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Geomorphic Expressions of Active Strike-slip faulting (Girnar Fault), Saurashtra, Western India

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ABSTRACT
The Talala region of Saurashtra in Western India has been rocked by three moderate seismic events of Mw 4.8 (2007), Mw 5.0 (2007) and Mw 5.1 (2011). Despite several seismological observation, which hint at monsoon, triggered earthquake activity responsible for swarm type activity, the moderate events may have another causal mechanism. There is limited data available pertaining to geomorphic / surface expression of faults in the region, which is crucial for understanding the crustal deformation going on in this seismically active intraplate region. In present paper, we report the geomorphic evidences of active left-lateral strike-slip movement with presence of oblique slip component along a fault (Girnar Fault). The zone of the fault extends for about 60 km in length in NE-SW direction, nevertheless the seismological observations suggests seismicity is only restricted to a length of 40 km. The drainage network of Hiren and Shetrunji rivers show anomalous pattern inform of offset channel, deflected streams and straight channels, which are characteristic signatures of strike-slip faulting, apart from aligned drainages and linear valleys. Unpaired terraces presence in the study area indicates presence of dip slip component along the fault. Our results suggest, factors other than monsoon-triggered seismicity, are also present and active in the region, which might have played a role in causing moderate earthquakes.

Key words: Strike slip fault, Girnar Fault, Intraplate earthquake, Saurashtra, Geomorphic anomaly

INTRODUCTION

The Saurashtra region in western India (Figure 1) is considered as one of the seismically active areas experiencing high rate of intraplate seismicity (Yadav et al., 2011; Rastogi et al., 2013; Singh et al., 2013). Post 2001 Bhuj earthquake, the Saurashtra region has witnessed three moderate seismic events of Mw 4.8 (2007), Mw 5.0 (2007) and Mw 5.1 (2011) (Yadav et al., 2011; Rastogi et al., 2013; Singh et al., 2013). Apart from these moderate seismic events, the region is also experiencing swarm type activity, coincidently after heavy rains (i.e. post monsoon), which has led some to believe that the cause for this seismic activity is monsoon induced (Rastogi et al., 2013; Singh and Mishra, 2015). Yadav et al., (2011) studied the spatial-temporal properties and coulomb stress transfer assessment, where he observed the seismicity to be in NE-SW direction. Rastogi et al., (2013) studied the 2011 earthquake and reported activity along an ENE oriented 40 km long zone. On the other hand, Hainzl et al., (2015) advocated the reservoir-triggered mechanism as cause of the swarm type activity, but also cautioned that the pore pressure changes with depth were of first order approximation and there may exist other mechanisms, which may be responsible for these earthquakes. Most recently, Mahesh and Gupta (2016) studied the Vp/Vs ratios and observed the possibility of crystallized mafic magma at moderate depths that may be responsible for moderate earthquakes and these may be filling fluids to shallow depths, which might be linked to the swarm type activity. Despite these studies, there exist limited attempts or literature pertaining to surface faults and/or its expression in geomorphology (Gandhi et al., 2015). The aim of the present paper is to explore tectonically active geomorphic expression of Girnar Fault using remote sensing techniques.

GEOLOGY AND GEOMORPHOLOGY

The Saurashtra, a horst, mainly enclosed with Mesozoic and Cenozoic rocks is covered by Cretaceous rocks, followed by the Deccan Volcanics, Tertiary and Quaternary sediments (Merh, 1995). Geologically most part of the Saurashtra region covered by the Deccan traps of different phases (Merh, 1995) (Figure 1). The Mesozoic sediments are divisible in to two formations Viz., Wadhwan and Dhrangadhra Formation (Merh, 1995). These sediments are present in the NE part of the Saurashtra (Merh, 1995; Sharma et al, 2017). Tertiary sediments, Gaj and Dwarka Formations are restricted to the coastal areas in the fringed zone of Mesozoic sediments (Merh, 1995, Bhatt, 2003). Tertiary formations are mainly marine to fluvio-marine in origin, which is deposited all along the northern, south-western and southern coast (Merh, 1995). Quaternary sediments are well exposed and are deposited by marine as well as continental processes during Pleistocene and Holocene epochs (Merh, 1995; Bhatt, 2000). The middle

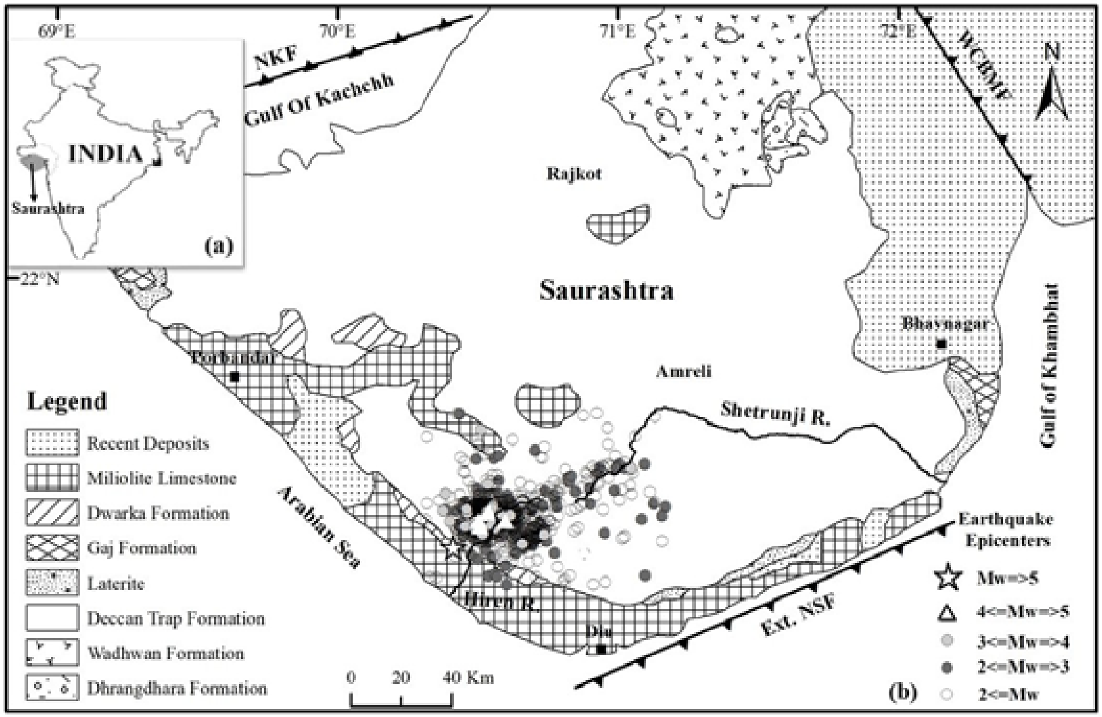

Figure 1. (a) Location map. (b) Geological map of the Saurashtra region and seismicity along Shetrunji and Hiren rivers. (ISR Catalogue 2006-2016). (Modified after Merh, 1995).

Pleistocene sediments - Miliolite Formation is the most striking deposits of Saurashtra, which is unconformably overlie the Tertiary Formations (Merh, 1995). The coastal Miliolite has both marine and aeolian origin, whereas the fluvially reworked Miliolite are found along the river channels (Merh, 1995; Bhatt, 2003). The recent deposits of Saurashtra comprise tidal-flat sediments, unconsolidated sands of present day beaches and fresh water alluvial sediments of major rivers viz., Bhadar, Ojat and Shetrunji Rivers (Merh, 1995; Sharma et al., 2017).

Geomorphologically, Saurashtra shows rocky tilted tableland, which is surrounded by the coastal plains. The centre part of the Saurashtra region shows zigzag outline and rugged topography considerably dissected by various rivers. Overall rivers of Saurashtra region flow out in all directions and exhibit radial pattern. Eastern side of the Saurashtra, which is split up from the Gujarat Mainland in the form of low-lying ground. This low-lying ground is seen as a saline wasteland, marshes and lakes (Merh, 1995). Northern boundary is marked by gulf of Kachchh and west and south boundary is marked by Arabian Sea (Figure 1) (Merh, 1995).

The present study area lies within two fluvial systems, Shetrunji River and Hiren River, where the Gir ranges act as a drainage divide between these two river systems (Figure 2). Gir Range is low mountain range present in the central part of the Saurashtra, is an extremely rugged mountain range with a steep slope towards the south and a gentle slope towards north. Shetrunji R. and Hiren R. systems are perennial and ephemeral in nature respectively. Both the river systems originate from the Dhundhi hills of Gir ranges to flow in the north-easterly and south-westerly directions respectively. The Deccan trap is dominating lithology in the upstream part of both the river systems, which is hilly terrain for both the fluvial systems. Rivers have developed piedmont surfaces along the slopes of the hills, which comprises of rocky clast of basaltic rocks. This is covered by the alluvial surfaces in the lower reaches. Alluvium surfaces are present in the form of valley fill as well as flood plain deposits along the river channels. Sandy beaches and mudflats are present at the mouth of the both the river systems.

Seismotectonics of Saurashtra

During the Late Cretaceous-Tertiary rifting of Narmada basin in the south, the second stage of Cambay rifting and tectonic inversion of Kachchh were responsible for the separation of the Saurashtra block as a horst surrounded by paleo-rifts (Biswas, 1987). These horst and graben structures were formed by reactivation of Precambrian basement trends, NNW-SSE and ENE-WSW (Naini and Kolla, 1982, Biswas, 1987). Geodynamically, the Saurashtra has considered as a seismically moderately active region of Gujarat and falls in the seismic zone III and IV of the seismic zoning map of Bureau of Indian Standards (BIS, 2002).

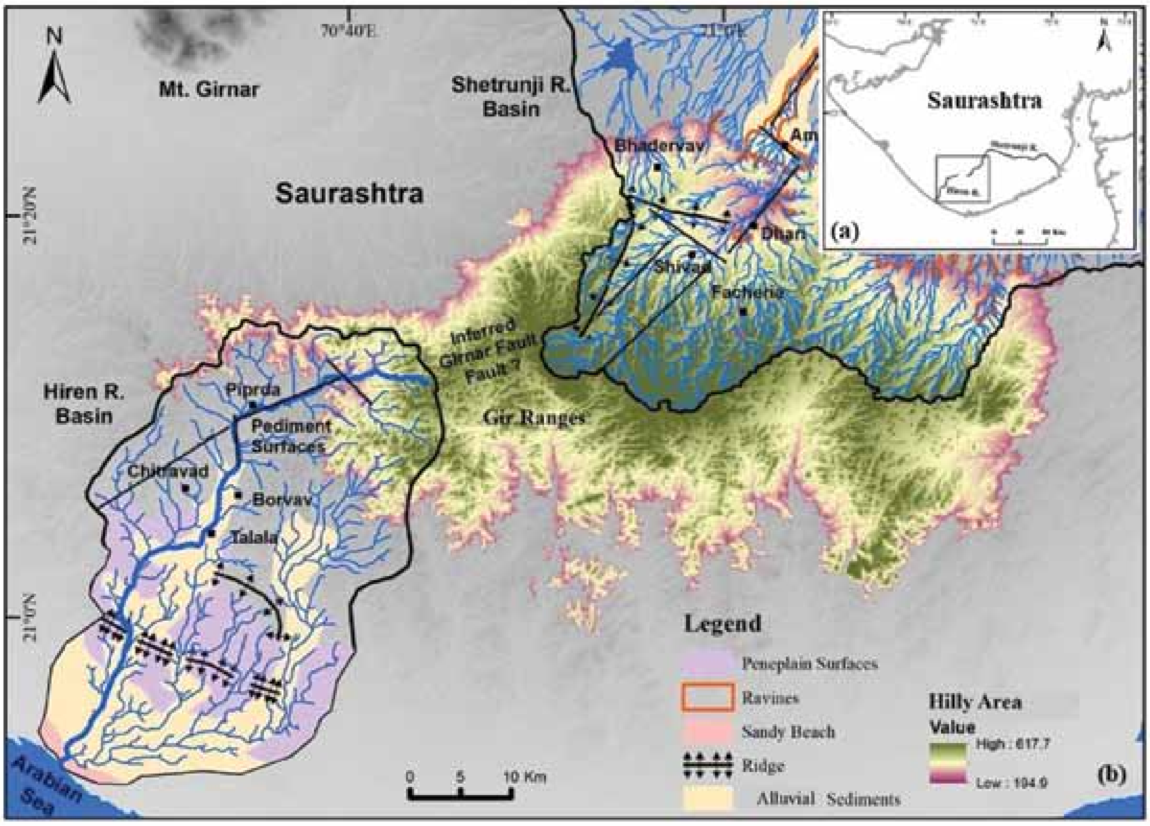

Figure 2. (a) Shows location of the study area (b) Geomorphological map of the study area with probable zone of Girnar Fault.

No major fault systems are present/have been reported, within the Saurashtra Peninsula. However, Saurashtra peninsula is bounded by the major faults namely, North Kathiawar Fault (NKF) to the north, extension of the Narmada Son Fault to the south and the West Cambay Fault System to the east (Figure 1) (Biswas, 1982). The Saurashtra region has witnessed of increasing earthquake activity in the recent past, such as 1872 Bhavnagar (M_w 5), 1883 Bhavnagar (M_w 4.4), 1886 Jamnagar (M_w 4.4), 1887 Rajkot (M_w 4.4), 1891 Amreli (M_w 4.4), 1919 Ghogha (M_w 5.7), 1938 Botad (M_w 5), 1940 Jamnagar (M_w 5), 2007 Talala (M_w 5.0) and 2011 Talala (M_w 5.1) (Bhattacharya et al., 2004, Rastogi et al., 2012; Singh et al., 2013; Mahesh and Gupta, 2016).

Several geophysical studies have been carried out in the Saurashtra region such as gravity and magnetic, which shows that NE-SW, ENE-WSW to E-W, NW-SE and N-S to NNE-SSW trends, as predominant in the entire Saurashtra region (Mishra et al., 2001). NE-SW and E-W structural trends are dominating in eastern Saurashtra (Mishra et al., 2001). Bhonde and Bhatt (2009) studied the joint pattern of the coastal landscape of Saurashtra, which suggest NE-SW pattern is most prominent and is the maximum horizontal compressive stress direction for the Indian subcontinent.

The Talala region of Saurashtra Peninsula situated in the centre part of the Hiren R. basin and 40 km SW from the Shetrunji R. basin. Talala is the main epicentral zone of 2007 (M_w 5.0, M_w 4.8) and 2011 (M_w 5.1) earthquakes. Previous study by using seismological datasets suggest that, these earthquakes occurred along the left-lateral strike-slip component (Yadav. et al., 2011, Rastogi et al., 2012). The aftershock events of 2011 earthquake at Talala region occurred along a 40 km long ENE to NE trending Girnar Fault (ISR Annual Report, 2011) and also its seismological evidence also shows left-lateral strike-slip fault which suggested that the region is neotectonically active (Singh et al., 2013) Mahesh and Gupta (2016) argued that the NNE-SSW trending faults were activated immediate after 2001 Bhuj earthquake (M_w 7.7), because of the stress perturbations.

METHODOLOGY

We used ASTER dataset having vertical resolution of 1arc second to generate a DEM of 30 m resolution. This data set was verified using Survey of India Toposheets of 1:50,000 scale (i.e. ~ 20 m resolution). The datasets were then analysed in ArcGIS 10.4 software on WGS-1984

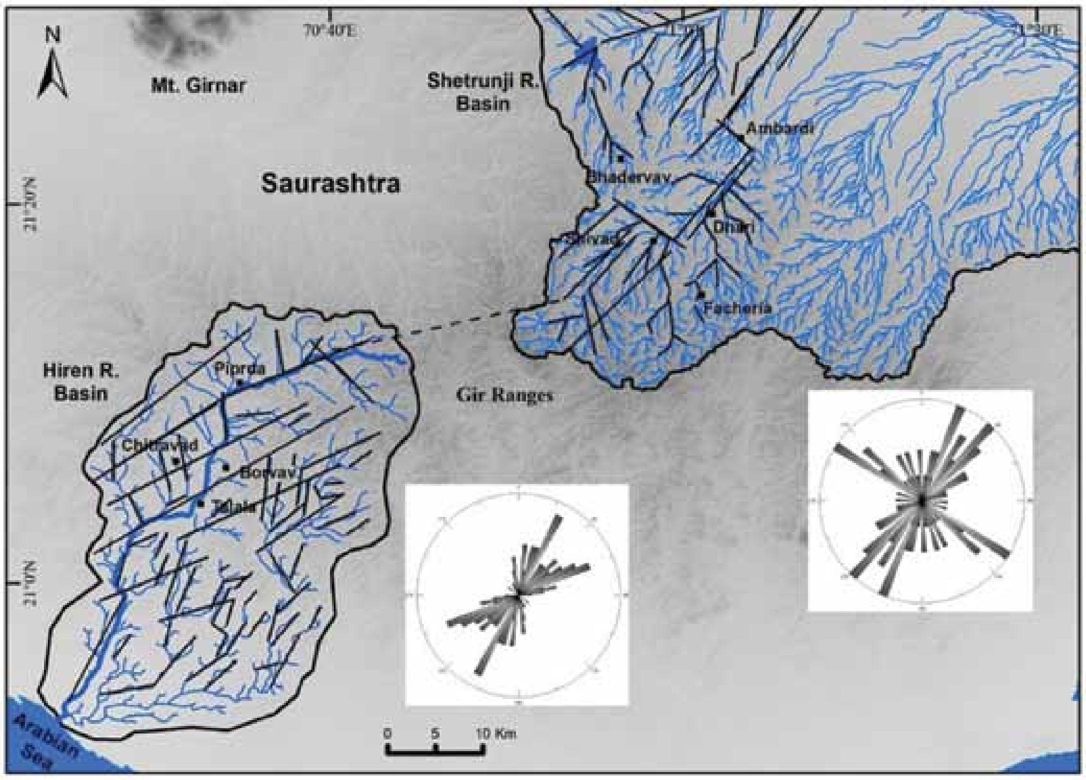

Figure 3. Lineament analysis along Shetrunji and Hiren river basins and rose diagram of those azimuthal distribution.

datum. The drainage network and contours was extracted on Global Mapper-18 for further analysis, which includes Drainage anomaly and lineament study along the probable zone of Girnar Fault.

RESULTS

Lineament Analysis

Lineament analysis of Hiren R. and Shetrunji R. basins were carried out by using ASTER DEM data in combination with Google earth imageries and Survey of India Toposheets. Lineaments were marked based on orientations of straight channel courses, offset in ridges, tonal contrast, deflection in streams and structural alignments. Azimuthal distribution of each lineament plotted as a rose diagram, the main peak of which shows the dominant orientation of lineaments in particular segment.

Girnar Fault mainly passes through the upstream part of the both the river basin, which is mostly covered by the Deccan trap rocks. Therefore, the drainage density in the upstream part is higher as compared to the lower reaches. In the Hiren R. and Shetrunji R., lineaments exhibit mainly three orientations ENE-WSW, NE-SW and NW-SE (Figure 3). Higher order streams reflect the NE-SW trend in both the river basins. Lower order streams reflect very complex orientations. Tributaries of Hiren R. shows NW-SE and NE-SW orientations in the right and left part respectively. With respect to Shetrunji R. basin, tributaries mainly reflect NE-SW orientations. E-W, ENE-WSW and N-S oriented ridges of igneous intrusive bodies are also present in the study area.

Drainage Pattern and Anomaly

Drainage pattern provides clues to *underlying* structure and to the chronology of events (Ouchi, 1985; Twidale 2004). Slope induces the formation of patterns such as parallel, radial and distributary, while structurally controlled regions produces straight, angular, trellis and annular arrangements (Twidale, 2004). Shetrunji R. and Hiren R. flow through two major lithology Deccan Trap and Quaternary sediments. Both the fluvial systems show parallel to sub-parallel and trellis drainage pattern in its upland part. Parallel drainage pattern usually develops in 1) uniform lithology in regional slope direction, 2) Parallel fault system and 3) due to presence of lineaments (Twidale, 2004; Raj, 2007), i.e. faults or fractures. In the eastern side of the Hiren R. drainage basin shows angular drainage pattern. The rivers and its tributaries adjusted with respect to slope and structure due to any catastrophic event such as climatic and tectonic, which is reflected as drainage

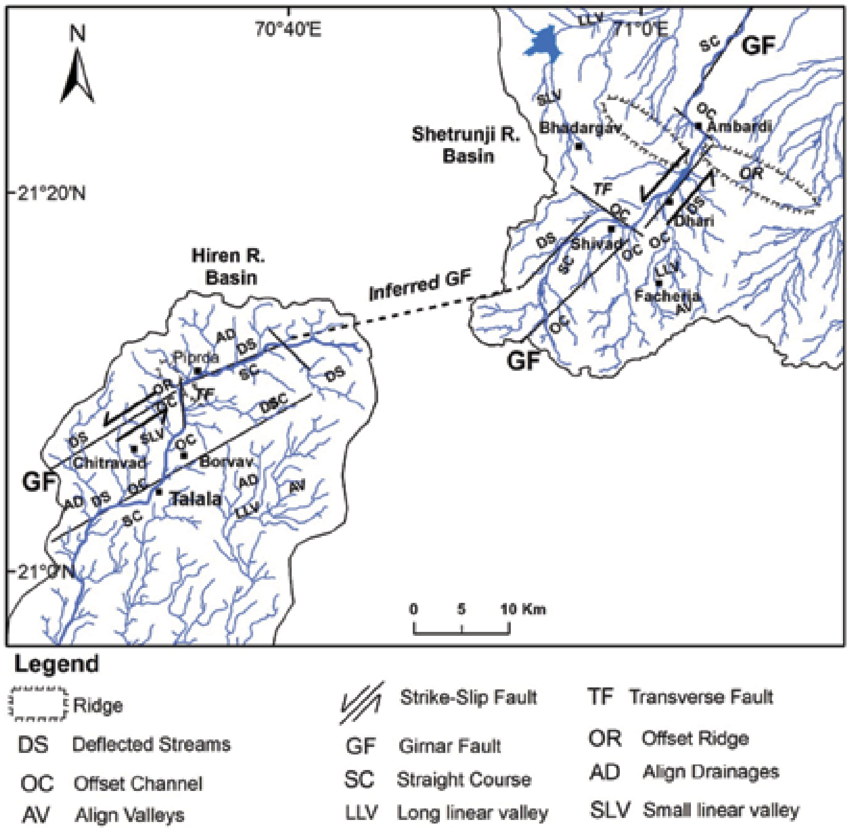

Figure 4. Drainage pattern illustrating sense of movement along the Girnar Fault.

deflection, offsetting or incision (Twidale, 2004). Such climatically governed and tectonically enhanced feature are well preserved in dry land system of western India. These landforms are Deflection Stream (DS), Offset Channel (OC), Small and Long Linear Valleys (SLV, LLV), Aligned Valley (AV), and Aligned Drainage (AD). We have analysed these landforms in study area along drainage network and extracted lineaments (Figure 4).

Hiren River as well as tributaries of all orders shows abrupt change in course along lineaments throughout along the Girnar Fault. All the drainages of Hiren R. from SW of chitravad to Piprda in NE show a deflection in streams under the influence of lineaments. Offset in channel present near Piprda, Borvav and Talala region, which is very well seen in the data along the NE-SW and NW-SE oriented lineaments. Near Bhalchhel, identified the offset in ridge due to NE-SW oriented lineaments. Straight channel courses up to few meter to kilometres is very well preserved in the river basin. Conventionally, Long Linear Valleys (LLV) are formed due to continual movement along the fault which crushes the rock and become more liable to erosion; streams try to flow along this zone of weaknesses and flow some distance along these valleys (Twidale, 2004). LLV is observed eastern side of the Talala region. SLV are observed in those regions where the bedrocks are highly fractured and weathered in nature. More specifically the strength of fractured and weathered rock is very low. However, erosive power of streams increases within the less resistive rocks, which causes river/stream to develop in linear pattern. SLV are preserved near the Chiravad village. Conventionally the AV and AD are associated with head ward erosion within the contractional overstep of a strike-slip fault (Keller, 1986; Raj, 2007). AD and AV are observed in the NW and SE part of the Hiren R. basin. Shetrunji River channel as well as tributaries up to 5^{th} order streams show abrupt deflection (DS) along the lineaments which are lying in NE-SW direction. Major tributaries and associated streams in the upstream part flows in a NW direction and as these stream approaches towards NE-SW oriented Girnar Fault between Shivd and Dhari shows deflection. LLV are observed in the northern part where tributaries flows parallel to a NE-SW oriented lineament. Small Linear Valleys (SLV) are observed in the central part of the segment near the Bhader Gav. The north-easterly flowing streams show a prominent Offset Channel (OC) along E-W trending fault/lineament, near Ambardi village. However, small-scale offset of tributaries have been observed between Facharia and Ambardi villages along E-W and NW-SE oriented faults/lineaments. Near Facharia and Bhader Gav localities SSW oriented Align

Valleys (AV) and Align Drainages (AD) have been observed. Offset in ridge is also observed between Dhari and Ambardi due to NE-SW oriented lineament along the trunk channel.

DISCUSSION

The studies pertaining to relationship between channel orientation and tectonics are still limited. (Ciccacci et al., 1986, Lupia Palmieri et al., 1998, Beneduce et al., 2004, Hodgkinson et al., 2006, Raj, 2007; Ribolini and Spagnolo, 2008). The study area shows very well geometric relationship between drainage style and lineaments in mainly three directions, viz. NE-SW to NNE-SSE, E-W and NW-SE. The NE-SW and NNW-SSE orientations are manifestation of the Aravalli and Dharwarian trend of the Precambrian orogeny (Biswas, 1987). The Girnar Fault mainly passes through the upland part of the both basins (i.e. Shetrunji and Hiran Rivers), orientated in NE-SW trend. These basins reflect parallel to sub-parallel drainage pattern without any lithological change, most likely due to presence of fracture/liniments present in the region i.e. Girnar Fault. Tricart (1974) discussed the offsetting in river channel due to the effect of faults. Several workers used offsetting in channels, deflected streams and displaced terraces and ridges as a tectonic landform to understand strike-slip movements of the fault (Sieh and Jahns., 1984, Gaudemer et al., 1989, Hubert-Ferrari et al., 2002, Lin et al., 2002b, Raj, 2007; Singh, 2014). We have also marked lineaments (E-W, NW-SE, NNW-SSE) which cut the drainage networks and deformed their course in few centimetre scale to few kilometre scale which are discussed as OC, DS, LLV and SLV, AD and AV which clearly indicate that Girnar Fault exhibits left-lateral strike-slip movement, which is also hinted by seismological observations (Singh et al., 2013).

Offsetting in Channel (OC) and Offsetting in Ridge (OR)

The activity of the strike-slip faults can be seen in the form of the Offset Channels (OC). In OC, stream flows in a particular direction and then sudden change occurred due to influence of faults in its course. In Hiren R. basin near Borvav and Talala region biggest offset in channel observed in trunk stream which is due to NE-SW oriented Girnar Fault. Offset in ridge is also observed near the Piprda due to NE-SW oriented Girnar Fault. In the SW corner of the Shetrunji R. trunk stream as well as tributaries of lower order flows in a NNE direction and sudden takes turn in SE direction like near Shivad under the influence of NW-SE oriented lineament/fault which is called an Offset Channel (OC). Trunk stream of Shetrunji R. flows in a NNE direction near Dhari village, in a straight course for up to ~ 11.5 km, then takes 90° turn near Ambardi and flows parallel to the E-W oriented lineament/fault for ~ 3.5 km distance. Its biggest offsetting found in Shetrunji R. basin. After that trunk stream, follow its original trend. Apart from this at many places, we have observed offsetting in streams due to presence of E-W, NE-SW and NW-SE oriented lineament/faults. One E-W oriented ridge is also displaced near northern side of the Dhari, which directly indicate that this fault is left-lateral strike-slip fault. We have also observed unpaired terraces near Ambardi, which also indicate that it has oblique slip movement.

Deflection in Streams

Abrupt deflections of streams along a main lineament are synchronous with strike-slip movements (Raj, 2007). Streams naturally tend to gravitate towards the regional flow direction to meet trunk stream but due to any processes, which causes obstacle/topographic barriers in river path, it tries to cut that barrier if it has a sufficient charge it incised the barriers otherwise it follows that barriers (lineaments) which is deflection from its original course direction (Keller and Pinter, 1996). Hiren R. under influence of the Girnar Fault from south of the Chitravad to north up to Piprda shows deflection. Near Talala and upland part towards Shetrunji R., tributaries flowing in a SE direction also deflected due to NE-SW oriented lineament/ Girnar Fault. In Shetrunji R. basin, streams which are in the eastern part with respect to trunk stream flowing in a SE to NW direction and sudden NE-SW deflection marking the influence of the lineaments, which is clearly visible at and around Dhari village. We have marked major deflections at many places along the NE-SW oriented lineament due to fracture and joint patterns, which is clearly visible in satellite data.

Linear Valleys

Linear valleys are a long narrow depression, developed along the fault zones (Keller and Pinter, 1996); however, it can be also generated along alternate layers of different rock type or different beds of tilted same rock type. These often developed because continued movement along fault traces crushes the rock, making it more vulnerable to erosion. Streams commonly follow these zones of weakness and flow some distances along the through (Keller and Pinter, 1996). The development of linear valleys up to scale of few kilometres in bedrock terrain is often related to presence of faults (Twidale, 2004; Raj, 2007), which we have marked as a Long Linear Valley (LLV). Small Linear Valleys (SLV) are formed due to exploitation of fractures by weathering and erosion (Twidale, 2004; Raj, 2007). LLV are present in the tributaries of both the river basins. In Hiren R., near Talala region we have seen LLV and within Shetrunji R. basin, in the NW corner, its tributaries where linear valleys are oriented in an ENE to WSW direction with a straight course up to few kilometres, which gives direct relation to subsurface structure. SLV are also present in both the river basins along the fractures and joints.

Align Valleys (AV) and Align Drainages (AD)

Linear Valleys are also marked as an Align Valleys (AV) and Align Drainages (AD) if they are aligning in a one particular direction. In Shetrunji R. basin, AV and AD are observed in the 1st to 3rd order streams at the SE corner and in the central part where they align in the NW-SE to NNW-SSE direction. In Hiren R., we have also observed AV and AD along the proximal zone of Girnar Fault.

CONCLUSIONS

Based on lineament and drainage pattern analysis following are the significant findings of the study

1. Presence of landforms such as offset of drainages, deflection of streams, linear drainages, and straight courses in the vicinity of Girnar Fault zone illustrates the influence of Girnar Fault in the fluvial sequences.

2. The NE-SW trending Girnar Fault extends for about 60 km in length, based on geomorphic expression of landforms such as drainage offset, deflected streams, offset in ridge and unpaired terraces illustrates a left-lateral Oblique slip motion.

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Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

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