fluid temperature ranging between 220°C to 350°C with a pH of 5.5 to 7 (Fulignati, 2020; Vidal *et al*., 2001). The occurrence of chlorite in such altered zones may be due to the replacement of biotite present in the granitoid basement, whereas illite may be the alteration product of K–feldspar and plagioclase. Although the source of the fluid can't be intimated at this preliminary stage of the investigation, still meteoric water can be one source of this fluid, as this region receives very high rainfall during the monsoonal period. The mean annual rainfall of the Koyna catchment is in the order of 4951.77 mm, out of which 40% occurs in July, 30% in August and a total of 97% during the June to October segment (Nanadargi & Muley, 2012). Hence, it can be assumed that the rainwater, which is also stored in these two reservoirs, may infiltrate through the highly vesicular and porous basaltic rocks occupying at the top and then percolate through the interconnected fracture networks as well as the permeable faults and joints in the Pre–Deccan granitoids basement rocks underlying the basaltic rocks (Fig. 8). As the Deccan traps, below the section comprising of pipe vesicles, consists of compact massive basalts with low permeability, so the presence of joints and deep–seated faults and fractures are predominantly responsible for fluid transport to the basement rocks. However, in the case of such meteoric water percolation, the source of heat either may be radiogenic or the heat generated due to fault friction or a combination of both. Another possible source of the fluid at the depth may be magmatic which occurred right from their formation and is responsible for the pre–existence of phyllosilicates. Nevertheless, the probability of magmatic fluid is relatively less, because alteration due to magmatic fluid should not be restricted only within the fractures which have been evidenced in our present study. Besides, the existence of hydrothermal fluid can't also be denied which may be confirmed only after further investigation. Thus, the major minerals of granitoid basement rocks, e.g. plagioclase, K–feldspar and biotite are highly reactive and after coming in contact with the warm/hot water they started to decompose and produced a new set of mineral assemblage. In addition to the fluid present along the faults and fractures, these neoformed hydrophilic secondary clay minerals may also evolve fluid pressure, which reduces the shear strength of faults triggering slip. Besides, their low frictional strength accelerates the fault–weakening process and causes the generation of slip surfaces (Ben van der Pluijm, 2011). In fact, such displacement along the fractures as a result of fluid–induced slippage has been prominently observed at a few places below 1100 m depths. Thus, the interplay between faulting, fluid migration, and the formation of clay minerals may influence artificial–water–reservoir–triggered recurring seismicity in this region (Halder *et al*., 2021). However, it is difficult to say (now) about the time of formation of these incipient secondary minerals or fluid–rock alterations and therefore in this regard, a further detailed study is required considering all the known and unknown facts. This study further corroborates that the fluid channelization effects up to



(a) EDS Spot 1

(b) EDS Spot 2

Fig. 5—Energy Dispersive Spectroscopy (EDS) data of an individual phyllosilicates obtained through point analysis at two different spots in the sample (sample no. KBH1_383) collected from 1286 m depth of borehole KBH1.

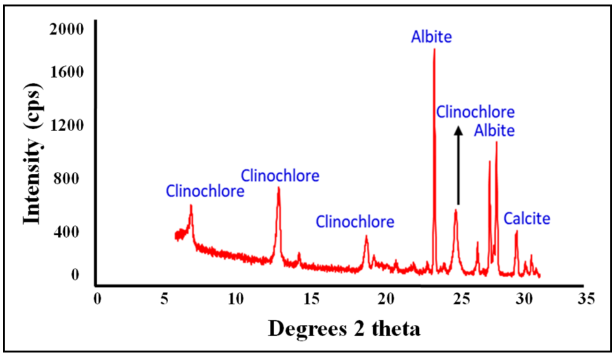


Fig. 6—Characterisation of mineral phases found in the altered samples at around 1073 m depth (Sample Id–KBH1_379)

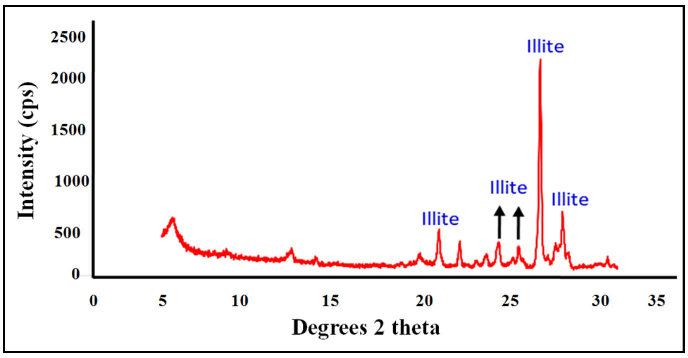


Fig. 7—Characterisation of mineral phases found in the altered samples at around 1145 m depth (Sample Id–KBH1_380)

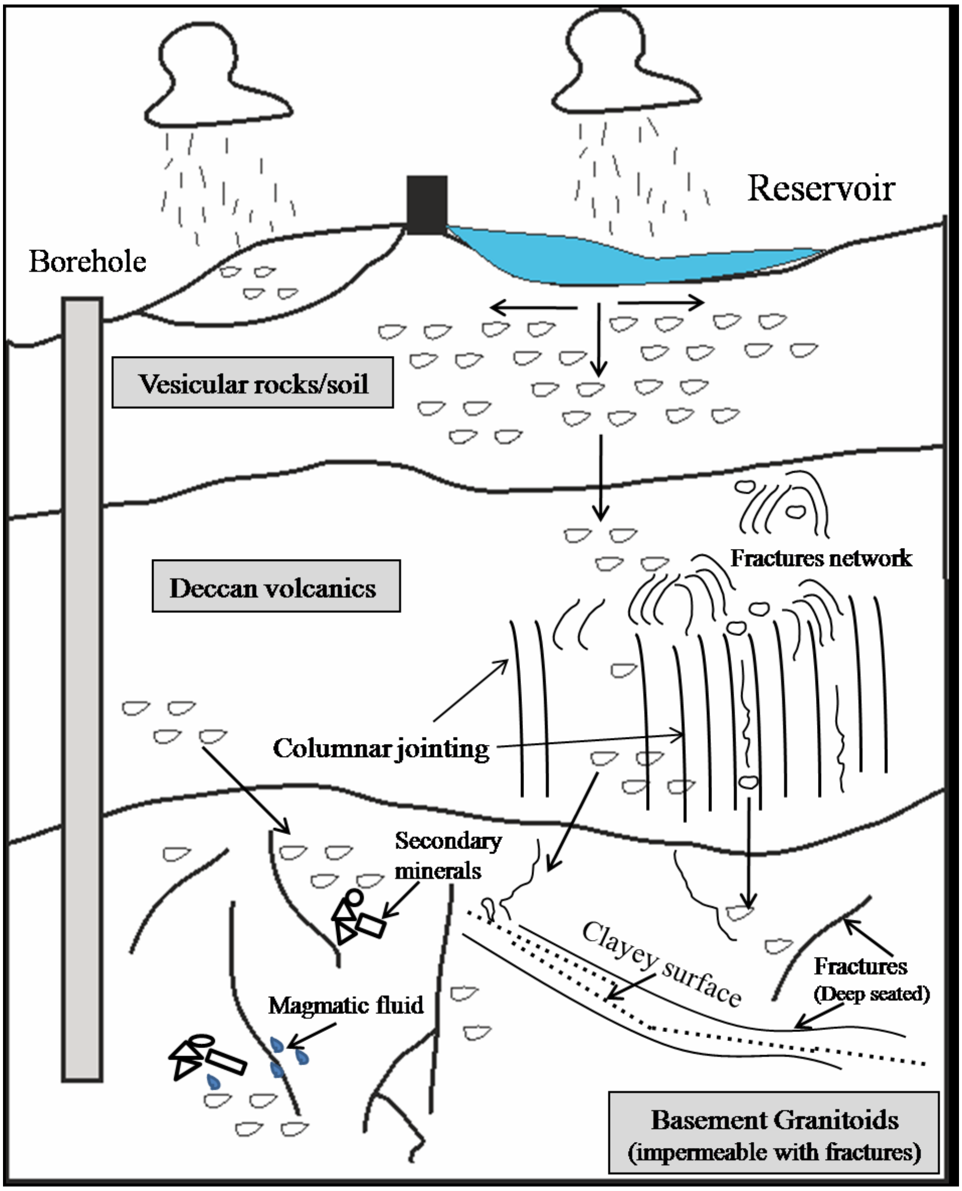


Fig. 8—Schematic diagram showing how meteoric water can be infiltrated and cause the secondary mineralization along the pre–existing fractures in the pre–Deccan basement rocks.

the deeper level in basement granitoids indicating the deep–seated nature of the fault zone in the area which may be a part of the Central Indian Tectonic Zone (CITZ).

CONCLUSION

Based on the preliminary mineralogical investigations, the present study concludes the following–

1. Fluid–rock alteration at shallow crustal level caused secondary mineralisation along the fractures and fault slip surfaces.
2. The pre–existing fractures in the basement rocks have probably acted as both ascend and descend paths for fluid/water propagation.
3. The alteration environment is favoured under acid–to–neutral solution conditions. The occurrence of calcite and clay minerals (e.g. chlorite and illite) is indicative of fluid–rock interaction under propylitic facies.
4. In addition to several seismotectonic features, fault geometry and existing stress pattern, the secondary mineralization along the existing faults and fractures may be responsible for the recurring pattern of the micro seismic activities in the region.

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