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Soft Sediment Deformation Structures from Khari River Section of Rudramata Member, Jhuran Formation, Kutch: A Testimony of Jurassic Seismites

M. G. Kale[1*], Ashwin S. Pundalik[1,2], R. A. Duraiswami[1] and N. R. Karmalkar[1]
[1]Department of Geology, Savitribai Phule Pune University, Pune - 411 007, India
[2]Department of Geology, St. Xavier's College, Mumbai - 411 001, India
***Email:** mgkale@unipune.ac.in

Abstract: Soft sediment deformation structures such as slump folds, clastic dyke, syn-sedimentary faults and convolute bedding are present in the coarse – fine grained yellowish buff coloured sandstone, and interbedded reddish brown fine grained sandstone and yellowish – white siltstone at the Khari River section belonging to Rudramata member of Jhuran Formation (Upper Jurassic), Kutch. These soft sediment deformation structures are confined to lower and middle parts of the section and are invariably underlain as well as overlain by undeformed beds that have restricted lateral and vertical extent and occur in close proximity of Kutch Mainland Fault, thereby suggesting that these structures were formed by seismic activity and therefore represents seismites.

Keywords: Soft sediment deformation, seismites, slump folds, clastic dyke, Khari River section, Kutch, Gujarat.

INTRODUCTION

The Kutch basin (Fig.1a) is a pericratonic rift basin on the western margin of the Indian Plate which formed during the breakup of Gondwanaland in Late Triassic (Biswas, 1991; Rajendran et al., 2001; Shankar, 2001; Biswas, 2005). This basin is situated between the subsurface Nagar Parkar Uplift in the north, Radhanpur-Barmer arch in the east and Kathiawar Uplift in the south; which exposes excellent Mesozoic and Tertiary sedimentary succession. The Kutch basin evolved through three tectonic phases: 1. Rift phase, 2. Late rift divergent wrench phase and 3. Post rift convergent wrench phase; corresponding to break up, drifting and collision of Indian plate respectively (Biswas, 2005). According to Biswas (1987, 2005) the rift was aborted in Late Cretaceous, following trailing edge uplift prior to collision with Asian plate and later became a shear zone during inversion stage following collision. Post collision compressive regime is responsible for present active neotectonic movements (Biswas, 2005). Sastry et al. (2008) carried out a regional magnetotelluric (MT) study in the Kutch region, which revealed that the deeper electrical structure in the Kutch region presents a mosaic of high resistive crustal blocks separated by deep-rooted conductive features. Two such conductive features spatially correlate with the known tectonic features, viz. Kutch Mainland Fault (KMF), and the Katrol Hill Fault (KHF) (Patidar et al., 2007; Sastry et al., 2008). In this basin, all known forms of intrusive igneous bodies i.e. plugs, cones, sheets, laccoliths, dykes and sills are concentrated in the narrow deformation zones accompanying the master faults (Biswas, 2005). Petrographic and geochemical studies reveal that these plugs consist of basanite-olivine nephelinite with xenoliths of spinel lherzolite, indicating that they are derived from upper Sub Continental Lithospheric Mantle (De, 1964; Karmalkar et al., 1999; Karmalkar et al., 2008). The intrusive bodies associated with marginal deformation zone in western Kutch Mainland unit are composed of basic and alkaline intrusions (Duraiswami, 2008; Kshirsagar et al., 2011). On the basis of study of these intrusive rocks, rift geometry and seismic tomography; presence of large ultramafic body in the lower crust is suggested (Mandal et al., 2004; Biswas, 2005). Based on structural and detailed depth-wise analyses of aftershock data, a conceptual domino-listric link fault model of Kutch rift involving lithosphere rupture and consequent subcrustal-lithosphere melting for simple/combined shear rifting is proposed by Biswas (2005) to explain the seismic activity of the Kutch basin.

The Kutch basin hosts 1500 to 2400 m thick Mesozoic sediments and 550 m Tertiary sediments (Biswas, 1977). The Mesozoic sediments range in age from Middle Jurassic to Lower Cretaceous and are exposed in six disconnected areas namely Kutch Mainland, Patcham Island, Khadir

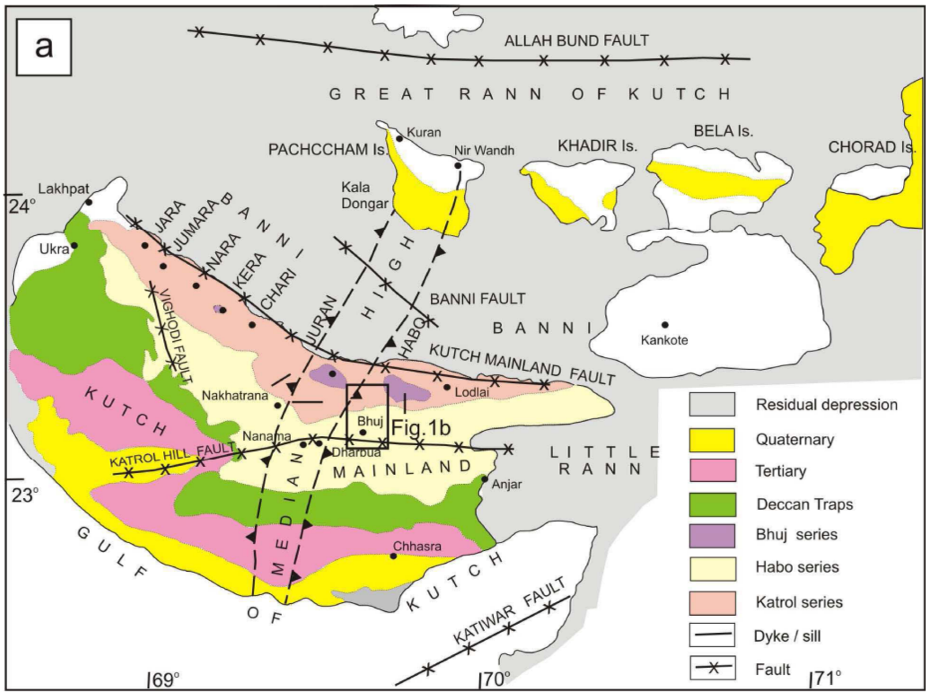

Fig.1a. Maps showing Geology and structure of Kutch basin (after Biswas, 1977).

Island, Bela Island, Chorar Hills and Wagad which are major uplift zones and form highland amidst extensive plains (Biswas, 1977). Biswas (1977) proposed lithostratigraphic classification of Kutch basin in which he recognized four formations namely Jhurio Formation (Bathonian to Lower Callovian), Jumara Formation (Callovian to Oxfordian), Jhuran Formation (Kimmererdigian to Valanginian) and Bhuj Formation (Lower Cretaceous i.e. Valanginian to Santonian) in ascending order. According to Biswas (1977), the Jhuran Formation comprises of thick sequence of alternating beds of sandstone and shale. Jhuran Formation is divided into four informal members viz. lower, middle (Rudramata shale), upper and Katesar members. The physical and biological characteristics of the sediments belonging to these members are indicators of deposition in sublittoral to supralittoral depositional environment (Biswas, 1977). The middle (Rudramata shale) member is best exposed in the Khari Nadi valley near Rudramata Temple north of Bhuj, which constitutes the reference section for this member (Biswas, 1977). It is predominantly shaly, comprising of dark grey to black laminated gypsiferous shale with bands of ferruginous sandstone, micaceous siltstone and yellow mudstone. Seth et al. (1990) identified some possible signatures of earthquakes in lower submarine fan complex of the Lower Member of the Katrol Formation (Upper Jurassic) near Jumara. They have recorded dying growth faults causing preferential basal brecciation of shale beds, frequent local intraformational unconformities resulting in reverse grading and have attributed this to mechanical sieving and intrabasinal mass flows through sand volcanoes. All these features together with abundant syn-sedimentary graben and horst structures and widespread liquefaction bear the distinctive records of seismicity (Seth

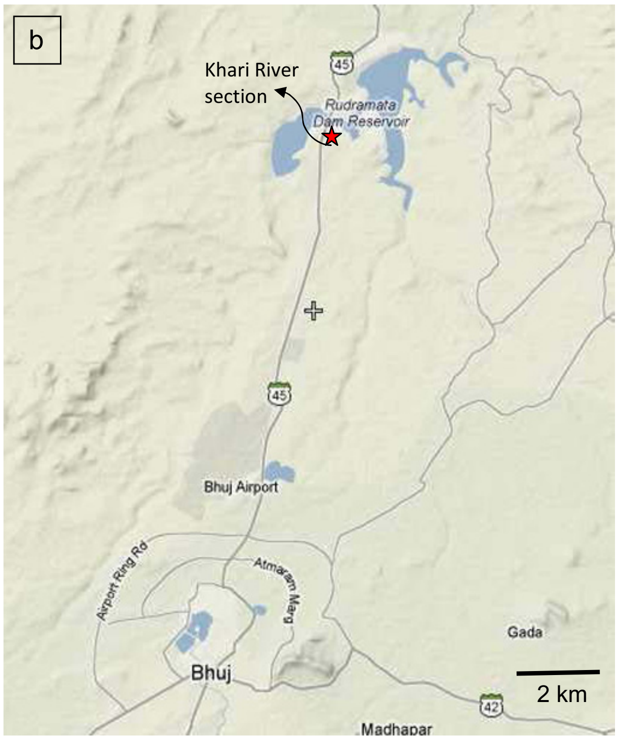

Fig.1b. Location of the Khari River section (star), north of Bhuj.

et al., 1990). In these associations, they have also recorded thinning and fining up channel-fill subsequences with a basal scour and lack of scoured base in higher beds and opined that they may represent flows triggered by aftershocks after a primary shock (Seth et al., 1990). The channel-fill subsequences with typical structural elements such as concave–up erosion surface, horizons of intraformational shale lag pebbles and grit filled scours were considered by Seth et al. (1990) to be represent a single earthquake and its aftershocks rather than conventional channel cutting and migration or abandonment. Despite excellent exposures and detailed lithostratigraphic descriptions of the Kutch Basin, the soft sediment deformation structures are cursorily described in published literature. The present paper reports soft sediment deformation structures from the Rudramata member of Jhuran Formation exposed in Khari River section, near Bhuj and attempts to explain their genesis vis-à-vis their triggering mechanisms/ basin instability.

KHARI RIVER SECTION

The sediments belonging to Rudramata member of Jhuran Formation are well exposed in the Khari River section (Fig.1b) and generally exhibit gentle dips of up to 11° towards north. A vertical section of more than 11 m is exposed on the southern bank of Khari River (Fig.2) wherein dark grey to black carbonaceous shale containing thin intercalations of white, yellowish white siltstone form the lower part of the section. These exhibit parallel laminations, low angle bedding which are typical of intertidal mud flat deposits (Reineck and Singh, 1980, Klein 1980, Reading, 1981). In the upper parts of this siltstone, ferruginous concretions formed during the burial diagenesis are observed. Yellowish buff coloured, fine grained sandstone overlies these siltstone-shale intercalations and these also contain thin siltstone layers. Development of low angle cross bedding and horizontal parallel lamination is noticed within this fine grained sandstone unit. This unit passes upward into yellowish buff coloured coarse grained sandstone that exhibits soft sediment deformation features and passes into horizontal parallel bedding at the top. The coarse grained sandstone passes upward into fine grained sandstone that exhibit large scale tabular crossbedding. This fine grained sandstone contains thin shale layers and passes upward into sandstone-shale intercalations with wavy, tidal bedding. Patwardhan and Soman (2004) reported occurrence of an unusual form of *Ancorichnus isp*. cf. *A. ancoichnus* from the siltstone-shale's forming the upper part of the section. In the upper part of the section, these yellowish buff coloured sandstone exhibit current ripple lamination, parallel lamination and large scale tabular crossbedding. Sinuous crested ripple marks are noticed on the bedding planes in the uppermost part of the section. All the aforesaid characteristics of the sediments represent intertidal sand flat deposits (Reineck and Singh, 1980, Klein 1980, Reading, 1981).

SOFT SEDIMENT DEFORMATION STRUCTURES

A variety of soft sediment deformation structures were observed and studied in the lower and middle part of Khari River section (Fig.2). Four types of soft sediment deformation structures namely slump folds, clastic dyke, syn-sedimentary faults and convolute bedding are seen in the Khari River section (Fig.2).

Slump Folds

Slump folding is developed in yellowish buff coloured coarse grained sandstone (Fig.3). The thickness of slump folded bed varies from 0.7 m to 1 m and the deformed bed pinches out towards east (Fig.3). It can be traced laterally for more than 8 m. The slump folded bed is underlain as well as overlain by undeformed beds (Fig.3). The individual

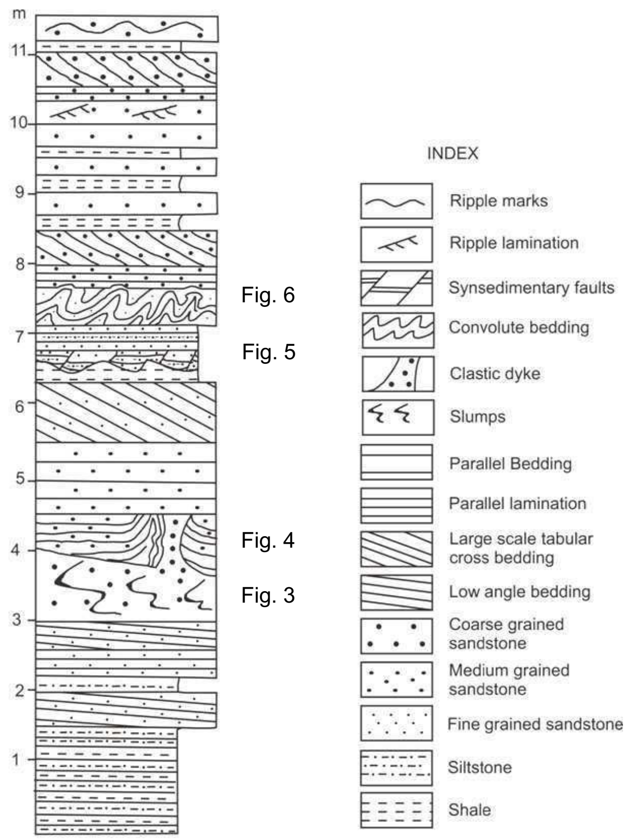

Fig.2. Lithosection of the Rudramata member, Jhuran Formation, Kutch basin.

Fig.3. Prominent horizon of slump folds underlain and overlain by undeformed beds.

layers are thrown into complex folds mostly isoclinals as well as overturned folds that consist of narrow anticlines and broad synclines, with inclined axial planes for anticlines (Fig.3). At places mushroom shaped anticlines are also noticed within these slump folds (extreme left part of Fig.3). Fold axes are mostly subhorizontal and are oriented in N-S direction. Some folds are 'U' shaped, broad, hinged folds with subvertical axial planes (cf. Tasgin and Turkmen, 2009). The limbs of one fold often continues with adjacent slumps fold and breached limbs are also common (Fig.3). Disruption within the folded layer is not uncommon within the slump fold (left hand part of Fig.3).

Clastic Dyke

Clastic dyke occur adjacent to slump folds (Fig.2). Clastic dyke occur as vertical sheet like body of sand that cuts across the overlying beds. It has a curvilinear form and can be traced vertically for more than 60 cm. The width of the clastic dyke varies from 6 cm to 15 cm. The dyke is made up of coarse grained grayish brown-buff coloured sandstone and truncates against the base of yellowish, yellowish brown coloured horizontal parallel bedded medium to fine grained sandstone (Fig. 4). The dyke thickens towards the top (Fig. 4) and exhibits layering that are parallel to the walls of dyke. Towards the left margin of clastic dyke, the laminae appear to bend from lower part becoming almost vertical in the middle part and pass into convolutions due to dragging in the uppermost part (Fig. 4).

Syn-sedimentary Faults

These structures are well exposed in vertical sections (Fig.5) and are about 1 m long and 20 cm thick within the interbedded reddish brown fine grained sandstone and yellowish – white siltstone. The interbedded sandstone and siltstones have sharp upper contact but their lower contact is irregular and loaded (Fig.5b). Lobes of sandstone sinking into underlying yellow siltstone and upwardly pushed siltstone lobes are seen. These syn-sedimentary faults are confined to lower part which is about 20 cm thick. There are five normal faults dipping 35°- 40° towards east (Fig. 5a). The fault planes are up to 10 cm in length, generally curved in nature, suggesting listric geometry, which dies out when traced towards left hand portion of Fig.5a. In general, the beds in the hanging wall are thicker than the beds in the footwall (central and right hand part of Fig.5a). Close-up view of syn-sedimentary faults exhibit displacement of interbedded sandstone and siltstone and related warping (Fig. 5b). All easterly dipping faults have eastern block

Fig.4. Clastic dyke terminating against overlying undeformed beds. Note the dragging of beds and internal lamination within the clastic dyke.

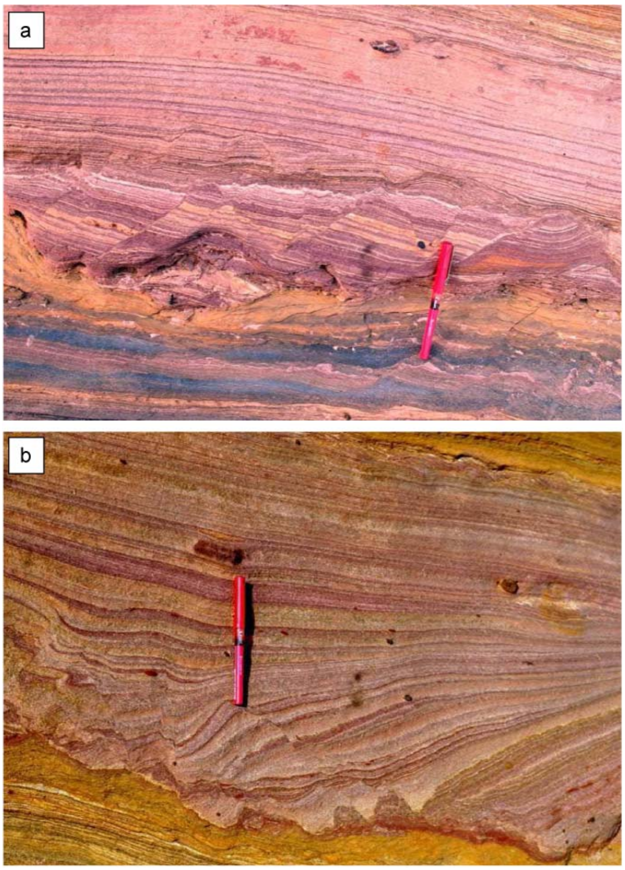

Fig.5. Field photographs showing syn-sediment microfaulting showing **(a)** horst and graben structures, and **(b)** undulatory loaded contact with underlying horizons.

downthrown, giving rise to step fault structure (Fig.5a). These easterly dipping faults are cut by three conjugate normal faults dipping 35° to 40° towards west. The westerly dipping faults have western block downthrown giving rise to small scale horst (central part of Fig.5a) and graben structures (right hand part of Fig.5a). These faults exhibit displacement varying from 0.5 cm to 5.5 cm. All the faults die out both in upward and down ward directions. Within the horst (right hand portion of Fig.5b) the beds are dragged in the upward direction and are probably related to liquefaction. Some of the faults pass into overlying horizontal parallel interbedded sandstone- siltstone and cause disruption particularly in the lower part (Fig.5a). The small scale faults are also seen to affect the upper layers of underlying carbonaceous shale-white siltstone laminations (Fig.5a).

Convolute Bedding

Convolute bedding is seen in the middle part of the section (Fig.2). It is developed in yellowish brown coloured fine grained sandstone (Fig.6a). It lies in the lower part of sandstone-shale intercalations (Fig.6a). Its thickness varies from 15 cm to 20 cm which tapers towards east and can be traced laterally for more than 2.5 m. Similar to that of slump folds, it is also overlain and underlain by undeformed beds (Fig.6b). The convoluted bed has planar lower contact and slightly undulatory, erosive upper contact (Fig.6a,b). Internally the convolute bedded fine grained sandstone consists of upright as well as overturned folds, the thickness of limbs being few centimeters. The laminations are thrown into small, narrow anticlines and broad synclines that die out in the upward direction (Fig.6b). The laminae are thin in anticlines and thicker in synclines. The axial planes of folds are haphazardly oriented (Fig.6b). The tops of convolutions particularly the anticlines are unbroken; intact hence represent metadepositional type of convolute bedding (Singh et al., 1993).

DISCUSSION

Soft-sediment deformation is the deformation that occurs in unconsolidated sediments, which usually occurs rapidly,

Fig.6. (a) Convolute bedding exposed in the upper parts of the Khari River section. **(b)** Close up of the same showing intricately folded layers.

close to the surface, during or shortly after deposition and before significant diagenesis; both in cohesive and noncohesive sediments (Lowe, 1975; Van Loon, 2009; Owen et al., 2011; Yong et al., 2013; Lee et al., 2014). Various terms have been used to propose this category of sedimentary structures viz. soft rock deformation, sedimentary deformational structures, penecontemporaneous deformation structures (Reineck and Singh, 1980), syn-sedimentary deformation (Patil and Kale, 2011), early diagenetic deformation, pre-lithification deformation or contorted bedding (Maltman, 1994a; Van Loon, 2009). Folding is typically most obvious of structures associated with deformation of poorly consolidated sediments (Woodcock, 1976 a, b, 1979; Maltman, 1984, 1994 a, 1994 b; Elliot and Williams, 1988; Collinson, 1994). Such soft sediment deformation gets facilitated by increase in pore fluid pressure which is responsible for reducing the shear strength of sediments (Maltman, 1994a, 1994b). Number of mechanisms, including seismicity; may result in local increase in pore pressure and hence trigger slumping (Alsop and Marco, 2011). Slump folds are considered to be formed by down slope movement of semi-consolidated sand layers over relatively more plastic layers under the action of gravity when the slope exceeds the angle of repose of sediment (Mills, 1983) or under the effect of large scale water movement (Siegenthaler et al., 1987) or sudden melting of buried ice in glacial outwash plains (Reading, 1981; Soman and Kale, 1993).

The sediments of Rudramata member of Jhuran Formation described in this study represents shallow marine deposits (Biswas, 1977, Patwardhan and Soman, 2004) thereby negating the glaciogenic origin of slump folds. The swaley crossbedding as well as hummocky crossbedding are not recorded in this sequence of sediments, hence possibility of development of these soft sediment structures due to storms is ruled out. Slumping of sediment within a particular horizon may happen due to earthquake (Ricci Lucchi, 1995; Shiki et al., 2000; Schnellmann et al., 2002). As the bedding planes in the sediments of Rudramata member are near horizontal, we consider that the original depositional attitudes of bedding planes are preserved. Hence, slumps formed due to slope induced slumping under the sole gravity pull; appears to be unlikely explanation for the observed slump folds (Upadhyay, 2001). Earthquake triggered slumping may take place on gentle slope with a dip as low as 0.25° where semi-consolidated strata may move *en masse* (Field et al., 1982; Kundu et al., 2011). The development of slump folds in the present study area is considered to be formed by fluidization of sediment under the influence of earthquake shocks (Field et al., 1982; Bhattacharya and Bandyopadhay, 1998; Moretti and Sabato, 2007; Koc Tasgin et al., 2011; Kundu et al., 2011; Alsop and Marco, 2011; Tucker, 2011; Perucca et al., 2014). The association of clastic dyke with slump folds in present case further supports shock induced mass flow in a plastic state (Kundu et al., 2011). Syn-sedimentary dyke are of two type's namely injected dykes that are emplaced from below and Neptunian dykes that are filled from above (Reineck and Singh, 1980; Montenat et al., 2007; Levi et al., 2006, 2008). The observed clastic dyke cuts across the upper boundary of deformed horizon and intrudes into the succeeding undeformed layers suggest its metadepositional nature. According to Mazumdar et al. (2006) such metadepositional deformational feature rarely get generated by causes other than earthquake shocks, although overpressure in the lower unit caused by rapid loading of sediments; can lead to the formation of injectitie (Hurst et al., 2011). Paranjape et al. (2014) reported the clastic injectities in the Terani Clay Member of Sivganga Formation of Cauvery basin, India, and correlated these to both syn-rift episodic seismicity and rapid loading of sediments as a consequence of high rate of sedimentation interpreted from ichnofauna present in the rocks. The clastic injection dykes are among the most impressive liquefaction features that form during strong (M $\geq$ 6.5) earthquakes (McCalpin, 1996; Levi at al., 2006). They form during fluidization of sediment when the source layer of dyke forming sediment is more permeable than the overlying sediment layer (Bhattacharya and Bandyopadhyay, 1998; Nichols, 2009). Escape pipes are fractures generated by brittle failure and fluidized sediment flows upwards through these pipes (Owen, 1995). The basal sand layer within which the root of dyke is situated becomes liquefied (Patil and Kale, 2011; Sukhija et al., 1999; Rodriguez-Pascua et al., 2000) and the fluid is separated from the sediment due to earthquake tremor (Montenat et al., 2007). When the pore water escape; pipes are filled by fluidized sediments and 'sedimentary dykes' develop (Mazumdar et al., 2009). The near vertical nature of the observed clastic dyke within horizontal strata suggests that dyke is perpendicular to the propagation of earthquake wave (Singh and Jain, 2007). The upward bending of confining lamination observed in the clastic dyke is further testimony towards the upward movement of sand and its origin related to liquefaction of basal saturated sand bed; triggered by seismic shocks (Audemard and De Santis, 1991; Obermeier et al., 1993; Berra F. and Felletti F., 2011; Rowe, 2013; Topal and Ozkul, 2014). The observed layering in the present case, parallel to wall of the clastic dyke; probably represents multiple intrusion of fluidized sediment.

The interbedded reddish brown fine grained sandstone and yellowish – white siltstone hosting the faults is overlain and underlain by undeformed sedimentary layers, indicating syn-sedimentary origin of faults (Seilacher, 1984; Owen, 1987; Montenat et al., 2007; Bahattacharya and Bandyopadhyay, 1998; Schneiderhan, 2008; Martin Chivelet et al., 2011; Koç Taºgin C. et al., 2011; Kundu et al., 2011; Patil and Kale, 2011; Dechen and Aiping, 2012). Seilacher (1969) first described such syn-sedimentary faults and considered them to be the result of sudden compaction due to seismic shaking. In these faults, the observed thicker beds in the hanging wall than the beds in footwall further substantiates that these faults are syn-sedimentary growth faults formed during deposition (Lee et al., 2014). According to Vanneste et al., (1999) and Singh and Jain (2007) such faults develop by earthquake shocks. The observed faults represent semi-brittle type of soft sediment deformation formed by an increase in pore pressure in the sediment due to instantaneous action of stress induced by seismicity (Anand and Jain, 1987; Miyata, 1990; Demoulin, 1996; Vanneste et al., 1999; Malgorzata and Piotr, 2013). These syndepositional growth faults are deformation band (Mollema and Antonellni, 1996; Eichhubl et al., 2010; Fossen, 2010). They form during the soft sediment deformation of fine sand during or shortly after deposition rather than tectonic deformation after deposition (Fossen, 2010).

Convolute bedding and /or lamination is related to fluidization-liquefaction event and a concomitant expulsion of pore water (Middleton and Hampton, 1973; Allen, 1977; Brenchley and Newall, 1977; Chakraborty, 1977; Reineck and Singh, 1980; Cojan and Thiry, 1992; Owen, 1996; Rossetti, 1999; Rossetti and Goes, 2000; Samaila et al., 2006). It is generally agreed that convolute bedding occurs in response with partial liquefaction and loss of strength in sediments associated with dewatering process (Lowe, 1975; Collinson, 1994). The most commonly invoked mechanism involves elevation of pore pressures in sediment layers; as this may occur during sudden episodes of consolidation (e.g. earthquake shaking) which results in loss of grain to grain contact, loss of strength and the overpressured sediment may then get liquefied. The absence of other dewatering structures such as dish and pillar structures in the studied section, suggests that movement of liquefied or fluidized sediment–water mixtures was the most common mode of dewatering rather than directly escaping water (McLaughlin and Brett, 2004). Though many mechanisms have been

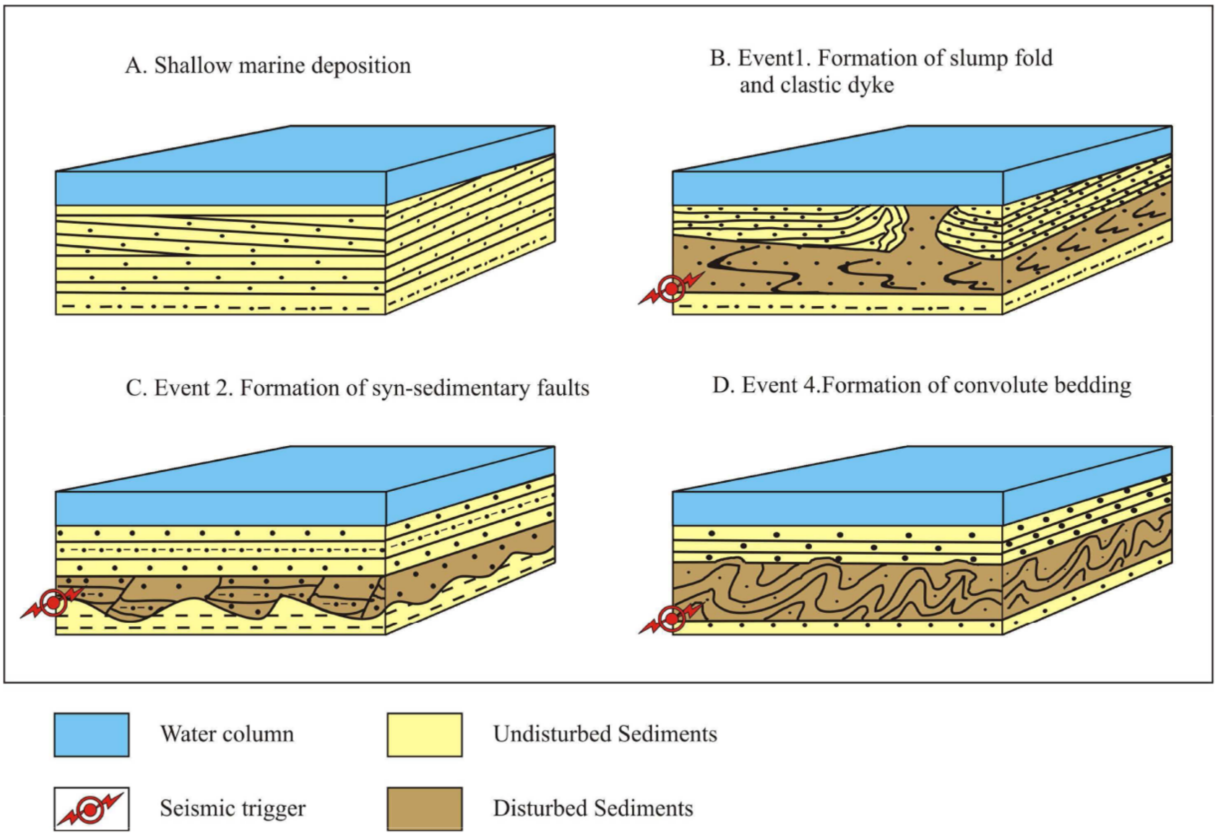

Fig.7. Cartoon depicting the stages in the development of soft sediment deformation from the Khari River section of Rudramata member, Jhuran Formation;, Kutch.

proposed for the formation of convolute bedding structure, earthquake is main factor responsible for the formation of convolute bedding (Yong et al., 2013). The observed co-occurrence of ductile deformation structures such as slumps, convolute bedding with brittle deformation features such as syn-sedimentary faults; can be attributed to changes in the stress rates determining the pore pressure within the sediments (Owen, 1987; Lee et al., 2014). The events leading to the formation of aforesaid soft sediment deformation structures in the Khari River section are depicted in Fig.7.

"Seismite" is the term coined by Seilacher (1969) to imply sediments deformed, deposited, slumped, or otherwise altered by earthquake waves and therefore are important as indicators of past seismic activity (Seilacher, 1984; Sims, 1973, 1975; Hempton and Dewey, 1983; Ringrose, 1989; Obermeier, 1996; Fortuin and Dabrio, 2008). Several workers viz. Sims (1975), Greb et al. (2002), Wheeler (2002) established the criteria for relating deformation structures with seismic events. The observed soft sediment deformation structures viz. slump folds, clastic dyke, syn-sedimentary faults and convolute bedding qualify the following criteria:

1. These occur in shallow marine sediments and have environmentally independent mechanism for their formation.
2. All these soft sediment deformation structures are invariably underlain and overlain by undeformed beds.
3. Slump folds can be laterally traced over a distance of 8 m while the clastic dyke, syn-sedimentary faults and convolute bedding has restricted vertical and lateral extent.
4. The lithosection belonging to Rudramata member of Jhuran Formation lies in close proximity of Kutch Mainland Fault (Biswas, 1987).

Hence, the observed soft sediment deformation structures are considered to represent "seismite". Several attempts have been done to relate magnitude of earthquake and formation of seismite (Atkinson, 1984; Ambraseys, 1988; Audemard and De Santis; 1991; Vittori et al., 1991; McCalpin, 1996). According to Atkinson (1984) and Audemard and De Santis (1991), earthquake of M 5 is the lowest which contributes to the probability of liquefaction; because earthquakes of magnitude <5 are not of sufficient duration to cause liquefaction. It is generally agreed that seismic activity of not less than 5.5 magnitudes on Richter scale can possibly be recorded in sediments as seismites (Ambraseys, 1988). Monecke et al. (2004) suggested that disturbed and convolute structures are generated by earthquakes when M = 5-5.5. Marco and Agnon (1995) documented that seismically related surface faults could be generated at magnitudes equal to or greater than 5.5.

The observed seismites exposed at different levels in the vertical section in the Khari River suggests episodic seismic activity of $M \geq 5.5$ (Seilacher, 1984, Ambraseys, 1988; Owen 1995; McCalpin, 1996; Bose et al., 1997; Mazumdar et al., 2006; Lee et al., 2014) experienced by the Kutch basin during the later part of Jurassic Period.

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