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Granite-gneiss Basement below Deccan Traps in the Koyna Region, Western India: Outcome from Scientific Drilling

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ABSTRACT

The Koyna region, located in the Deccan Flood Basalt Province of western peninsular India has been experiencing reservoir triggered seismicity since the impoundment of the Shivajisagar water reservoir in 1962. Scientific drilling carried out to 1522 m depth in the vicinity of the seismogenic zone exposed the granitic basement that lay below the Deccan Traps and provided a unique opportunity to study the rock types, petrological characteristics and microstructures. Cores obtained from drilling at four sites considered to be representative of the Koyna region, were studied. The boreholes include KBH-1 (Rasati) in the northern part, KBH-5 (Phansavle) in the western part, KBH-6 (Ukhalu) and KBH-7 (Panchgani) in the eastern part of the region. Each borehole penetrates the entire pile of Deccan basalt and pass through a few hundred metres of the granitic basement. The salient results are as follows: (i) The basement granitoids are dominantly composed of granite-gneiss, granite and migmatitic gneiss, typical of cratonic gneiss exposed in peninsular India. (ii) Petrology and microstructure study confirm the occurrence of strained quartz and unstrained plagioclase feldspars in the basement granitoids. (iii) Localized fault zones within the basement section, with prominent evidences of fault breccia, fault gouge, slicken lines with slickensides and pseudotachylite veins are observed in the individual boreholes. (iv) Anastomosing fracture network within these fault zones are good pathways for water channelization, which is supported by the higher abundances of ferruginous and siliceous secondary precipitations following the fractures.

INTRODUCTION

The Koyna region located in the Deccan Traps of western India is characterized by shallow and persistent reservoir triggered seismicity during the past five decades since the impoundment of the Shivajisagar reservoir (Gupta, 1992, 2002, 2011; Gupta et al., 2015, 2016). A notable feature is that the entire seismic activity is restricted within a relatively small volume, covering an area of ~20km x 30km and extending to a depth of ~10km, located to the south of the Koyna Dam. A map showing the locations of the Koyna and Warna reservoirs vis-à-vis the seismicity in the region is shown in Fig. 1. The pile of Deccan flood basalt comprises a few tens of lava flows that erupted as a result of India's passage over the Reunion hot spot about 65 my ago (Duncan and Pyle, 1988). The thickness of the Deccan basaltic pile in the region was estimated from seismic and other geophysical studies to be in a wide range, from a few hundred metres to more than 2 km (Kailasam et al, 1976; Kaila et al., 1981). Direct information about the thickness of Deccan Traps and the rocks comprising the underlying basement was not available due to lack of deep drilling in the region.

Scientific drilling carried out during the last few years in the region provided the first direct information about the thickness of the Deccan flood basalt pile and the nature of the underlying basement rock (Roy et al., 2013; Gupta et al., 2016). A set of nine cored boreholes, KBH-1 through KBH-9 was drilled to depths ranging from 906m to 1522m. The boreholes are located in the vicinity of the Koyna seismogenic zone, as shown in Fig. 1. Individual boreholes penetrated the entire thickness of Deccan basalt (range 412-1250 m) and passed through a few hundred meters of the underlying granitic basement. Also, it has been established that the basaltic pile is directly underlain by granitic basement rock, without intervening sediments. Misra et al. (2017) mapped the surface fissure zone around the Koyna region and demonstrated its continuation below the Deccan flood basalt pile as fractures and fissures. The information obtained from drilling has therefore established that the earthquakes occur below the Deccan basaltic pile. The cores of the granitic basement, exposed for the first time, provide unique opportunities to study potential brittle deformation in the area as a result of the past and ongoing seismic activity.

In this paper, we report for the first time, detailed lithologs of the basement granitoids in the Koyna region from studies on cores obtained from four representative boreholes, KBH-1 (Rasati), KBH-5 (Phansavle), KBH-6 (Ukhalu) and KBH-7 (Panchgani) that were drilled up to depths of 1522.5 m, 906.5 m, 1503 m and 1500.7 m in the northern, western and eastern parts of the seismogenic zone respectively. Further, we study the petrographic and textural features, mineralogy and microstructures to describe the major rock types, the deformation features and the scale of those events. We conclude that a number of brittle deformation features are likely to be related with recent earthquake activities in the study region.

ROCK TYPES

Core samples from boreholes KBH-1 (Rasati), KBH-5 (Phansavle), KBH-6 (Ukhalu) and KBH-7 (Panchgani) provide a representative sampling of the granitic basement rock underlying the Deccan flood basalt in the Koyna region. The boreholes are vertically oriented and pass through the entire Deccan flood basalt pile. In all boreholes, the transition from Deccan basalt to granitic basement rock occurs over a relatively short span of 2m in borehole KBH-1, 45cm in KBH-5, 11m in KBH-6 and 90cm in KBH-7. In these sections, rocks appear to be intermixed with both basaltic and granitic composition. Coarse grained granitic and basaltic clasts are embedded within a fine grained dark matrix (Fig. 2a,b,c,d). In most cases, the transitional sections are highly compacted. Clasts of quartzofeldspathic aggregates are embedded except in KBH-7 where basalt clasts are observed. Clast sizes vary from 1mm to 5cm in length. They are enriched mostly with pink K-feldspar. These transitional sections are not associated with any mesoscopic deformation signatures like foliations or fractures. The depths to the base of Deccan flood basalt pile in each borehole are shown in Table 1; depths are measured with respect to the borehole collar.

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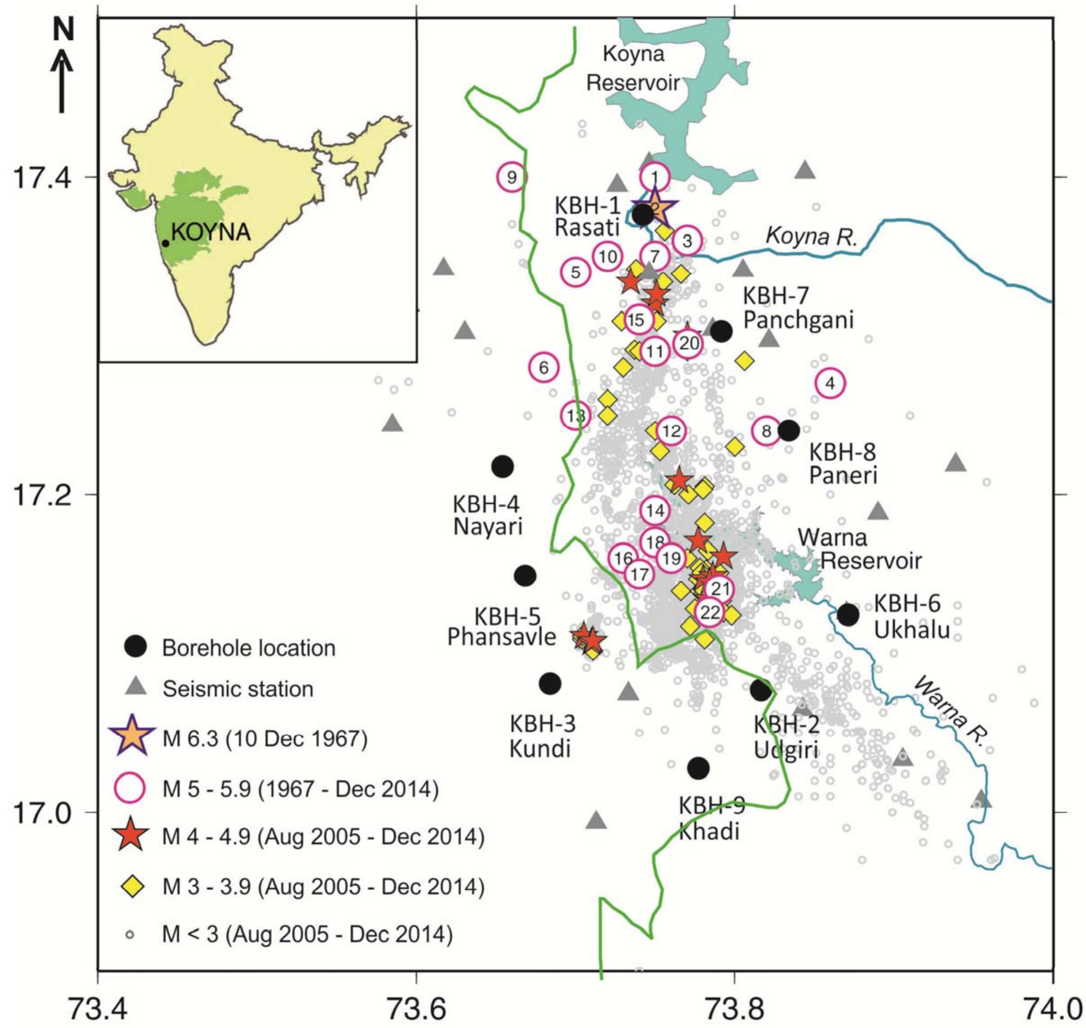

Fig.1. Map of Koyna-Warna region showing the distribution of cored boreholes located in the vicinity of the seismogenic zone (modified after Gupta et al. (2015)). Inset shows the location of Koyna in the Deccan Traps province (shaded green) on the outline map of India.

Basement rocks underlying the Deccan flood basalt pile are composed of granite, granite-gneiss and migmatitic gneiss with local occurrences of amphibolites in different boreholes. Lithologs have been prepared for individual boreholes, which show the variations in rock type within them (Fig. 3). The dominant rock types in each borehole core are summarized below.

KBH-1

The basement section from 932.5-1522.5m depth is dominantly composed of granite-gneiss (~60%), migmatitic gneiss (~25%), granite (~10%), amphibolite and other mafics (~5%). The litholog is shown in Fig. 3. Granite-gneiss generally occurs as segregated alternate bandings of felsic and mafic rich minerals. Thicknesses of these bandings do not exceed 3 cm in most sections. Igneous and metamorphic textures are well preserved following this gneissosity. Bands contain granular minerals with interlocking arrangement. The segregated bandings show well defined penetrative planar boundary throughout the entire granite-gneiss section. On the other hand, migmatitic gneisses are the mixture of both igneous and metamorphic rocks. In this rock, leucosomes are observed within melanosomes. Thicknesses of melanosomes vary up to 30 cm at places. Partial melting behaviour is observed at locales following the contact between the leucosomes and melanosomes. Light coloured leucosomes are dominantly composed of felsic minerals and observed as veins in most sections. The leucosomes are generally formed by the partial mixture of generated liquid during metamorphism and separated as veins within

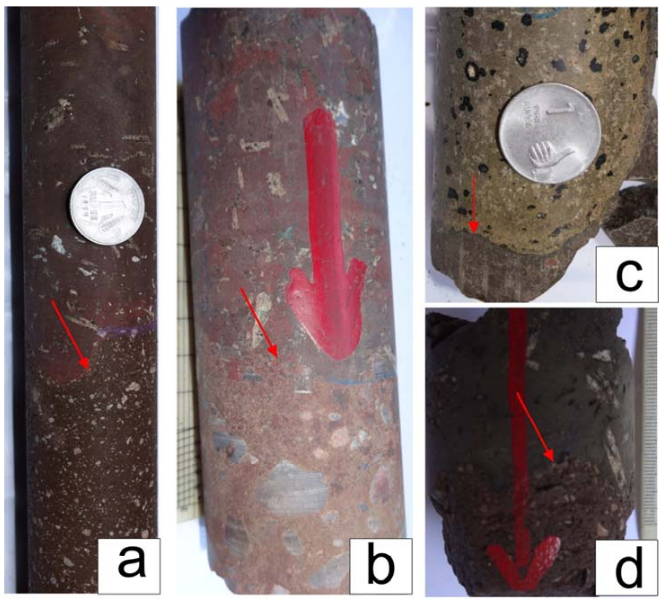

Fig.2. Core samples representing the contact of Deccan basalt and granitic basement rock (red arrows) in different boreholes **(a)** KBH-1, at 932.50m depth **(b)** KBH-5, at 499.70m depth. Large clasts of basalt and basement rock are seen below this contact. **(c)** KBH-6, at 775.04m depth. **(d)** KBH-7, at 1251.23m depth. Phenocrysts of plagioclase laths are seen within the overlying basalt.

Table 1. List of boreholes of the present study along with locations,total depths and thickness of Deccan Trap

Borehole designation	Location	Total depth w.r.t. borehole collar, m	Latitude, Longitude	Elevation of borehole collar (w.r.t. msl), m	Depth to base of Deccan basalt (w.r.t. borehole collar elevation), m
KBH-1	Rasati	1522.5	17°22'38.5" N, 73°44'27.8" E	580 m	932.50
KBH-5	Phansavle	906.5	17°09'1.2" N, 73°40'2.6" E	131 m	499.25
KBH-6	Ukhalu	1503.0	17°07'33.1" N, 73°52'08.8" E	570 m	775.04
KBH-7	Panchgani	1500.7	17°18'07" N, 73°47'28.2" E	960 m	1251.23

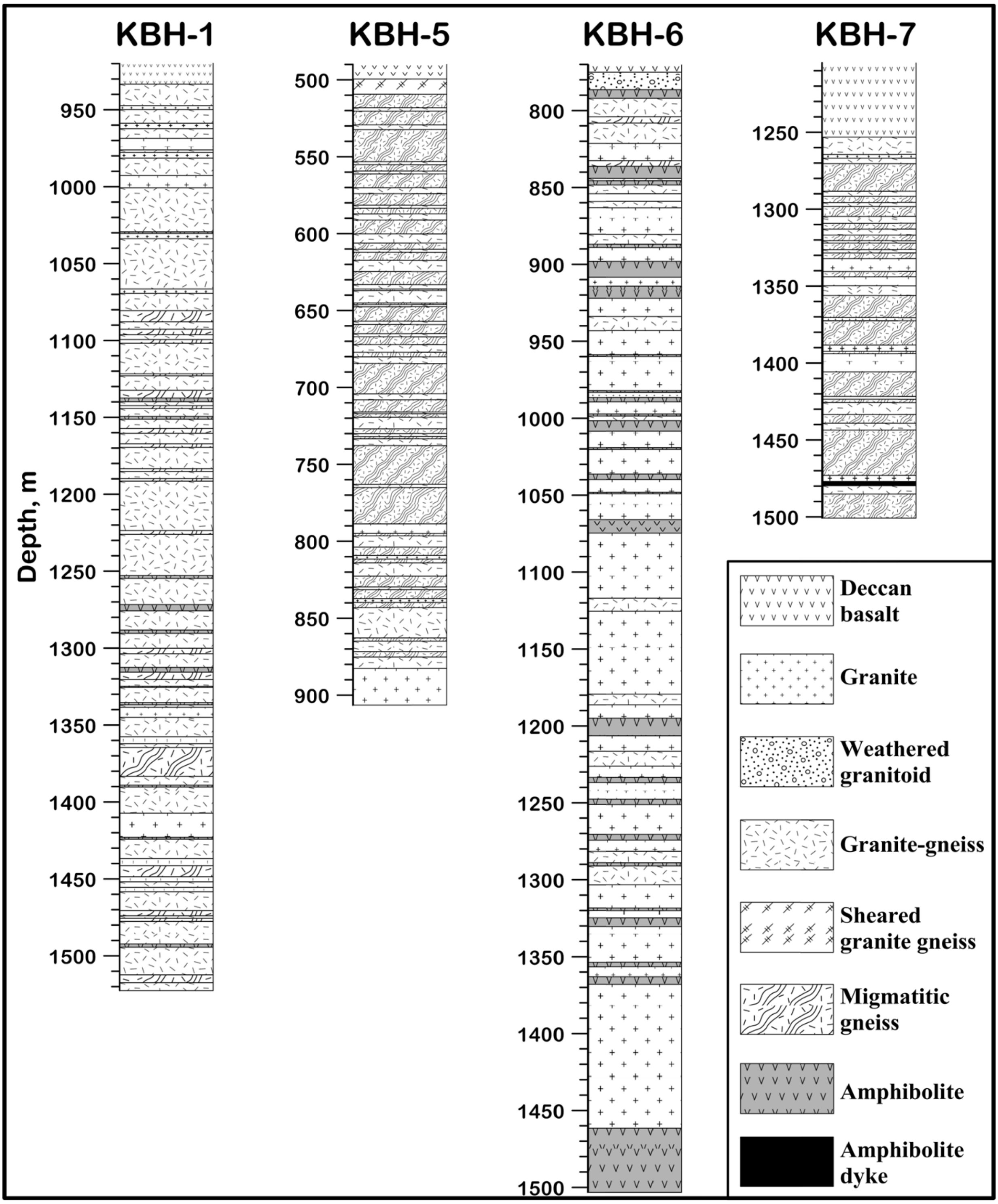

Fig.3. Detailed lithologs of granitic basement sections met with in four representative boreholes KBH-1, KBH-5, KBH-6 and KBH-7 in the Koyna region. The dominant rock types constituting the basement are granite, granite-gneiss and migmatitic gneiss. The proportions of these constituents vary between the different borehole sites.

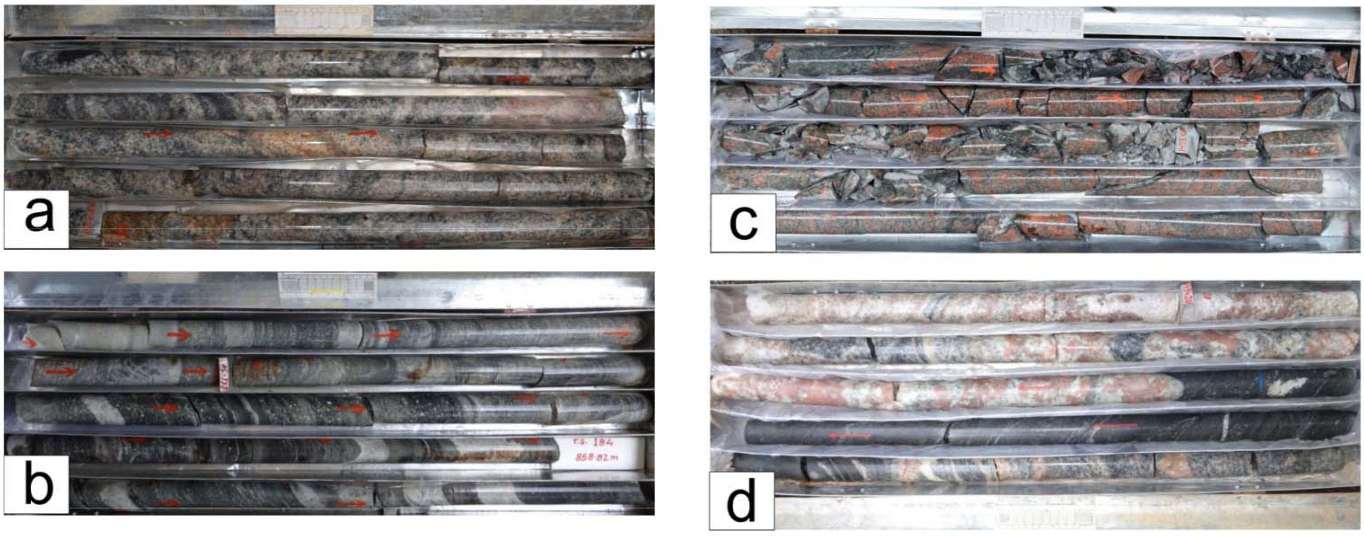

Fig.4. Core samples of representative rock types comprising the granitic basement below the Deccan Trap cover in the four boreholes of the present study. **(a)** Cylindrical cores from borehole KBH-1 showing the major rock type granite-gneiss. **(b)** Cylindrical cores from the borehole KBH-5 representing major rock types sheared migmatitic gneiss and granite-gneiss. **(c)** Cylindrical cores from borehole KBH-6 representing major rock types granite and granite-gneiss. Core samples are highly shattered and fractured. **(d)** Cylindrical cores from borehole KBH-7 representing major rock types granite and migmatitic gneiss.

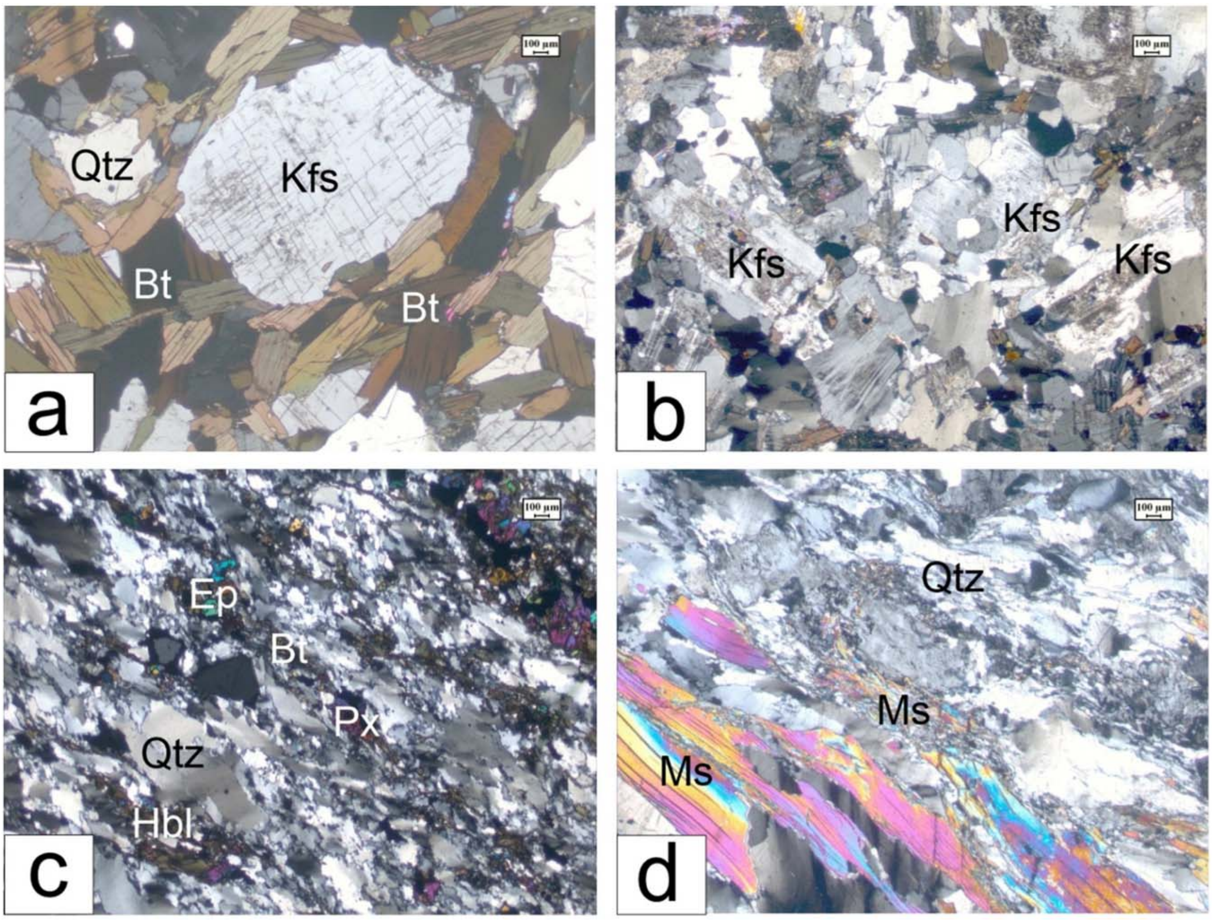

Fig.5. Photomicrographs of basement granitoids from Koyna region showing major mineralogy, textures and deformations. **(a)** Photomicrograph of granite-gneiss from KBH-5, showing biotite-defined gneissosity and mosaic texture within minerals. Here, biotites (Bt) are wrapped around the large crystal of K-feldspar (Kfs) that indicates metamorphic texture. **(b)** Photomicrograph of pink granite from KBH-7 showing phenocrysts of K-feldspars with interlocking arrangement indicating igneous texture. **(c)** Photomicrograph of sheared granite-gneiss in KBH-5 representing highly strained and dynamically recrystalized quartz grains. Biotite (Bt), Hornblende (Hbl) and Pyroxene (Px) retain the gneissosity. **(d)** Photomicrograph of recrystallized muscovite (Ms) and dynamically recrystallized quartz (Qtz) grains indicating deformation under greenschist facies condition in KBH-5 basement granitoids.

the host melanosomes. Metamorphic textures are strongly developed within melanosomes. Additionally, all rock types exhibit localized sheared fabrics with average angle of 54° with respect to the vertical borehole axis(Fig. 4a).

KBH-5

The basement section from 499.25-906.5m depth is dominantly composed of migmatitic gneiss including amphibolite (~65%), granite-gneiss (~25%), and granite (~10%). The litholog is shown in Fig. 3. Metamorphic textures are well preserved within this granite-gneiss (Fig. 5a). Intense shearing of rock throughout the section provides evidences of ductile deformation (Fig. 5c,d). Strongly developed sheared planar fabric has average angleof 56° with the borehole axis, which is consistent throughout the section. Occurrences of granitic schists and mylonites at places suggest the high strained zones of ductile deformation. Gneissosity is still preserved in low strain or strain hardening zones (Fig. 4b).

KBH-6

The basement section from 775.04-1503.0m depth is dominantly composed of granite (~55%), amphibolite and other mafics (~20%), granite gneiss (~15%), and migmatitic gneiss (~10%). The litholog is shown in Fig. 3. The cores are mostly shattered and fractured throughout the section (Fig. 4c). Shearing features overprinted on the gneissosity are frequently observed, although not so intense as in KBH-5. The intensity of shearing is higher than KBH-1 and KBH-7 cores. Well-developed, sheared planar fabrics have an average angle of 51° with the vertical borehole axis throughout this borehole section.

KBH-7

The basement section from 1251.23-1500.7m depth is dominantly composed of migmatitic gneiss (~60%), granite-gneiss (~20%) granite (~15%), and amphibolite (~5%). The litholog is shown in Fig.3. The entire section is intact; samples are mostly collected as cylindrical cores. Granites predominantly show igneous textures with interlocking arrangement within grains (Fig. 5b). Hornblende is dominantly present as metamorphic mineral within mafic domains of migmatitic gneisses and amphibolites. Evidences of very localized shearing are found with average angle of 56° with the borehole axis.

FAULT ZONES AND FRACTURES WITHIN BASEMENT ROCKS

In borehole KBH-1, fracture and fault zones are observed in the core at multiple depths in two distinct depth sections, 940-1075m and 1142-1238m. Two sets of fracture angles are commonly observed – one set with a range of 30°-40° and the other with a range 10º-20º measured with respect to the borehole axis. At a few places, 0°-10° angled fractures are also observed. In all cases, pre-existing features are overprinted by the later features. Interconnected fracture network is well developed, with secondary mineral precipitation along fractures

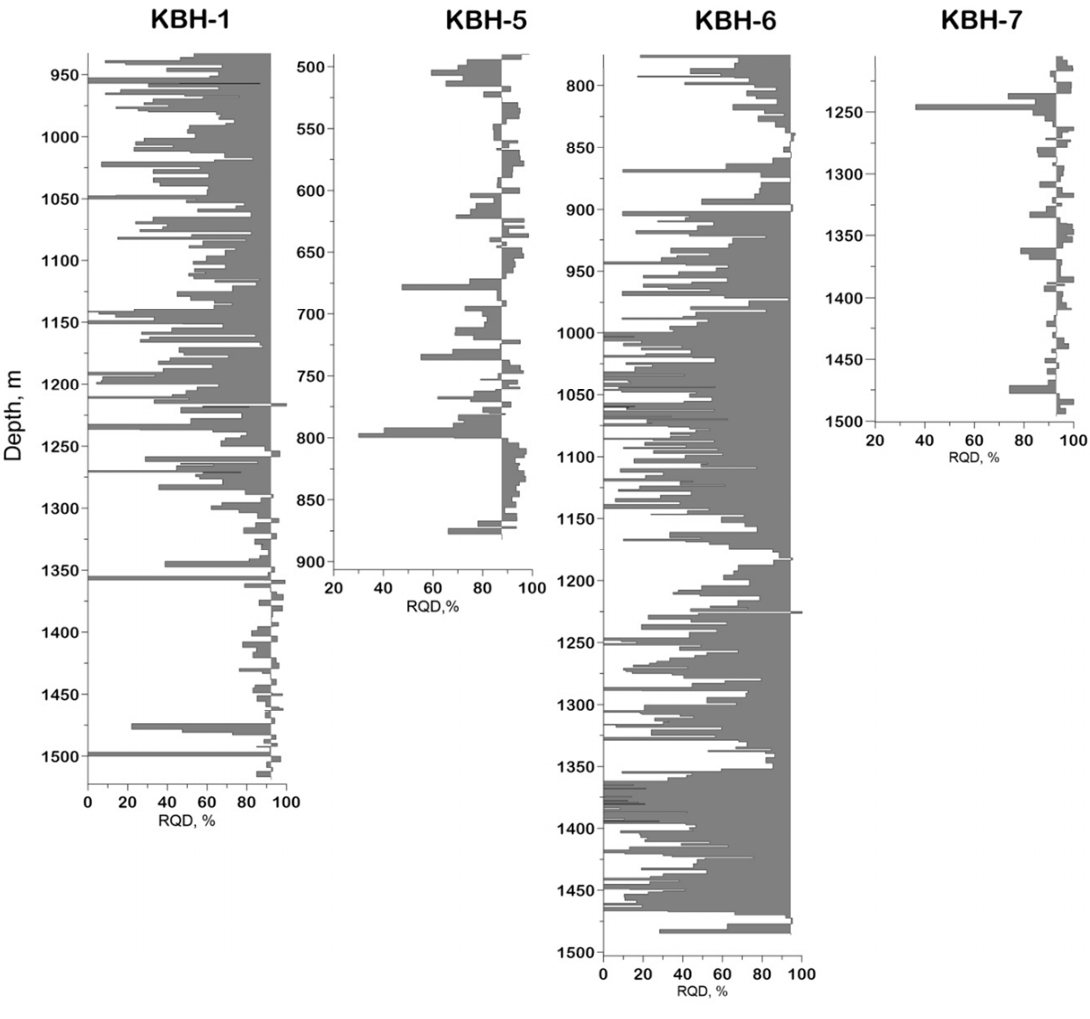

Fig.7. Plots of depth vs. RQD (%) in the four boreholes KBH-1, KBH-5, KBH-6 and KBH-7 of the present study. Fault and fracture zones within the basement sections are associated with low RQD values. The two boreholes KBH-1 and KBH-6 showing poor RQD over large sections are associated with higher frequency of fracture and fault zones relative to KBH-5 and KBH-7. The fault and fracture zones in the latter are restricted to localized sections.

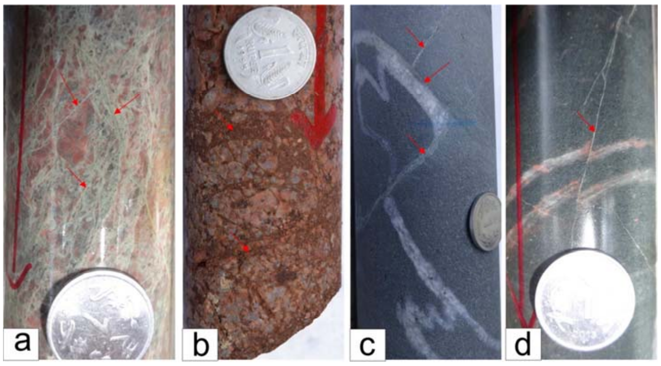

Fig.6. Cylindrical core samples from different boreholes representing deformation signatures in the basement rocks. **(a)** Anastomosing fracture network with fillings of secondary precipitations (red arrow). **(b)** Reddish ferruginous precipitations along fractures are seen following fractures (red arrow). **(c)** Localized fractures and faults (red arrows) following the pre-existing planar fabrics. Also seen are evidences of repeated faulting in basement rocks. **(d)** A near-vertical fracture displacing the gneissosity within basement granite-gneiss.

(Fig. 6a). Secondary mineralization, silicification, cementation and reddish brown iron staining are commonly found along these fractures (Fig. 6b); A few isolated fractured zones are observed between 1286m and 1480m depth.

Presence of faults and fractured zones in KBH-1 are also indicated by the low Rock Quality Designation (RQD) values plotted in Fig. 7. Rock Quality Designation (RQD) represents the percentage of intact core pieces that are ≥10cm in length (Deere, 1963) and provides a good measure of the overall quality of the recovered core. The depth vs. RQD plots for the basement sections in individual boreholes are shown in Fig. 7. In borehole KBH-1, RQD of cores in the range 0-50% correspond to the zones of fracturing and faulting.

In borehole KBH-5, three fractured zones are readily identified, 500-630m, 682-804m and 850-906.55m depth. These zones show up as RQD range 30-70% in Fig. 7. The brittle fractures predominantly follow the general trends of pre-existing shear planes. Mesoscopic studies on cores suggest an average angle of 56° with respect to the borehole axis for the pre-existing shear planes (Fig. 6c). The general orientation of fractures is identical to that of shear planes. But at places fractures have near-vertical orientation that displaces all pre-existing fabrics (Fig. 6d).

In KBH-6, granitoids are highly shattered and fractured throughout the borehole section when compared to those in the other boreholes. Here, rocks from 904.42-973.75m, 981.85-1148.60m, 1248.34-1307.40m, and 1358.78-1472.45m depth sections are highly fractured and shattered. The RQD range 0-50% represents the possible zones of intensive fracturing in this borehole (Fig. 7). The zones of intense shattering correlate well with the zones of concentration of natural fractures. Fracture angle with respect to the borehole axis are dominantly oriented with near-vertical dip throughout the entire basement section.

In KBH-7, the basement granitoids are found to be relatively less fractured compared with the cores of KBH-1, KBH-5 and KBH-6. Fractured zones are localized, e.g., at 1253.43-1289.91m, 1331.67-1370.95m, and 1478.15-1491.80m depth. The RQD range 30-80%

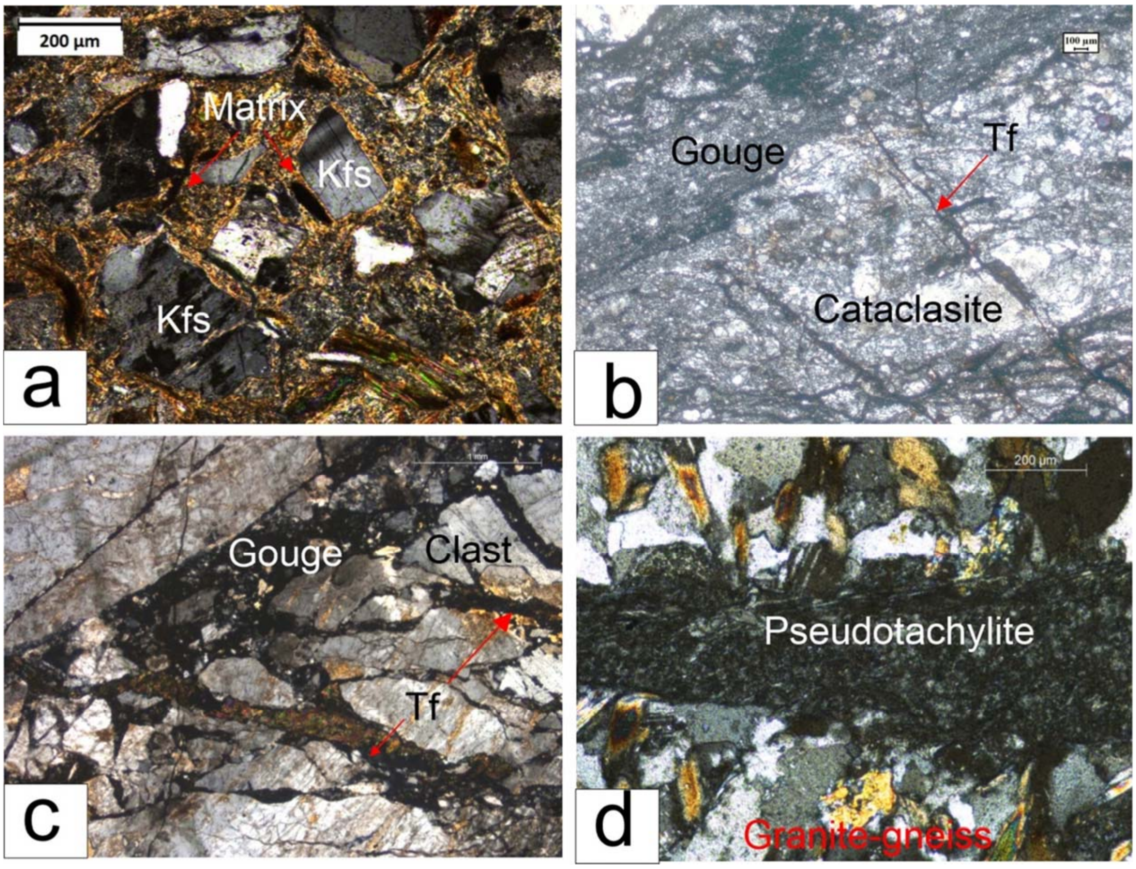

Fig.8. Photomicrographs of basement granitoids from Koyna region showing evidences of brittle deformations. (a) Fault breccia occurring in KBH-5, showing angular clasts of quartz and feldspars entrapped within fine siliceous and ferruginous matrix. The matrix is secondary in origin. (b) Photomicrograph representing cataclasite that is transected by a narrow band of fault gouge. Finally, all features are transected by transgranular fractures (Tf). These fractures are filled with black-coloured ferruginous precipitations. (c) Narrow zone of fault breccia within basement granite shows transgranular fractures (Tf) and clasts of quartzofeldspathic minerals. Fractures are filled with gouge material and dark coloured ferruginous precipitations.

represents highly localized fault and fracture zones in this borehole (Fig. 7). Associated fracture angles show a wide range from 0° to 90° at different depth levels. At a depth of 1476.70m, the borehole intersected a mafic dyke that has been metamorphosed to an amphibolite. The contact between amphibolite and granite-gneiss is near vertical (~7°). Along this contact, rock is highly fractured and mostly filled with mafic injections from the dyke body.

PETROLOGY AND MICROSTRUCTURES

The great majority of basement granitoids beneath the Koyna region are mainly composed of quartz + feldspars as felsic, and pyroxene + biotite + hornblende as mafic constituents. Interlocking arrangement within these minerals indicate igneous origin of granite(Fig. 5b). Higher percentage of K-feldspars is observed as pink-granite within KBH-1 and KBH-6 cores (Fig. 4d &5b). Segregation bandings of quartzo-feldspathic minerals alternating with mafic layers are the typical features of granite-gneiss within the basement sections (Fig. 5a). At places, epidotes are seen following this gneissosity (Fig. 5c). Layers of paleosome and leucosome are commonly observed within migmatitic gneiss. Granite-gneiss and migmatitic gneiss are strongly defined by biotite + hornblende defined metamorphic fabric that developed under amphibolite facies condition. Overprinting and transposition of this fabric by later chlorite + recrystalized muscovite defined fabric suggest deformation under greenschist facies conditions (Fig. 5d). Presence of highly strained and recrystalized quartz grains following this later fabric indicates high shearing strain during this later greenschistfacies deformation (Fig. 5c, d).

The most significant deformation within the basement granitoids is related with brittle fractures and faulting. Most of the core samples bear signatures of granular flow of brecciated and pulverized clasts, fault gouge, cataclasite, pseudotachylite, slickenlines and slickensides. Under microscope, fault breccia are seen as angular fragmented clasts embedded within fine siliceous and ferruginous matrix (Fig. 8a). Repeated brittle deformation within basement rock is inferred from the evidences of overprinting and transposition of earlier features by later events (Fig. 8b). The brittle deformation signatures are mainly concentrated within the localized fault zones in each borehole (8c). At places, pseudotachylite veins are seen along tensile fractures within this basement granitoids (8d). These brittle deformation signatures within the basement granitoids are possibly related with the recurrent seismicity in the Koyna region.

CONCLUSIONS

1 Scientific drilling up to depth of 1522m in the Koyna seismogenic zone reveals the nature of basement rock beneath varying thickness of Deccan flood basalt. The basement rock is typically cratonic gneiss, comprising granite and granite-gneiss inter-layered with varying proportions of migmatitic gneiss, which is likely an extension of the Peninsular Gneissic Complex of the Dharwar craton.

2 The granitoids show segregation bandings of felsic and mafic minerals, which are reoriented and transposed by sheared fabrics. These evidences of ductile deformation are over-printed by brittle deformation represented by fractures and fault rocks. Local occurrences of pseudotachylite veins provide direct evidence of seismic energy release along fault zones.

3 Other deformation features are present as fault breccia and cataclasites in zones of intense brittle deformations, granular flow of brecciated and pulverized clasts, fault gouge, slickenlines on slickensides, clast-cortex aggregates and crystal plastic deformations of quartz grains.

4 Fractures within the fault zones are filled with secondary precipitation, which are frequently ferruginous, but also comprise carbonaceous, siliceous and clay minerals. Occurrences of epidotes and sericitized feldspars along the fractures constitute direct evidence of hydrous alteration. These observations provide strong support for water channelization through the fractures in granitoid rocks at depth.

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