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Soft Sediment Deformation Structures in Quaternary Sediments from Dadra and Nagar Haveli, Western India

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ABSTRACT

Quaternary sediments are preserved in disconnected patches along the middle and lower reaches of major river valleys like Damanganga, Par, Ratakhadi and Dongarkhadi in the Dadra and Nagar Haveli region of Konkan coastal belt, Western India. These deposits mainly consist of stratified sand, silt, clay and gravel beds. The study area has been earlier affected by moderate earthquakes. The identified soft-sediment deformation structures (SSDS) are mainly developed in the sand silt, sand gravel and clay beds; and includes intrusive sedimentary bodies (dykes and sills), slump structures, suspended clast blocks and convolute structures. The nature, shape and dimension of SSDS suggest that the trigger mechanism and driving forces for the origin of these structures were seismic shock waves. Sediment loading and storm events as a trigger for the SSDS are less likely the reason and the proximity of these structures to the faults support the inference that it may be of seismic origin. Deformation in the Quaternary sediments of Dadra and Nagar Haveli imply the presence of neotectonic activity and points to an earthquake of magnitude >5.5 that struck the study area after sediment deposition.

INTRODUCTION

Before the Koyna earthquake of 1967, peninsular India was considered as stable region (Chandra, 1977). However, the seismic activity in Koyna (M 6.5, 1967), Killari (M 6.2, 1993) and Jabalpur (M 5.8, 1997) has stressed for the deeper understanding of tectonics in the region. The detailed study of the Konkan coastal belt, Panvel flexure seismic zone (PFS zone), Koyna, Son-Narmada Tapi lineament zone, and the Kurduwadi lineament zone revealed tectonically induced deformation activity (Auden, 1949; Chandra, 1977; Biswas, 1982; Watts and Cox, 1989; Sheth, 1998; Bansal and Gupta, 1998; Dole et al., 2000, 2002; Raj et al., 2003; Naik et al., 2003; Mohan et al., 2007; Kaplay et al., 2013, 2016; Kale et al., 2016; Jade et al., 2017) in the Deccan Volcanic Province (Figure 1a).

The presence of folds (antiform folds), the anomalous drainage pattern as well as the faulted, deformed Quaternary sediments in Nanded area of Maharashtra are attributed to be a result of neotectonic activities (Kaplay et al., 2013, 2016). The deformed Quaternary sediments from the northern river valleys of Deccan upland region show evidence of neotectonism as a result of Holocene events (Kale et al., 2016). Block tilting (in south direction), differential upliftment and incised river basins of Karjan river are ascribed as a result of active tectonics in Deccan Volcanic Province (Raj et al., 2003). Further, the presence of unpaired terraces, river piracy and higher bifurcation ratio are the geomorphic evidence of neotectonic activities in the Koyna region of DVP (Naik et al., 2003). The deformational features like flexure, warp, buckle folds and vertical offset in the Quaternary sediment sections of Ter village 40km NW of Killari in Osmanabad regions are the manifestation of ancient earthquake (Rajendran, 1997). The soft sedimentary deformation structures, liquefaction features such as slump, dislocations, sand dykes, controlled laminations and load cast structures are the manifestation of neotectonism in the Pravara and Pushpavati river valleys of Deccan upland region (Dole et al., 2000). SSD structures from Quaternary sediments are designated as 'seismites' in the Chandnapuri valley of the Deccan plateau (Dole et al., 2002) (Fig.1a).

Soft sediment deformation structures are formed in unconsolidated sediments during deposition or shortly after deposition (Lowe, 1975; Owen, 1996). These are the record of processes during a deformational event, which influences unconsolidated sediments at or near the existing surface prior to, or shortly after, burial (Leeder, 1987; Bhattacharya and Bandyopadhyay, 1998). These are formed after sediment deposition, but before sediment compaction, and with the sudden failure of loosely packed water-saturated grain structure having low to zero shear resistance resulting due to tectonic and sedimentary processes (Alfaro et al., 1997, 2002; Moretti and Ronchi, 2011). Liquefaction and fluidization are two processes which result in the formation of SSD structures (Lowe, 1975; Owen, 1987; Molina et al., 1998; Jones et al., 2000; Singh and Jain, 2007). The SSD structures were related to numerous origins such as shaking by earthquakes (Jones et al., 2000; Moretti and Sabato, 2007), storm waves (Molina et al., 1998; Chen and Lee, 2013), and tsunamis (Alsop and Marco, 2012).

Dadra and Nagar Haveli area is located in the western part of Deccan volcanic province in the Konkan coastal belt in Western India (Fig.1a). The West Coast of India has witnessed constant rifting events from the late Triassic/early Jurassic to late Cretaceous periods, with the opening of the Kachchh rift, followed by Cambay and Narmada rift (Biswas, 1987). The opening of these three rifts on the western margin of the Indian plate has led to the opening of the Indian Ocean, with the separation of the Indian-Madagascar plate from Africa (Besse and Courtillot, 1988). With the activation of the NE-SW trending mega shear, Madagascar separated from the Indian plate and led to the opening of the Indian Ocean around the western margin of the Indian plate (Reeves, et al., 2002). Followed by the faulting along the West Coast of India, during Pliocene, known as NNW-SSE trending West Coast fault, the West Coast fault joined the West Cambay fault in the north to form a triple junction (Krishnan 1953, 1982; Burke and Dewey, 1973). The Panvel flexure seismic zone (PFS zone) and the West Coast fault are in close proximity of the West Coast of India (Krishnan, 1953; Chandra, 1977). The PFS zone that extends between latitudes 16^o to 21^{o}N is an active fault and is responsible for the seismicity along it (Chandra, 1977; Mohan et al., 2007; Jade et al., 2017). The present study area also lies in the PFS zone (Fig.1a), which has been experiencing earthquake occurrences since 1618 (Rao and Rao, 1984; Rao, 2005) and is still active (https://isr.gujarat.gov.in/).

The SSD structures have been previously reported by many researchers from the Deccan Upland region (Fig.1a) (Rajendran, 1997;

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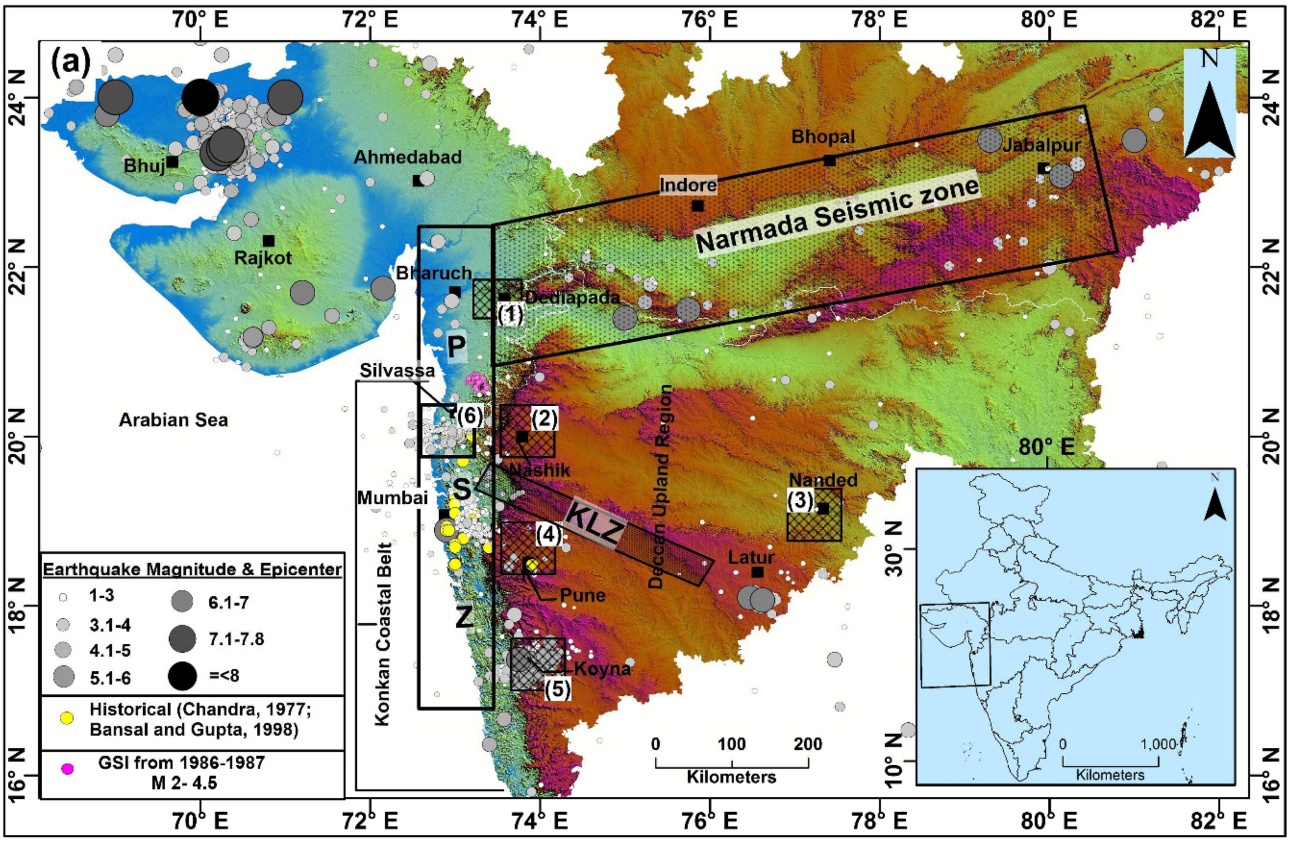

Fig.1a. The earthquake epicenter and magnitude distribution map of the Western India with significant earthquakes since 1856-2018 (ISR, IMD). **(1)** Raj et al., 2003, **(2)** Dole et al., 2002 ; 2000, **(3)** Kaplay et al., 2016 ; 2013, **(4)** Kale et al., 2016, **(5)** Naik et al., 2003, **(6)** Present study area. **PSZ**- Panvel Seismic Zone, **KLZ**- Kurduwadi Lineament zone.

Dole et al., 2000; Dole et al., 2002; Kaplay et al., 2013, 2016; Kale et al., 2016). However, there are no significant studies related to SSD structures in west of Deccan upland region (Konkan coastal belt) hence, this is the first study in which we report the presence of SSD structures in the northern part of Konkan coastal belt. This study will be significant to understand the seismotectonics of the region to precisely assess the seismic hazard. Therefore, the present research is targeted to study (i) the SSD structures, to document different markers of neotectonic deformation, (ii) to identify the different kinds of SSD structures in the Quaternary sediments of the study area, (iii) to interpret the possible trigger mechanism, (iv) for estimation of palaeo-earthquake magnitude and (v) to correlate these observations with regional tectonics.

GEOLOGICAL SETTING AND STUDY AREA

The Deccan flood basalt erupted at approximately 65 Ma in the Indian peninsula and covered more than 500,000 km^2 area (Watts and Cox, 1989; Renne et al., 2015). The Deccan flood basalts are well developed in the Western Ghats escarpment in the SW part of India (Sheth et al., 2013), where Kaila et al. (1981) suggested thickness of Deccan flood basalt to be ranging from 1.7-2.0 km. The western part of Deccan volcanic province consists of two geomorphic features the Sahyadri upland and the Konkan coastal belt delineated by the Western Ghats escarpment (Fig.1a) (Powar, 1993).

The study area lies in the northern part of Konkan coastal belt in western India between Latitudes 20.0°- 20.50° N and Longitudes 72.7° – 73.10° E) (Fig.1a). It is bounded by the west coast fault in the west, Western Ghats escarpment in the east and the Panvel flexure located in the central portion (Fig.1a). The study area is dominated by the Deccan basalt, trachyte and rhyolite complex with dykes of dolerite. In the central portion, the basaltic rocks are overlain by Quaternary sediments which are preserved in disconnected patches along the middle and lower reaches of major rivers (GSI, 2002) (Damanganga, Ratakhadi and Dongarkhadi rivers) (Fig.1b). The West Coast of India was developed as a result of faulting during Pliocene (Krishnan, 1953). In Western India, the west coast fault is a major tectonic feature, which trends in the NNW-SSE direction and is considered to give a straight alignment to the west coast up to the Gulf of Cambay in north and further extend to the south of Mumbai (Bombay) (Krishnan, 1982). In southern Gujarat, the flow dips in the western direction and present as a monocline flexure structure, the axis of which passes through Kalyan and Panvel (Rao et al., 1991). This flexure is called the Panvel flexure, which is fractured along its axis and witnesses many hot water springs along its length (Rao et al., 1991). In the early Tertiary period, Western India perceived a large tectonic event resulting in the formation of west coast fault along the Precambrian basement and the formation of Panvel flexure, which is also related with this event (Crawford, 1971; Mahoney, 1988; Cox, 1988). White et al. (1987) suggested that the NNW-SSE trend of west coast fault and parallel fracture system (that runs and controls the West Coast of India and the Panvel flexure) could be an expression of the extending and breaking of continental lithosphere in reaction to rifting, while Burke and Dewey (1973) suggested that the west coast fault and its fracture system are parallel to one limb of the triple junction situated around Cambay.

MATERIAL AND METHOD

The soft-sediment deformation study is accomplished in the following steps: The SSD structures were located and then identified in Quaternary sediments deposited in the study area. The measurement of these structures was carried out and also the correlation of SSD structures and the containing layer of sediments was done. The review of previous studies related to SSD structures available worldwide (Lowe, 1975; Leeder, 1987; Owen, 1987; Owen, 1996; Rajendran,

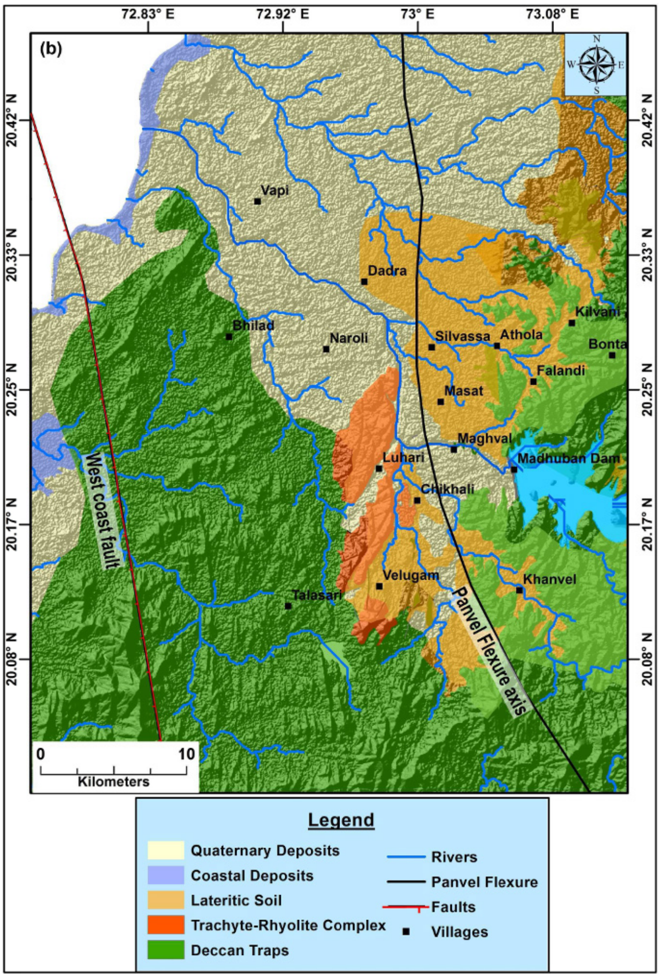

Fig.1b. Geological and Tectonic map of study area (modified after GSI, 2002; Dessai and Bertrand, 1995).

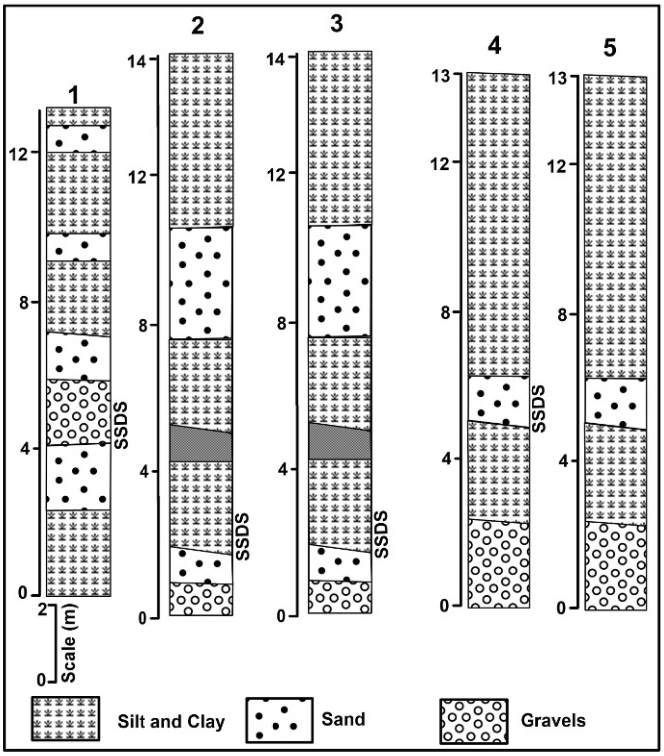

Fig.2. Field sections prepared for different locations shown in Fig. 1b in the quaternary deposits which are susceptible to deformation.

1997; Alfaro et al., 1997; Bhattacharya and Bandyopadhyay, 1998; Molina et al., 1998; Dole et al., 2000, 2002; Moretti and Ronchi, 2011; Kaplay et al., 2013, 2016; Kale et al., 2016) was done and the factors (whether primary or secondary) that could be responsible for the formation of SSDS were studied. Also, to highlight the objective of the study, the trigger mechanism and the distribution of the earthquakes and the presence of active faults in the area was studied. Further detailed geological field investigations had been conducted to highlight the signatures of neotectonic deformations in the study area.

SOFT SEDIMENT DEFORMATION STRUCTURES

In the present study, different kinds of SSD structures have been analyzed from several outcrops sections during the field investigation (Fig.2). These structures were mainly observed in sandy silt, silty clay and sandy gravels, as the SSD structures are mainly developed in the sand silt, sand gravels and clay beds. Major SSD structures in the study area include intrusive sedimentary bodies (dykes and sills), slump structures, suspended clast blocks and convolute structures (Fig.3).

Soft Ssediment Intrusions

Soft-sediment intrusions are generally developed due to liquidized sand injection into the adjoining, mostly in superimposing sediment layer (Lowe, 1975; Potter and Pettijohn, 1977). These structures show variable morphology, composition and size as defined by Lowe (1975). These structures occur in the form of clastic dykes and sills at various locations in the study area.

Clastic Dykes

The clastic dykes have been recorded close to Masat village (Lat. 20°15’47.75"N, Long. 72°59’27.38"E). The dykes cut across layers of sandy gravels which vary in size. The sediments beneath the intruded sediment layer and occasionally intruded layer itself have shown the bending in an upward direction (Fig.4). Therefore, liquefaction results in bending of sediment contacts/edges, which is a distinctive feature of dykes. During an event of an earthquake, the water-rich sandy sediments are injected into argillaceous sediments and results in the formation of veins/ dykes under pressure. The formation of the dyke is increased prominently when the superimposing layer is simply dragged apart by tension; produced at the site of lateral spreading as well as by strong oscillatory shaking at the surface. The dykes I, II and III have an irregular finger-like shape (Figs. 4 a, b and c). The dykes penetrate into the host strata up to the depth of 20 to 50cm. The discordant nature of these dykes is well evident in the exposure and is easily identifiable due to the stratified nature of the host sediments and unstratified nature of the intruded dykes. The forceful upward drive of the sand dykes can be manifested as up warping of the host sediments as observed in Fig.4. Liquefaction is the main reason for the upward bending of host soil layer edges and it is also a characteristic feature of the dyke (Topal and Özkul, 2014). The formation of dykes increased significantly when the overlying layer of sediments simply pulled apart due to tension; due to lateral spreading and as well as due to strong oscillation at the surface. According to Bhattacharya and Bandyopadhyay (1998), the dykes develop through liquefaction and fluidization of sediments while the sediment layer that injected as dykes is more permeable than the overlying layer. The clastic dykes are formed perpendicular to the propagation direction of earthquake waves (Singh and Jain, 2007). Therefore, the dykes are inferred to have originated due to the liquefaction of the water-saturated sand layers at the base, probably by triggering mechanism related to earthquake shocks (Audermard and De Santis, 1991; Obermeier et al., 1993).

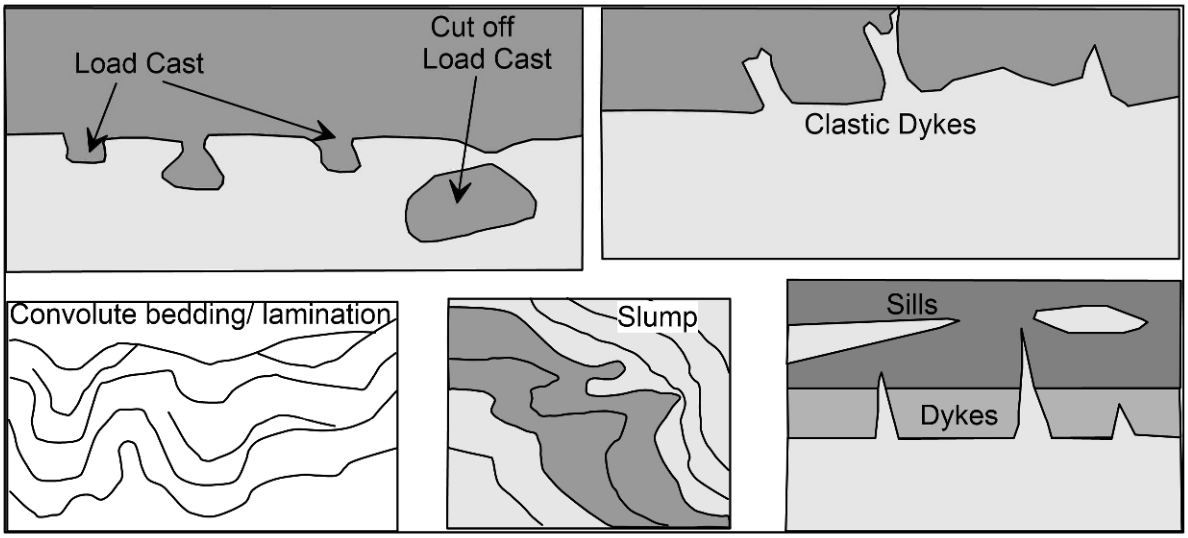

Fig.3. Different types of soft-sediment deformation structures encountered in Quaternary sediments of Dadra and Nagar Haveli.

Clastic Sills

Clastic sills are a form of horizontal clastic intrusions recorded from the sediments near Maghval village (lat. 20°11'50.46"N, long. 73°2'58.02"E) and Madhuban village (lat. 20°11'31.96"N, long. 73°3'33.59"E). The sediments consist of grey sandy gravels, fine to coarse sand and brown sandy silt (Fig.5). The clastic sills emplace parallel to the layers of sediments and are ascribed as liquidized intrusions (Lowe, 1975). The length of these clastic sills ranges between 1 to 1.5m. The sills are associated with the lateral flow of sandy material into the overlain beds, which also causes upward/ downward bending of layers (Fig.5). This deformation can be caused by liquefaction or fluidization of the underlying water-saturated source-beds. The clastic dykes and sills are formed by the intrusion of water-saturated sandy soil into the overlying strata, which has been inferred as a result of liquefaction triggered by seismic shocks (Rodríguez-Pascua et al., 2000). Thus, clastic sills recorded from the Quaternary sediments of the study area are related to lateral flow of sandy soil by the liquidized intrusion, which has also caused upward/downward bending of layers.

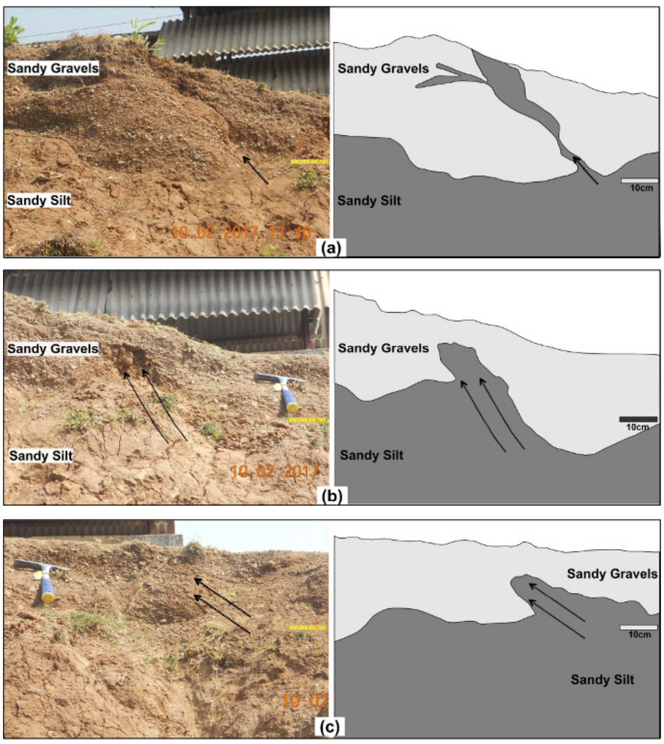

Fig.4. (a, b and c) Clastic Dykes observed near Masat village (Lat. 20°15’47.75"N, Long. 72°59’27.38"E) (ref. section 1 in Fig. 2).

Slump/Fold Structures

Slump structures were observed in the sediments deposits near the Maghval village (lat. 20°11'50.46"N, long.73°2'58.02"E) and Madhuban village (lat.20°11'31.96"N, long.73°3'33.59"E) (Fig.6a). In the exposed field section south of the river a very well preserved slump structure is observed. The syncline folding nature of brown fine sand intruded layer is clearly visible in Fig.6a. The formation of this slump/fold implies that the deformation has taken place in the unconsolidated state of sediments probably having the consistency of a fluid. A large earthquake (usually M 5.5) can produce different kinds of syn-depositional structures due to the liquefaction of unconsolidated sediments (Obermeier, 1996) and to the lateral movements slumps and landslides can be formed (Seilacher, 1984). The slumping in these sediments must have been triggered by an external agent either by an earthquake shock or by a lateral movement.

Convolute Structures

Convolute structures are complex folding or crumpling of the laminae in a sedimentation unit, which can be well-demarcated (Kuenen, 1953; Potter and Pettijohn, 1963). The convolute structures are recorded from the Quaternary sediment deposits of Damanganga river near Madhuban village (lat. 20°11'31.96"N, long.73°3'33.59"E). Convolute bedding consists of regular to irregular contortions of contacts of beds (Fig.6c). The folds resulting from convolute bedding are defined as distorted stratifications that form laterally alternating convex and concave-upward morphology (Rossetti, 1999). Convolute lamination/bedding is expressed as more-or-less regular folds that develop either throughout or are limited to the upper part of a single sedimentary unit (Allen, 1982). Elevated pore-water pressure in association with the fluidization contributes to origin of various SSD structures such as dish structures, pillars, and convolute laminations (Potter and Pettijohn, 1963). According to Cojan and Thiry (1992), this deformation can be concluded to be syn-depositional and most probably due to seismic shocks. Therefore, the best probable mechanism for the origin of convolute lamination was associated with seismic shocks occurred in the study area.

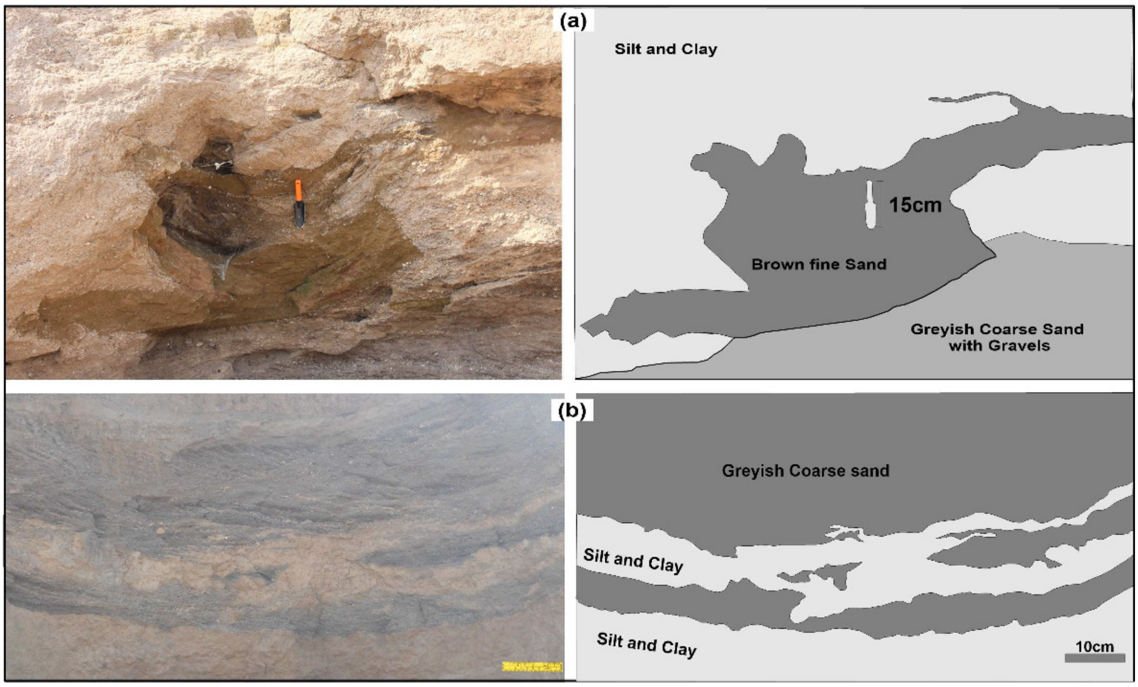

Fig.5. (a) and **(b)** Clastic sills encountered near Maghval village (Lat. 20°11'50.46"N, Long. 73° 2'58.02"E) and Madhuban village (Lat. 20°11'31.96"N, Long. 73° 3'33.59"E) (ref. sections 2 and 4 in Fig.2).

Load Cast Structures

The load cast structures (Owen, 2003) were encountered at the boundary of sand and silt superimposing mud layer (Figs. 6b and c). These structures have different heights from 2 to 5 cm with semicircular shape and with minor penetration into the underlying layer. The load cast (Figs. 6b and c) showed minor intrusive behaviour into the underlying sediment layer and a characteristic concave outline. They showed resemblance to the 'sagging load cast' described by Alfaro et al. (1999) and minor deformed lamination related with other deformational structures.

The formation of load casts is generally ascribed to reverse density gradient (Anketell et al., 1970). The gravitational readjustment carries instantaneous descent of denser sediment layer and an ascent of the lighter sediment layer. The sediment which sinks into the underlying sediment layer forms the load casts (Tipper et al., 2003). Therefore, the load cast structures must have been triggered by reverse density gradient.

INTERPRETATION OF DEFORMATION STRUCTURES

Deformation Mechanism

Studies in the Deccan upland region viz. Nashik, Nanded and Osmanabad districts of Maharashtra have recorded the presence of seismites, flexures, warping, folding, offsets and a deformation in Quaternary sediments (Rajendran, 1997; Dole et al., 2000; Dole et al., 2002; Kaplay et al., 2013, 2016; Kale et al., 2016).

The SSD structures are formed by disturbance of non-lithified, water-saturated sedimentary layers (Mills, 1983). The mechanisms of deformation for SSDS has been studied by many researchers (Lowe, 1975; Mills, 1983; Owen, 1987, 2003; Moretti and Sabato, 2007). Allen (1982) suggested that the failure in slope by slumping, shear stresses, liquidization, may take place if the driving force results in reverse density. Various driving forces can take place at the same time, as formerly discovered by Anketell et al. (1970); Mills (1983); Owen (1987); Rossetti (1999). The liquidization can be classified into the four categories: fluidization, liquefaction, thixotropy and sensitivity (Owen, 1987). Liquefaction or fluidization are the most significant cause for the formation of SSD structures in water-bearing and cohesionless layers of sediments (Allen, 1982). Generally, the mechanism for the trigger and the deformation caused can be caused due to the effect of external agents such as fluctuations in groundwater, gravity and storm currents, earthquakes (Lowe, 1975; Sims, 1975; Owen, 1987, 1996). There can be a different possible driving force and deformation mechanism for the formation of each of the SSD structures.

Trigger Mechanism

Numerous possible trigger mechanisms have been described for SSD structures. The most known are (i) sediment loading (Anketell et al., 1970; Lowe and LoPiccolo, 1974; Moretti and Sabato, 2007), (ii) turbiditic currents, storm current (Dalrymple, 1979; Molina et al., 1998; Alfaro et al., 2002), (iii) collapse structures (Moretti et al., 2001; Waltham and Fookes, 2003; Moretti et al., 2011), (iv) liquefaction through preexisting cracks (Guhman and Pederson, 1992; Holzer and Clark, 1993), and (v) seismic (Seilacher, 1969; Lowe, 1975; Sims, 1975; ; Calvo et al., 1998; Rossetti, 1999; Alfaro et al., 1999; Vanneste et al., 1999; Rodríguez-Pascua et al., 2000; Moretti et al., 2011).

Sediment loading and storm currents can be a triggering mechanism for the formation of SSD structures, but these seems to be of minor importance for structures found in the sediments deposited in the study area. The SSD structures identified here show the wide extent, which suggests a more regional trigger mechanism as compared to the local actions of sediment loading and storm current, the turbiditic currents, collapse structures and liquefaction through pre-existing cracks. Seismic shaking was the most possible trigger mechanism that could be the factor behind the formation of these structures in the study area, as the area is surrounded by neotectonically active faults like, west coast fault, Panvel flexure fault. The structures reported in the sediments from the study area can likely be classified as seismites, on the basis of their nature (fluvial sediments), shapes (dykes, sills, convolute bedding and load cast structures) and dimensions (Sims, 1975; Owen, 1996; Calvo et al., 1998; Rossetti, 1999; Vanneste et al.,

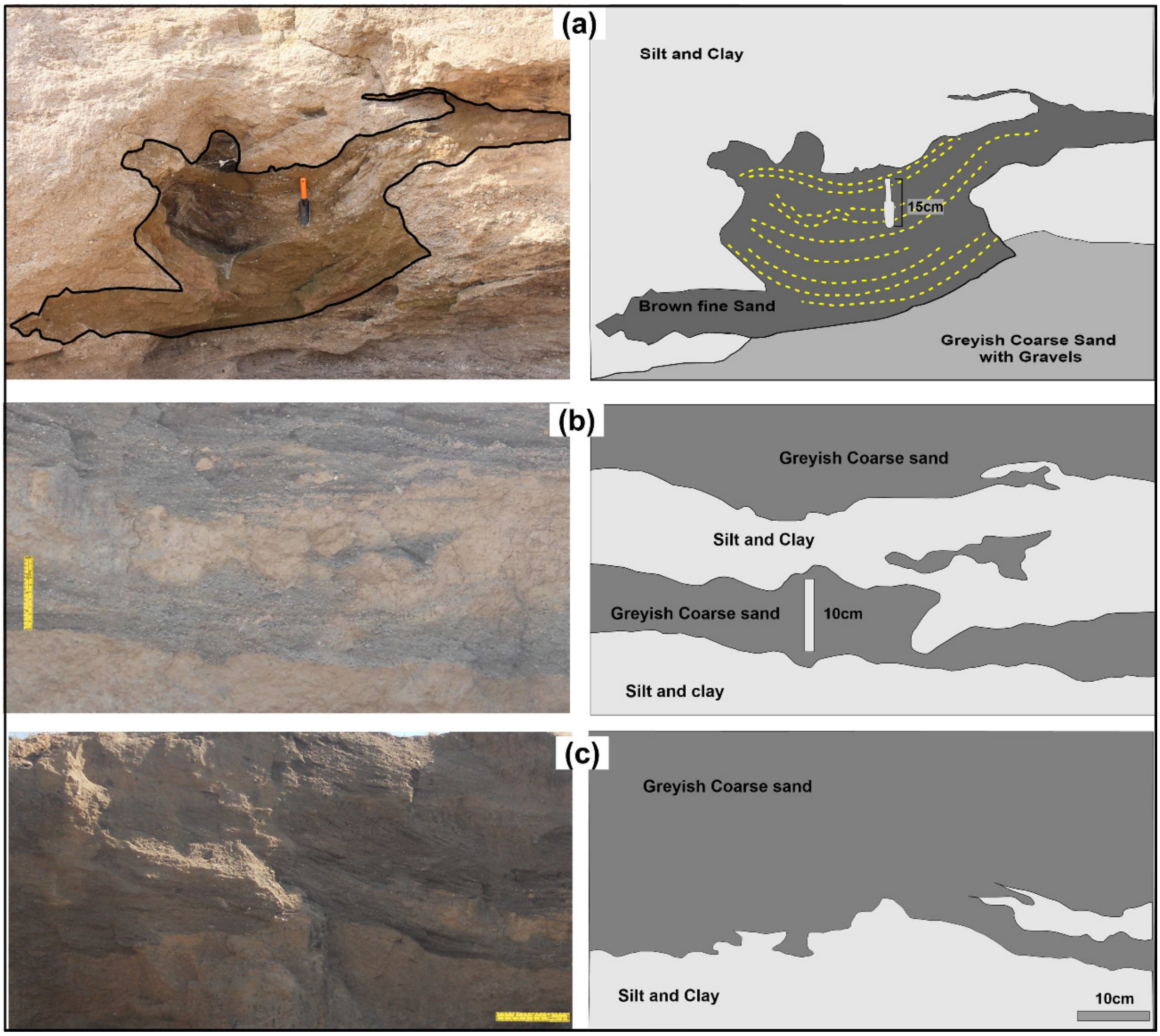

Fig.6. (**a**) Slump/fold, (**b**) and (**c**) Load cast and Convolute bedding/ lamination near Maghval (Lat. 20°11'50.46"N, Long. 73°2'58.02"E) and Madhuban villages (Lat. 20°11'31.96"N, Long. 73°3'33.59"E) (ref. sections 3 and 5 in Fig.2).

1999; Rodríguez-Pascua et al., 2000; Moretti, 2000; Owen and Moretti, 2011; Owen et al., 2011). The SSD structures can be induced by seismic shock after an earthquake and for the formation of these structures, an area should have experienced the tectonic and seismic activities (Jones and Preston, 1987; Moretti and Sabato, 2007; Storti and Vannucchi, 2007). The shaking of ground induced by an earthquake is one of the well-known phenomena for the fluidization of sediments. During the event of shaking, the pore pressures are temporarily raised resulting in the loss of grain-to-grain contact and temporary loss of strength because of localized ejection of pore water (Chakraborty, 1977; Allen, 1977). In the Quaternary deposits from the study area, the evaluated SSD structures can be ascribed to the seismic source based on the following observations: (i) the presence of undeformed soil beds above and below the deformed beds; (ii) the grain size of deformed sediments in the range of liquefaction of soil due to seismic shaking (Balkema, 1997); (iii) the SSD structures and their morphology, dimensions, facies, sedimentological properties are similar to the studies on seismites by Sims, 1975; Rossetti, 1999; Vanneste et al., 1999 and Jones et al., 2000; (iv) the present study area lies in a seismically active zone known as the PFS zone (Chandra, 1977) and has experienced earthquakes with magnitude $M \geq 5$, therefore the SSD structures in the sediments from the study area satisfy major criteria to be categorized as seismites.

The SSD structures originated by liquefaction can be related to moderate to high-magnitude $M \geq 5$ seismic shakings (Kuribayashi and Tatsuoka, 1975; Atkinson, 1984). An earthquake of magnitude 2-3 is sufficient for triggering liquefaction in soils (Seed and Idriss, 1971). Marco and Agnon (1995) suggested that for triggering liquefaction the earthquake magnitude should be > 4.5. The faults present in and around the study area are observed at distances of 15 km to 50 km and more (Fig.7). The relationship of SSD structures is very similar to structures formed by current earthquakes with a Richter magnitude larger than 5 (Berra and Felletti, 2011; Brandes and Winsemann, 2012). In view of earthquake magnitude and distance to faults, SSD structures present in the study area may have developed by earthquakes from active faults ruptured during the formation of sediments. It can be recommended that the earthquake which may have produced the seismites could be between magnitude 5 and 7 in the vicinity of the area. The faults namely West Coast fault (Biswas, 1982) and Panvel flexure fault (Chandra, 1977; Sheth, 1998; Mohan et al., 2007) are close to the SSD structures (seismites), and could be source of the past damaging earthquakes in the study area (Fig.7).

The study area lies in the seismically active zone (Zone III, BIS) of Panvel flexure, which is a listric fault (Sheth, 1998), is seismically active and has been experiencing the seismic activities with historic

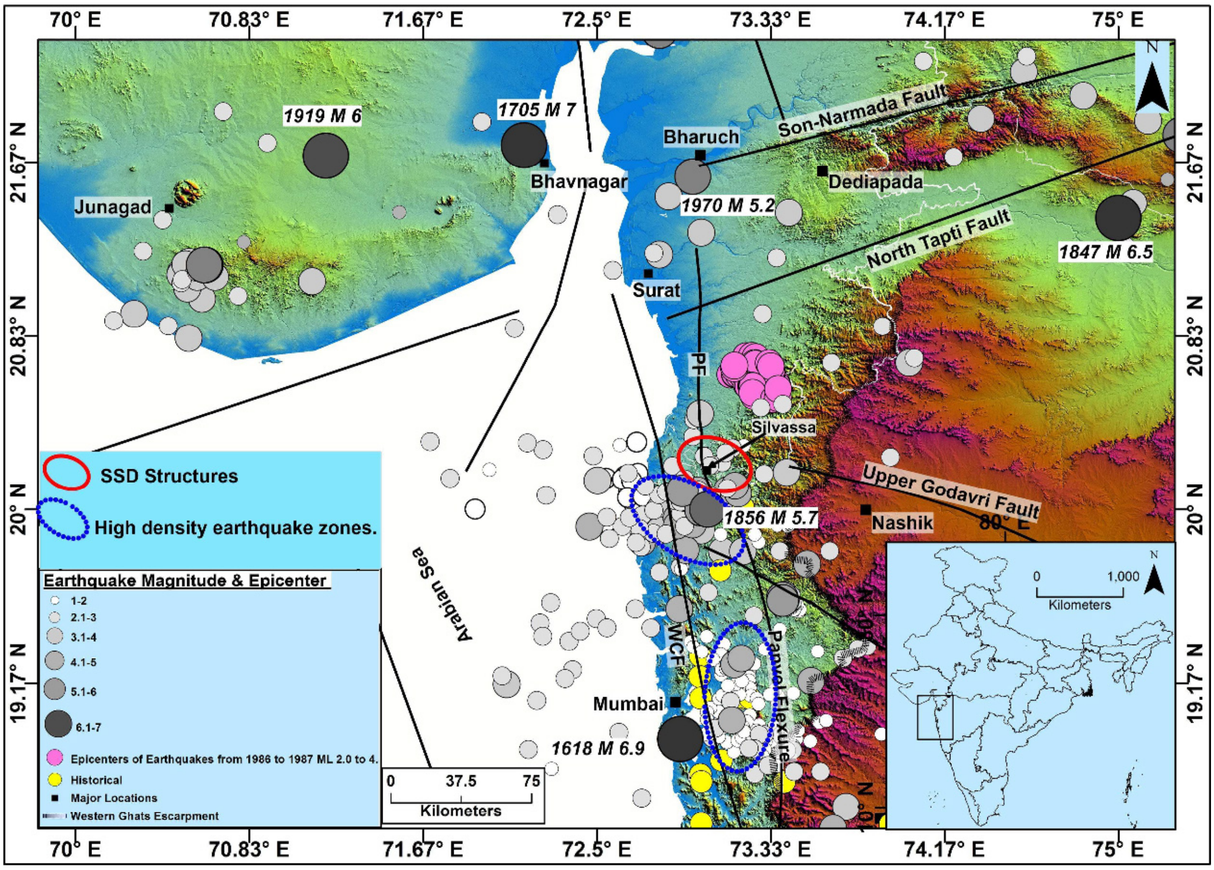

Fig.7. Epicenter distance variation of SSDS (blue ellipse) in their development and 1618, 1856 earthquake (M6.9 and 5.7) affected the Panvel seismic zone and the study area.

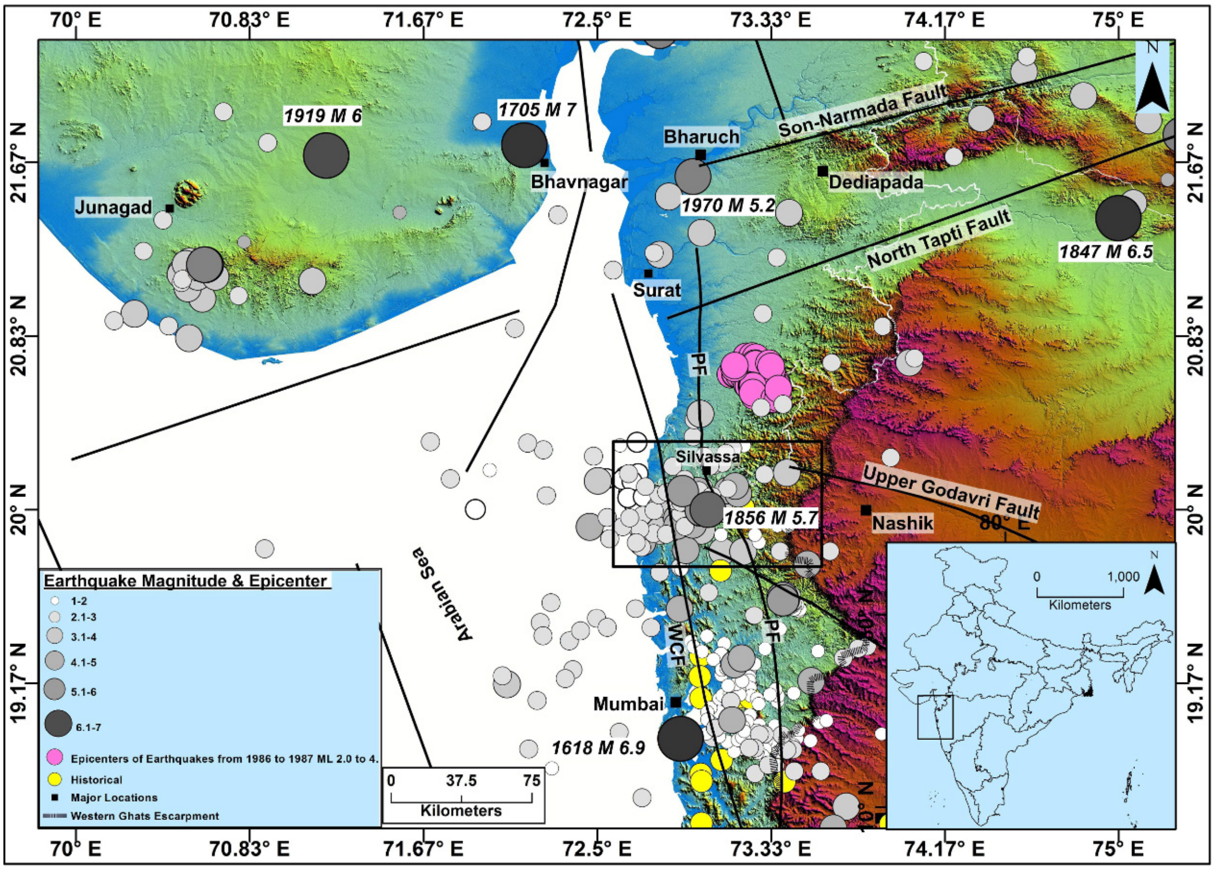

Fig.8. Seismotectonic map of the Konkan Coastal Belt (study area is shown in black box) (From 1856 to January 2019), **PF**-Panvel flexure, **WCF**-West coast fault.

events (Chandra, 1977). The presence of seismicity along 150 km long axis of Panvel flexure provides a reliable indication of active sub-surface faulting along the axis of flexure (Mohan et al., 2007). The results of microseismicity studies conducted by Mohan et al. (2007) in Panvel flexure zone reveals the occurrence of a total of 158 numbers of earthquakes (Mc 1-3.6) and almost 41 earthquake shocks of magnitude (Mc ≥ 2.5) happened along the Panvel flexure zone. The hypocenter estimation results of 20 earthquakes suggest that these earthquakes occurred near the surface and this reveals the existence of an active fault system underneath the Panvel flexure (Mohan et al., 2007). The seismicity along the Panvel flexure with earthquakes of magnitude M 6.5 in 1618 (Rao, 2005; Rao and Rao, 1984), M 5.7 in 1856 (Chandra, 1977), M 5 in 1935 (Bansal and Gupta, 1998), M 4.1 in 1989 (ISC) and a low-intensity earthquake between M 1 to 4.3 in the study area (>200) (http://www.imd.gov.in/pages/earthquake_prelim.php and https://isr.gujarat.gov.in/) supports the tectonically active nature because their epicentres are present along the Panvel flexure (Fig.7). Moreover, the earthquake epicentre data highlights the presence of a large number of recent earthquake epicentres in the study area and the high-density earthquake zone in SW showing concordance with the tectonic features present in the region (Figs. 7 and 8).

Studies in Deccan upland region like Nashik, Nanded and Osmanabad districts of Maharashtra state have recorded the presence of seismites, flexures, warping, folding, offsets and a deformation in alluvial sediments (Rajendran, 1997; Dole et al., 2002; Kaplay et al., 2013, 2016; Kale et al., 2016) similar to those is observed in the sediments of Damanganga river in Dadra and Nagar Haveli. According to Rajendran (1997) the magnitude of palaeo-earthquake, which caused the deformation in sediments at Ter village, was estimated to be similar to the 1993 Killari earthquake (M6.2). All these locations are in Deccan Trap Province mainly in Deccan upland region, where the sediment deformational structures are reported, and these locations exhibit the bedrock of basaltic flow covered by the alluvial sediments and soil. The similarity of this geological framework with that in the present study area is significant. The presence of seismicity, SSD structures and historic earthquake records lay emphasis on the occurrence of a major earthquake event (>5.5 Magnitude) in the area along the axis of Panvel flexure during the Quaternary period.

CONCLUSION

The present study is focused on the Dadra and Nagar Haveli area of Konkan Coastal Belt region and has attempted to identify and to suggest the trigger mechanism for the SSD structures documented from the Quaternary sediments deposited in the study area. The Quaternary sediments preserved in the segment of the Damanganga river in the Dadra and Nagar Haveli have been deformed at various places. Different processes formed the SSD structures; the intrusive clastic dykes are interpreted as a result of liquefaction and sills are interpreted as a result of fluidization process; gravitational instabilities related with inverse density gradients resulted in the formation of convolute beddings; slumps are related to gravitational downslope movements. Based on the extensive range of diverse SSD structures along with the tectonic setting of the Dadra Nagar Haveli and surroundings it is concluded that the structures originated due to seismic activity. The relationship of various SSD structures established on the basis of their distribution and their vicinity to faults implies that an earthquake of magnitude >5.5 affected the study area and its surroundings in the past.

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