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Fissures and Fractures in the Koyna Seismogenic Zone, Western India

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ABSTRACT

The 1967 M6.3 earthquake near the Koyna dam produced a surface rupture zone following a NNE-SSW structural trend. The rupture zone is documented in a report by the officers of the Geological Survey of India (GSI, 1968). The surface expressions of the rupture comprising fissures, en-echelon fractures, oblique or diagonal tensional cracks and mole tracks, termed here as the Koyna Fissure Zone (KFZ), were reported over a limited area, about 1000m in length and 200 m in width, located to the southeast of the Koyna dam between Donichawadi and Kadoli. The Koyna region was revisited recently for investigating the fissures, to help in locating potential sites for scientific deep drilling. Most of the reported surface deformation features are obliterated due to intense weathering and laterization of the exposed basalt surface during the past 48 years. However, careful field investigations in the Donichawadi-Kadoli area as well as in the surrounding region show that fissures and fractures are still preserved at several locations. The fissures trend between N30°W to N50°E, similar to that reported previously. The mean orientation of these fissures is 25°/89°-E. Transposition of one set of fissures by another set provide strong evidence for repeated brittle deformation in the area. Physical and microstructural studies on core samples of granite-gneiss basement rock underlying Deccan basalt in the area, obtained from a 1522 m deep borehole at Rasati, confirm the extension of the surface fissures to depth. Occurrences of secondary mineralization along these fissures indicate the percolation of water through fractures within basement granitoids. The evidences for water channelization may have direct implications for the occurrence of reservoir triggered earthquakes in the Koyna region for the past five decades.

INTRODUCTION

On December 10, 1967, a M~6.3 earthquake occurred around the Koyna region located in western Maharashtra, India. The epicentre of the earthquake was located around Rasati village near the Koyna dam. In the wake of the earthquake, a field survey was conducted around the Koyna region by the Geological Survey of India to document possible direct effects of earthquake and their areal extent. A surface rupture zone comprising en-echelon fractures, near vertical fissures, oblique or diagonal tensional cracks, mole tracks, soil lumps and laterite boulders within paddy field areas was delineated and documented in a detailed report by officers of the Geological Survey of India (GSI, 1968). The location of the surface rupture zone vis-à-vis the Koyna dam is shown in Fig. 1. This zone showing the fissures and other deformations is referred as the Koyna Fissure Zone (KFZ) in this paper. The KFZ extended from 905m hill near Kadoli village in the south to Nanel village in the north via Donichawadi village. The majority of these fissures and fractures were found to be oriented within the range N10°W–N25°E, and restricted to a ~1000m long and ~200 m wide area (Fig. 2). Several tensional cracks were seen with trends in the range N10°W–N40°W. The individual fissures were 10 – 40 m in length and a few cm to 40 cm in width within the KFZ. Evidences for dextral rotational movement on near vertical shear planes, landslides along the foothills, ground deformation and changes in groundwater level in and around the KFZ were also reported.

Soil-gas helium surveys carried out by CSIR-NGRI during the mid-1990s across the fissure zone mapped earlier near Kadoli village provided clinching evidence that the KFZ indeed represents the surface rupture zone of the 1967 earthquake (Gupta et al., 1999). High helium concentrations in the range 1-7 ppm coinciding with the surface fissures, relative to regional background value of 0.2 ppm at distance of 40-60 m on either side of the fissure zone, confirmed that the fissures constituted the surface expression of a NNE-SSW oriented seismically active fault and that the fault zone had not healed even 30 years after the 1967 earthquake.

Core drilling in the fissure zone was undertaken to intersect the fault and ascertain the dip of the fault plane in the sub-surface (Gupta et al., 1999). On the basis of the helium anomaly and reported surface evidences, two boreholes were drilled along a traverse perpendicular to the NNE-SSW trending fissure zone near Kadoli. Both the holes were inclined at 43° towards ESE direction. A highly shattered and brecciated zone was intersected between 47.6m and 51.8m along the length of the first hole and between 25.5m and 45.65m along the second hole. A 60° dip towards WNW for the fault was obtained by connecting the points of first intersection of the breccia zone in the two boreholes and its extrapolation to the surface fissure. Therefore, this study resolved a long-standing debate about the direction of dip of this fault.

The Koyna region has experienced persistent reservoir-triggered earthquakes since the impoundment of the Shivaji Sagar lake in 1962 (Gupta and Rastogi, 1976; Gupta and Combs, 1969; Gupta 1992, 2002, 2011; Gupta et al., 1969, 2015). The 1967 M6.3 Koyna earthquake is the largest so far. The seismicity includes 22 earthquakes of $M \geq 5$, over 200 earthquakes of $M \geq 4$ and several hundred smaller earthquakes. As a consequence, superimposition, overprinting and transposition of previous evidences are expected along the KFZ. Another finding is the absence of earthquakes within the top 1 km but repeated activity between about 2 km and 10 km depth (Gupta et al., 2015). Scientific drilling undertaken recently in the region shows that the Deccan basalt pile at Rasati is 932.5 m thick and is underlain directly by granitic basement rock (Roy et al., 2013). The study, therefore, indicates that the focal depths of earthquakes are located in the granitic basement rock in this region. Consequently, the cores recovered from drilling provide an unique opportunity to study the sub-surface rocks and evidences of seismic activities, if any, below the basalt cover.

In the present study, an attempt has been made to (i) study the evidences of the surface deformation features in the Koyna seismogenic zone, including those associated with the 1967 Koyna

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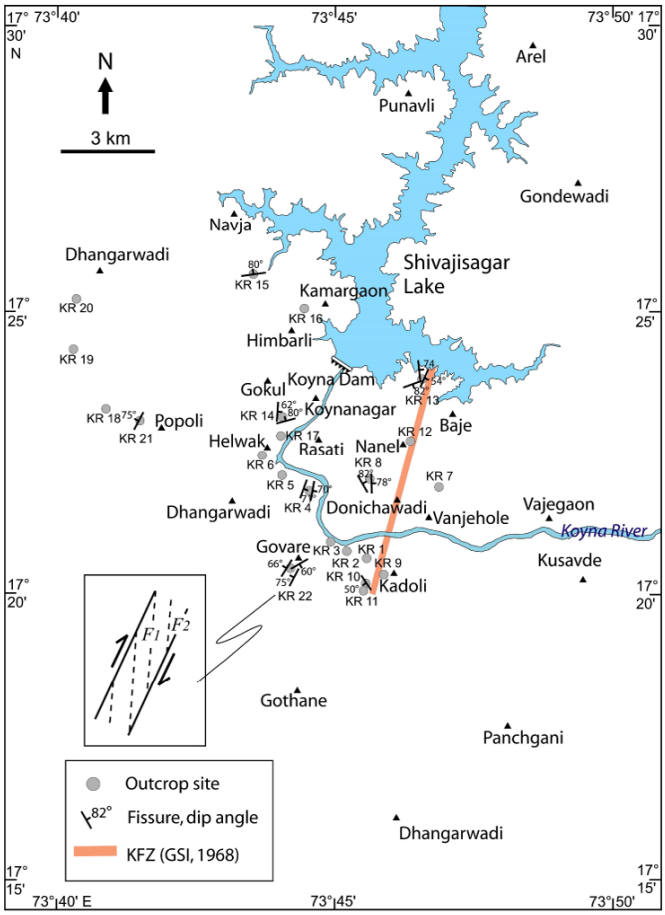

Fig. 1. Location map of Koyna region showing the field locations and structural data of the present study. The shaded linear feature to the south of the Shivajisagar lake represents the surface rupture zone reported in GSI (1968). Inset: Schematic diagram showing the transposition of first set of fissures (F_1) by second set of fissures (F_2) at location KR22. The field photograph is shown in Fig. 3c.

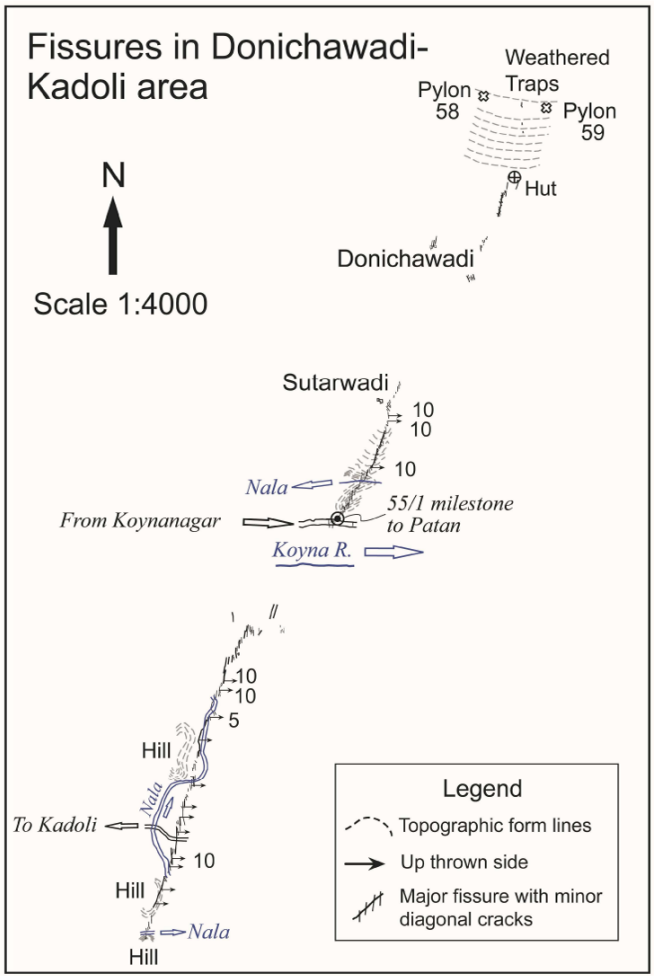

Fig. 2. Surface fissures in the Donichawadi-Kadoli section mapped by Geological Survey of India in the wake of the 1967 Koyna earthquake (redrawn from GSI, 1968). The fissures mapped in the three sections (Donichawadi, Sutarwadi and Kadoli) delineate a NNE-SSW trend of the Koyna Fissure Zone (KFZ).

earthquake, by field mapping, (ii) investigate the extension of the fissure zone in the granitic basement below the Deccan Trap cover through examination of available drill cores for the first time in the region, and (iii) explore signatures for repeated activation of the KFZ.

INVESTIGATIONS OF SURFACE FISSURES

Field investigations were undertaken in and around the Koyna region to study the surficial evidences of fissures / fractures formed due to the 1967 M~6.3 Koyna earthquake. Detailed field mapping was carried out in three domains: (a) south of the Koyna river – Kadoli section, (b) east of the Koyna river – Donichawadi and Nanel sections, and (c) west of the Koyna river – Koynanagar to Chiplun section. Field studies in the domain (c), i.e., along the western embankment of the Koyna river and also further west towards Chiplun has not been reported earlier. The study covered 22 field locations, KR1 to KR22, distributed in the three domains (Fig. 1). A list of the field locations, descriptions of the outcrops and observations of deformation features, if present, is given in Table 1.

The exposures of massive Deccan basalt in the study area generally show well developed columnar joints (Fig. 3a). A few of these outcrops show fissures and fractures. These outcrops generally occur along a linear trend from Kadoli to Nanel. Most of the deformation features associated with the KFZ in the low lying areas along the Koyna river are covered by lateritic soil. Even the flat tops of the neighbouring hills are also covered with lateritic soil. In contrast, exposures along the hill slopes, available as road cuts from Donichawadi to Nanel provide tell-tale evidences of the fissure zone.

South of the Koyna River (Kadoli Section)

Field locations within this area are KR1, KR2, KR3, KR9, KR10, KR11 and KR22. Among these, KR10, KR11 and KR22 show prominent outcrops of massive basalt with deformation features such as fissures and fractures. Fissures at other locations, although documented by GSI (1968), are hidden under lateritic soil cover. Trenching carried out earlier in this section had suggested the presence of a fissure zone underlain by a 30cm - thick soil cover (Talwani and Kshirsagar, 1995). The outcrop at KR10, located south of the Kadoli village, shows massive basalt with well developed joints (Fig. 3a). A nearby outcrop at the location KR11 shows en-echelon shear fractures near the 905m hill peak with very localized sinistral shear (Fig. 3b). These shear fractures show a strike of 166° and vertical dip at most locales within the study area. Local evidences of repeated activation are also observed as disposition of dextral strike-slip duplex, for example at location KR22 near Govare village, to the south of the Koyna river (Fig. 3c). Here, one set of fractures / fissures have orientation of 24°/80°-W, which are dextrally displaced by another set of fissures with orientation of 32°/66°-W. This data indicates localized occurrences of repeated brittle deformation of massive basalt in the KFZ. The field location

Table 1. List of the field locations, descriptions of the outcrops and observations of deformation features (if present).

Location	Latitude and Longitude	Description
KR1	17°20'38.2"N73°45'34.1"E	NW of Kadoli village, near NGRI borehole station. Outcrops are of lateritized soil cover used for cultivations.
KR2	17°20'51.6"N73°44'43.7"E	Along the metalled road, south of the local nallah. Outcrops are laterites.
KR3	17°20'49.6"N73°44'27.3"E	Road cutting section towards Koyna and just western side of the right angle turning of the local nallah. Exposures of massive basalt and amygdaloidal basalt.
KR4	17°20'50.6"N73°44'26.3"E	Road cutting section and just north-western side of KR3. Exposures of massive basalt and amygdaloidal basalt with very localized exposures of fissures and fractures at variable orientations. Orientations are: 76°/72°–N transposed by 20°/71°–W (Fig.3h)
KR5	17°22'02.7"N73°44'06.5"E	Road cutting section at a right angle turning point of the metalled road runs towards Koyna. Outcrops of massive basalt with prominent joints. Exfoliated surfaces are available but no fractures or fissures were seen.
KR6	17°22'25.0"N73°43'39.5"E	Nallah section present just below the bridge connecting Koyna-Chiplun road. Rocks are predominantly massive basalt with well developed joints. No fractures or fissures were seen.
KR7	17°21¹55.1¹¹N73°46¹36.4"E	Donichawadi-Nanel unmetalled road cutting section and located along the southern slope of the hill peak. Rock is massive basalt with excellent columnar joints.
KR8	17°22'07.9"N73°46'11.7"E	Donichawadi-Nanel unmetalled road cutting section and located along the southern slope of the hill peak. Rock is basalt which is highly fractured and fissured (Fig.3d). Secondary precipitates observed along these openings (Fig.3i). Common orientations of planar fabrics are: 358°/78°–E, 164°/70°–E, 150°/82°–E, 152°/79°–E
KR9	17°20'19.1"N73°45'52.4"E	South of the Kadoli vllage, towards the 905 hill peak. Scattered exposures of massive basalt present, and most of the area is covered with laterite soil.
KR10	17°20'14.8"N73°45'33.0"E	Near the 905 hill peak, following a nallah section. Massive basalt with excellent columnar joints were observed (Fig.3a).
KR11	17°20'13.9"N73°45'33.2"E	Near the 905 hill peak, following the same nallah section. Massive and vesicular basalt present with very localized en-echelon shear fractures (Fig.3b). Orientation of this fracture set is 166°/90°
KR12	17°22'47.1"N73°46'08.9"E	Located near Nanel village; exposures are of laterite cover which are very intact and devoid of any fractures and fissures.
KR13	17°23'31.9"N73°46'22.0"E	Located NW of the Baje village and eastern embankment of the Koyna reservoir. Exposures are of massive basalt with prominent columnar joints. Localized fractures/fissures are seen with orientations of 24°/54°–E, 177°/74°–E, and 25°/70°–W (Fig.3e).
KR14	17°23'09.1"N73°44'03.9"E	A road cutting section just north of the Helwak bridge and western side of the Koyna river. The metalled road runs towards the Koynanagar. Here excellent exposures of massive basalt are present with prominent surficial fissures and fractures along the western side of the metalled road. Most of these fissures are filled up with secondary precipitates from channelized fluid. Orientations of these fissures are 4°/62°–E, 162°/70°–E, and 15°/80°–W (Fig.3f).
KR15	17°25'34.8"N73°43'41.6"E	Near Ozarde waterfall; exposures are of massive basalt showing a set of very localized fractures with orientation 82°/80°–N.
KR16	17°25'11.9"N73°44'36.7"E	Near Kamargaon village and western side of the metalled road; exposures are of massive basalt with excellent columnar joints, but no fissures/fractures are observed.
KR17	17°22'38.0"N73°43'59.3"E	Near the Helwak bridge and western side of the Koyna river; exposures are of vesicular basalt having brownish color on surfaces due to surfical weathering, but no fissures/fractures were seen.
KR18	17°23'18.9"N73°40'51.4"E	Exposures located along Koyna-Chiplun metalled road cutting section. Rocks are massive basalt with excellent columnar joints but no fractures or fissures were seen.
KR19	17°24'20.3"N73°40'16.5"E	Outcrop located along the right side of the metalled road after crossing the Kumbarli Ghat towards Chiplun. Along this section, most of the exposures show excellent columnar joints within the massive basalt. But no evidences of deformation fractures or fissures were seen.
KR20	17°25'14.0"N73°40'21.1"E	Located near the Sonovaprasanna temple on the Koyna-Chiplun metalled road. The exposures are of massive basalt with columnar joints, but no deformation features were seen.
KR21	17°23'00.1"N73°41'35.8"E	A nallah section located south of the Koyna-Chiplun road near the Popoli village. Exposures are of massive basalt with columnar joints, but very localized fissures are seen in a few centimeter thickness (Fig. 3g). Orientations of these fissures are 50°/80°–NW, 40°/80°–NW, 63°/84°–NW, and 28°/75°–W.
KR22	17°20'39.1"N73°44'21.8"E	The exposure is located within a narrow, E-W trending and very localized nallah near the Govare village. The rock type is basalt, which is highly fractured and fissured. One set of fractures has orientation 24°/80°–W which is transposed by later-developed fracture set having orientation of 32°/66°–W (Fig.3c).

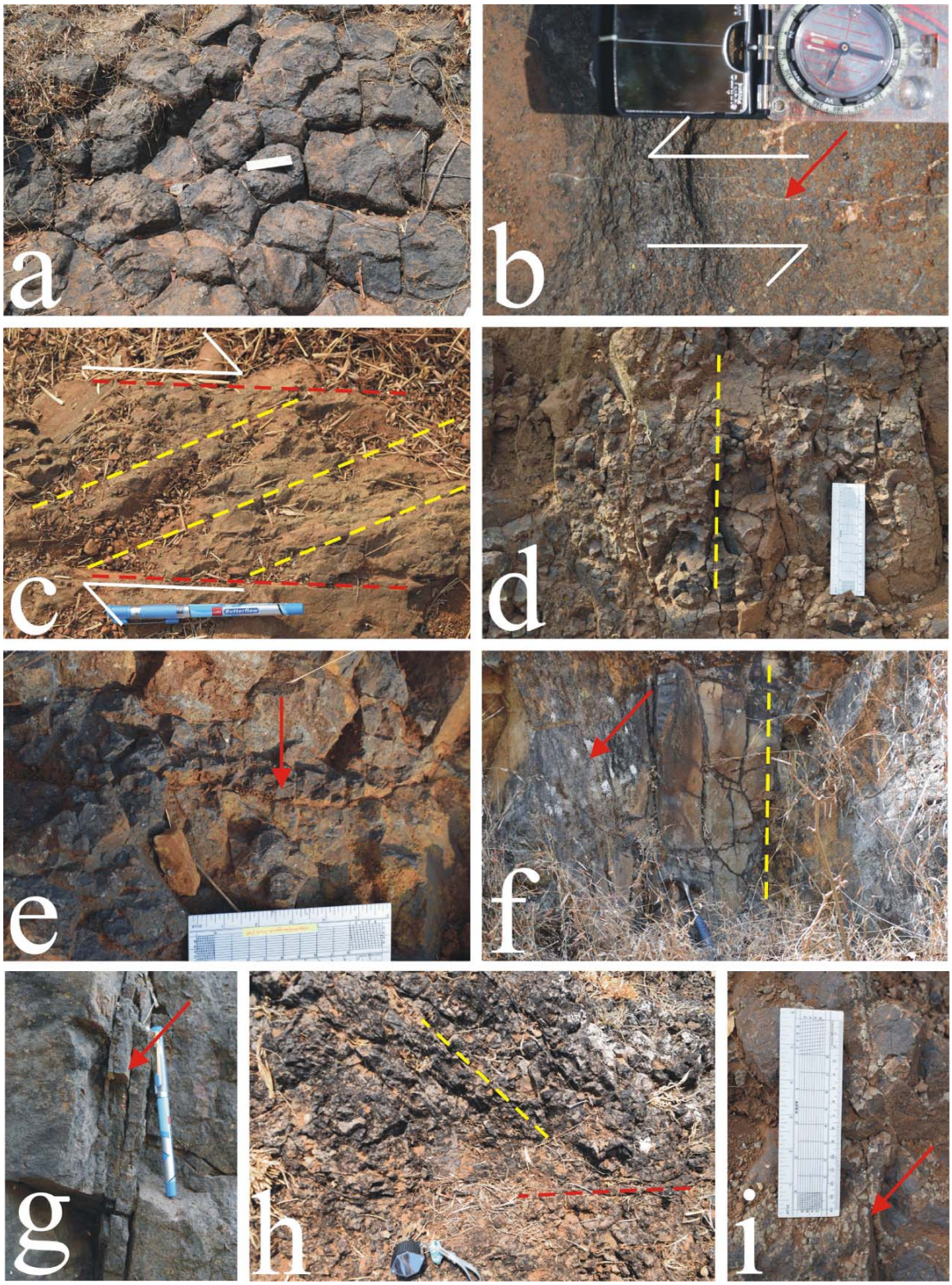

Fig.3. Field photographs documenting salient features of the Koyna Fissure Zone (KFZ). **(a)** Columnar joints in massive basalt at KR10. The outcrop is a horizontal surface. **(b)** En-echelon shear fractures (red arrow) at KR11 near 905m hill, south of Kadoli village. The compass is aligned along the strike of 166° on a vertical plane. Outcrop is a horizontal surface. **(c)** Dextral strike-slip duplex structure present in massive basalt at KR22 along a nallah section near Govare village. One set of fissures (24°/80°–W) (yellow dashed line) is transposed by another set (32°/66°–W) (red dashed line). This is a horizontal outcrop. **(d)** Vertical fissures and fractures (yellow dotted line) preserved in fragmented basalt at KR8. This is a vertical exposure facing towards south. **(e)** Brecciated basalt (red arrow) at KR13 caused by intense brittle deformation. This is a horizontal exposure **(f)** Near-vertical fissures (red arrow) at KR14, mostly filled up with secondary precipitation. The general orientation of these fissures is 162°/70°–E (yellow dotted line). This is a vertical exposure facing towards north. **(g)** Localised vertical fissures (red arrow) at KR21. The outcrop is vertical and facing towards north. **(h)** One set of fractures (yellow dashed line) is transposed by the another set of fractures (red dashed line) at KR4. This is an inclined surface facing towards south. **(i)** Secondary precipitation along a near-vertical fissure (red arrow) at KR8, north of Donichawadi village. The general orientation of these fissures is 164°/70°–E. It is vertical exposure facing towards south.

KR22 appears to be a part of the KFZ developed in the wake of the 1967 M~6.3 Koyna earthquake on the basis of structural data.

East of the Koyna River (Donichawadi and Nanel Sections)

Field locations within this area are KR7, KR8, KR12 and KR13. Here, outcrops KR7 and KR12 are massive basalt with laterite cover. At KR7, well developed columnar joints are exposed on a vertical cliff with no fissures or fractures. On the other hand, the outcrops KR8 and KR13 bear clear evidences of surface fissures and fractures with near vertical orientation. Most of these fissures and fractures are filled up with secondary minerals. KR-8, located along the southern part of the hill slope near the Donichawadi village, clearly shows fissures within massive basalt (Fig. 3d). The northern most location KR-13, near Nanel village, showing fractures and fissures within massive basalt marks the northernmost limit of KFZ within the study area (Fig. 3e).

West of the Koyna River (Koynanagar-Chiplun Section)

Field locations within this area are KR4, KR5, KR6, KR14, KR15, KR16, KR17, KR18, KR19, KR20 and KR21. Localised occurrences of fissures and fractures are observed in massive basalt outcrops at the locations KR4, KR14, KR15 and KR21. Among these locations, KR-14 and KR-21 show very localized exposures of surface fissures along the Koyna-Chiplun road, on the western side of the Koyna river (Fig. 3f, 3g). At KR-4, a set of fissures having orientation of 76°/72°-NW displaced by another set of fissures having orientation of 20°/71°-W are observed (Fig. 3h). The superimposition of fissures and fractures indicates a sequence of deformations following the regional trend of NNE-SSW in the study area. Most of the fissures and fractures in the Koyna area are filled with secondary minerals (Fig. 3i).

Structural data of fractures and fissures collected from three domains in the Koyna region are plotted with poles in an equal area stereographic projection (Fig. 4). The plot shows two clusters of distributions; one in SE direction and another in WNW direction of this projection. The mean principal orientation of this distribution is 25°/89°-E. This orientation is consistent with the orientation of the KFZ reported previously by GSI (1968). Unlike the KFZ where the maximum deformation is concentrated over a ~1000m long and ~200 m wide area, the fissures / fractures outside the KFZ are distributed over a large area, between Donichawadi (KR-8) in the east and Popoli (KR-21) in the west (Fig. 1).

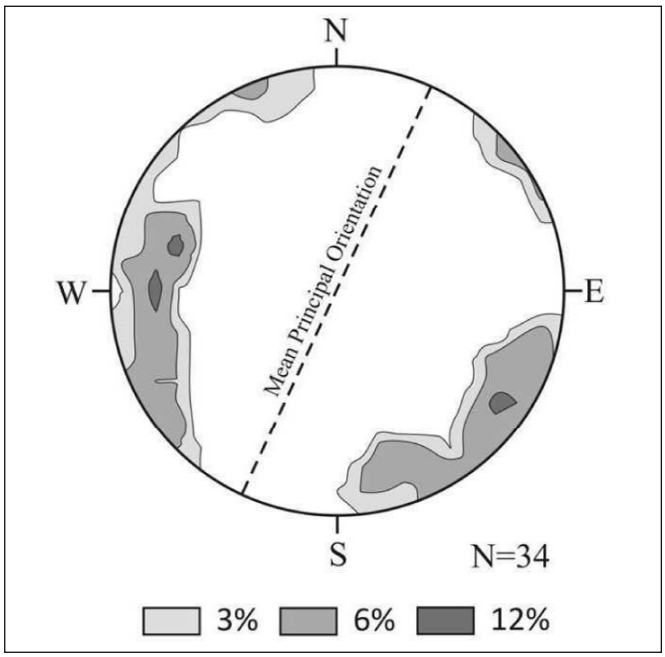

Fig.4. Equal area stereographic projection of the poles of all planar fabric data collected from the study area. Data are presented with contours of 3, 6 and 12% shaded area. The data show a variation in concentration from SE to WNW direction. Three clusters of 12% data fall within these directions.The mean principal orientation is 25°/89°-E, which is identical with the regional trend of the Koyna surface rupture zone documented in GSI (1968).

EVIDENCES OF FISSURES WITHIN BASEMENT GRANITOIDS

A major programme comprising scientific deep drilling investigations has been launched by the Ministry of Earth Sciences, Government of India to comprehend the genesis of reservoir triggered seismicity in the Koyna region. During a preparatory phase of the programme, scientific drilling was carried out during 2012-14 to constrain the sub-surface geology and structure. Core drilling has been carried out at 9 sites distributed in the Koyna-Warna region (Gupta et al., 2016). One of the boreholes, KBH-1, is located near Rasati village, just south of the Koyna dam and in close proximity to the Donichawadi fissure zone. The borehole KBH-1, drilled to a depth of 1522 m, passed through 932.5 m of Deccan basalt and 589.5 m of granite-gneiss basement rock directly underlying the basalt column (Roy et al., 2013) (Fig. 5a). At different depths within this borehole, basement granitoids clearly show prominent fractures and fissures. Figure 5b shows the occurrence of such fractures and fissures at a depth of 1039.00m. Most of these fractures and fissures are oriented at angles in the range 75°-85° measured with respect to the borehole axis. Most of these fractures and fissures are filled with siliceous and calcareous materials. Ferruginous precipitates are also observed at places along these openings. These fractures and fissures are closely associated with localized fault zones within this rock column. Displacement ranging from a few mm to a few cm occur along these fault planes. The photomicrograph shown in Fig. 5c provides a clear evidence for transgranular fractures associated with a localized fault zone at a depth of 1505.07m. The deformation features shown in Fig. 3 are related with rupturing of rocks around the Koyna area.

DISCUSSION

The Koyna region is located on the Western Ghats, which experiences heavy monsoon rainfall during four months of every year. As a consequence, the rocks are subjected to intense weathering. Moreover, Deccan flood basalt, which is exposed throughout the region, is very susceptible to chemical weathering due to the presence of mafic minerals such as olivine, pyroxene and opaques (Colman, 1982). The fractures and fissures in the basalt pile provide generous pathways for water channelization, which further enhances chemical weathering. Therefore, the great majority of exposures of basalt in the KFZ near Donichawadi are highly weathered and covered by lateritic soil, which obiliterates the fissures and fractures that were formed in the wake of the 1967 Koyna earthquake. Nevertheless, one can still find a few exposures where such features are preserved. Through careful field investigations carried out in the western, eastern and southern parts of the Koyna dam, evidences of fissures / fractures associated with the earthquake could be observed and mapped at 11 locations in the region. Outside the KFZ, which marks the zone of maximum deformation, the fissures/fractures are observed as isolated occurrences following the NNE-SSW trend of the KFZ.

Fissures mostly occur as a stack of fine penetrative planar fabrics formed due to brittle deformation of rocks in a fault zone. The adjoining spaces between fabrics are either filled with air or secondary materials precipitated by groundwater. The exposures comprise dominantly of massive basalt, which are mostly devoid of any other deformational features except these fissures and fractures. Also, the study shows that weathering is predominant in the lower elevations relative to the hill

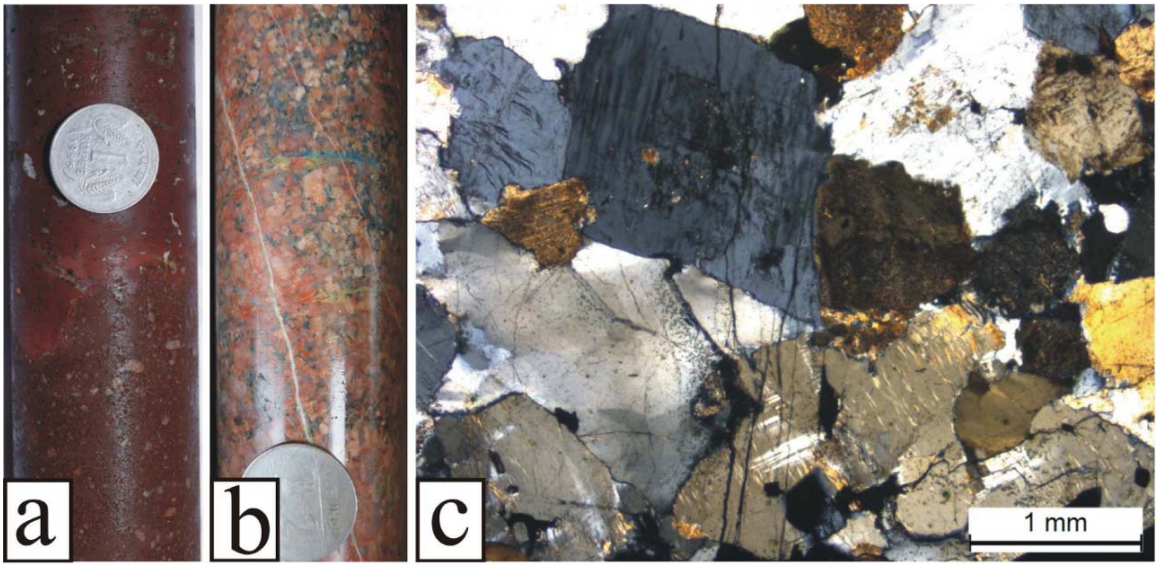

Fig.5. Evidence for extension of surface fissures to the basement granitoids at depth. (a) Core sample showing the contact between Deccan basalt and basement granitoid at depth 932.50 m in the borehole KBH-1 at Rasati. (b) Basement granitoid in the same borehole at a depth of 1039 m showing near-vertical fissure filled up with secondary mineralization. (c) Photomicrograph of basement granitoid from depth 1505.07 m in the same borehole showing distinct fracture network with secondary mineralization.

slopes and hill-tops, in line with the observations of Mitra et al. (2016) regarding weathering of basalts in the Kachchh region of Gujarat state. For example, the exposed rupture zone near the relatively flat areas around Kadoli village, south of the Koyna river, are highly weathered and converted to lateritic soil. In contrast, the inclined surfaces along the southern hill slopes near the Donichawadi village are relatively less weathered and the evidences of surface fissures and fractures are well preserved (Fig. 3d). The fissures and fractures are frequently filled with secondary material which precipitated along these openings due to weathering of parent rock (Fig. 3i). At places, massive basalt has become fragmented (Fig. 3e). At other places, siliceous precipitation is seen along the fissure planes (Fig. 3i). All of these evidences are related to brittle deformation of massive basalt and temporal weathering of rocks.

Orientations of most of the fissures and fractures range between N30°W and N50°E. The mean principal orientation of the fissures is 25°/89°–E, which is consistent with the observations reported previously from Donichawadi to Kadoli by the Geological Survey of India (GSI, 1968). Other evidences, such as en-echelon fractures near 905m hill and fragmentation of rocks and occurrence of sets of fractures along the Donichawadi to Nanel section, observed during the present study, are also consistent with those reported by GSI (1968). These multiple lines of evidences provide strong support that the fissures and fractures mapped during the present study represent the fissures created in the wake of the 1967 M~6.3 Koyna earthquake, the largest reported so far in the Koyna region. Twenty-two earthquakes with magnitude $5.0 < M < 5.9$ have occurred in the Koyna region since 1967; none of them has produced a surface rupture. There are, however, strong evidences to suggest reactivation of the KFZ, such as the occurrence of overlapping deformation features such as dextral strike-slip duplex structure (Fig. 3c) and transposition of pre-existing fissures and fractures at different locales (Fig. 3c, 3h). The spectacular soil-gas helium anomaly of crustal origin over the KFZ, reported by Gupta et al. (1999), confirmed that the fissures were a surface expression of an underlying fault zone in the upper crust. Further, the observation of the soil-gas helium anomaly 30 years after the 1967 earthquake strongly suggests that the fault zone represented by the KFZ is active and may be contributing to the persistent seismicity in the region.

The study shows that fissures are distributed over a large area extending as far as Donichawadi village to the east and up to Popoli village in the west (Fig. 1). In contrast, the field mapping carried out by the Geological Survey of India in the wake of the 1967 M~6.3 Koyna earthquake reported fissures concentrated in a ~1000m x 200m zone, located to the southeast of Koyna dam (GSI, 1968). An earlier study by Chandrasekharam and Parthasarathy (1976) have also reported evidences of surficial fissures and fractures with NNE-SSW and N-S orientations in and around the Koyna area, including the area covering the KFZ. The occurrence of those features were attributed to a deep seated fault along the Panvel flexure proposed by Auden (1949). However, the studies carried out by GSI (1968) strongly suggest the association of the fissures constituting the KFZ to the 1967 Koyna earthquake. The studies carried out by Sathe et al. (1968), soon after the Koyna earthquake, have reported the occurrence of fissures near Morgiri, located about 10 km to the east of Kadoli, although they were not as well developed as in the KFZ near Donichawadi and Kadoli. However, these fissures could not be observed during the present study possibly because of intense weathering of basalt at the low elevations. In any case, the association of these fissures with the KFZ is not established. On the other hand, the absence of fissures further to the west of Popoli on the Koyna-Chiplun road is confirmed by the present study. In the N–S direction, fissures have been mapped up to a distance of 10 km from KR15 in the north to the 905m hill peak in the south. The area to the south of the 905m hill peak could not be mapped due to inaccessible terrain.

Scientific drilling carried out recently in the Koyna region provides new evidence of the extension of the fissures into the granitic basement rocks underlying the pile of Deccan flood basalt. Physical and micro-structural studies on core samples of granite-gneiss basement rock, obtained from a 1522 m deep borehole at Rasati, confirm the extension of the surface fissures to depth. Occurrences of secondary mineralization along these fissures indicate the percolation of water through fractures within basement granitoids. The evidences for water channelization may have direct implications for the occurrence of reservoir triggered earthquakes in the Koyna region for the past five decades.

CONCLUSIONS

1. Although intense weathering of basalt has obliterated most of the evidences of Koyna Fissure Zone (KFZ) of 1967, field

observations show that deformation features as fissures / fractures are preserved 48 years after the earthquake.

2. Most of the planar fabric orientation in this study area range within N30°W to N50°E. The mean principal orientation of the fissures is 25°/89°–E, which is consistent with the observations reported previously from Donichawadi to Kadoli by the Geological Survey of India.
3. Fissures with similar orientation as those in the KFZ are observed over a larger area, extending ~9.5 km to the west of Donichawadi. The association of these fissures with the 1967 M6.3 Koyna earthquake could not be established. In the N–S direction, fissures have been mapped up to a distance of 10 km from KR15 in the north to the 905m hill peak in the south.
4. Transposition of one set of fissures / fractures by another set of fissures / fractures, observed at two sites, KR4 and KR22, between Rasati and Govare suggest repeated activation of the fault zone.
5. Physical observations and microstructural studies on core samples from the borehole KBH-1 at Rasati reveal repeated brittle deformation episodes within granitic basement rock underlying the Deccan basalt. The observations are consistent with the information obtained from field studies and confirms that the fissure zone extends to the granitic basement.

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