Correlation between Joint Strikes and Stream Orientation in Seismically Active Regions: A Case Study Near 2001 Bhuj Earthquake Zone, Gujarat, India

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Abstract: Stream bearing is thought to be affected by active tectonics, such as earthquakes. To explore this, this study focuses on the analysis of structural data, specifically joint strikes and stream bearings, in relation to the affected area near the 2001 Bhuj earthquake, Gujarat, India. The topography of the study area, structure, and lithology were considered as the influencing factors in the formation of streams. The software GEOrient and ArcGIS 10.5 were utilized to extract and analyze streams from the SRTM image. The orientations of different order streams extracted using ArcGIS were correlated with the joint data collected from outcrops exposed in the study area. The data, including stream and joint orientations, were used for plotting rose diagrams. The results revealed the predominant orientations of streams for different orders, as well as the predominant joint strike orientation. The study found that all stream orders are in conformity with the predominant joint orientation. Within a 30° angle on either side of the joint orientation, the consistent pattern of streams indicates a direct correlation between joint orientation and stream flow direction. This suggests that the geological structures influence both lower-order and higher-order streams, especially in areas prone to recurring earthquakes of moderate magnitude. The findings highlight the significance of considering geological structures when studying stream flow patterns and their relationship with deformation generated due to seismic activity.
Keywords: Stream, Joint, Earthquake, Bhuj, Gujarat.

Introduction

The 2001 Bhuj earthquake, also known as the Gujarat earthquake, was a major seismic event that occurred on January 26, 2001, in the Kachchh region of Gujarat, India. It had a moment magnitude (Mw) of 7.7 and a focal depth of 22 kilometers (Gupta et al., 2001). Longitudinal and some transverse faults near the Kachchh Mainland Fault (KMF), responsible for the Bhuj earthquake, which are the resultant product of convergence between the Indian and Eurasian Plates in the Kachchh region (Biswas and Khattri, 2002; Mandal et al., 2004). Those faults had not been previously identified and mapped before the earthquake, which made unexpected and devastating events. Following the earthquake, extensive geological studies were conducted to understand the tectonic and geological aspects of the Bhuj earthquake (Bendick et al., 2001; Biswas and Khattri, 2002; Mandal et al., 2004; Mandal and Dutta, 2011). Stream orientation modification, new joints, faults, folds, or topographic structures have been developed due to post-seismic activities after this major event (Sohoni and Karanth, 2003; Maurya et al., 2003; McCalpin et al., 2003; Maurya et al., 2017). More than 30 earthquakes of magnitude greater than 4.0 have occurred in the study area since the major event of 2001 (ISR, 2020). In the context of the Bhuj earthquake, there may be some indirect relationships between stream order and the seismic event. The earthquake caused widespread damage to the region's infrastructure, including the disruption of river systems. The intense ground shaking and subsequent surface effects, such as ground deformation and landslides triggered by the earthquake, could have impacted the stream order and morphology of rivers in the affected area. These changes in river systems could have resulted from seismic activity, which has not been explored yet. This study focuses on the joint analysis with respect to the drainage system, examining its characteristics in the earthquake-prone area of the Bhuj region. The generation and modification of the drainage system in relation to this major event are discussed and interpreted. In this study, the orientation of joints in relation to the order of the drainage system has been presented and discussed, regardless of the timeline of drainage modification and joint system development. The relationship between the orientation of joints and the order of the drainage system has been analyzed.

Lithology and Geomorphology of the study area

The region affected by the Bhuj earthquake is characterized by geologically complex tectonic activity. The Indian Plate is subducting beneath the Eurasian Plate, leading to the development of the highly active and seismically hazardous Himalayan and Indus-Tsangpo tectonic belts (Chakrabarti, 2016; Valdiya and Sanwal, 2017; Roy and Purohit, 2018). However, the Kachchh region, located further south, experiences different tectonic processes.

Researchers have proposed the classification of Jurassic rocks in Kachchh into four groups: Patcham, Chari, Katrol, and Umia, based on field observations (Stoliczka, 1871; Waagen, 1875; Nath, 1932; Fürsich et al., 2001). The study area primarily consists of Mesozoic rocks, with a particular focus on the Katrol Formation, which spans the Upper Jurassic to the Lower Cretaceous periods. This formation is characterized by burrowed sandstone, shale rich in mica and gypsum, limestone containing fossils, marl, and clay. Adjacent to the Katrol

Formation is the Bhuj Formation, which belongs to the Cretaceous period. It is composed of feldspathic and ferruginous sandstone, ironstone, kaolinitic clay, pyritous and carbonaceous shale, as well as marine and plant fossils. The Chari Formation, from the Middle to Upper Jurassic, is found in an elliptical shape at four locations. Its lithology includes gypsiferous shale, ferruginous and calcareous sandstone, ferruginous limestone, and oolitic limestone (Fig. 1).

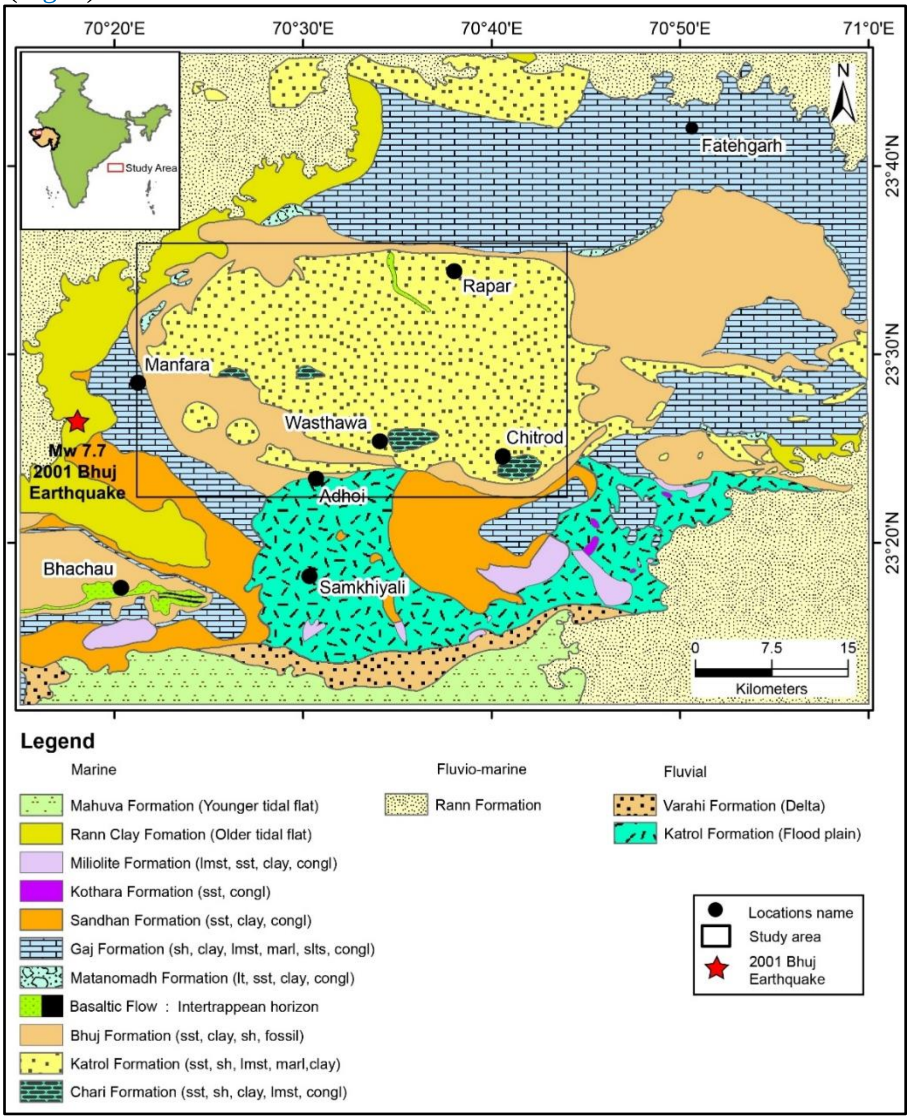

Fig. 1. Geological map of the study area (after GSI, 2003). Inset: Location map of the study area in India. Star mark (red colour) is the epicenter of the 2001 Bhuj earthquake.

Within the study area, the sedimentary units primarily display a horizontal to sub-horizontal topography, indicating a general quaquaversal dip of up to 10 degrees. This dip pattern suggests the presence of domal structures. However, as indicated by Biswas (1981), it is important to note that steeper dips can be observed in proximity to the faults found in the region. The structural highs within the area exhibit elongated patterns, creating antiformal geometry in certain locations. In the central portion of the Wagad Highland, the beds tend to dip sub-horizontally. Towards the western region, the dips predominantly face westward, while in the northern part, a northerly dip is observed. The eastern section displays an easterly dip, while the southern part showcases a southward dip.

The topography of the region is characterized by undulations, featuring curved hills, domal uplands, and hillocks. The elevation within the area varies, with the highest point in the northeast reaching 222 meters, and the lowest point on the southern side, measuring 1 meter. The western, northern, and southern sides of the area are bordered by flat regions, while the eastern side displays slight undulations with small mounds. Within the highland, there are six primary river systems: The Adhoi River, Bhimguda River, Chang River, Khari River, Kersi River, and Narelawali River (Fig. 2). The central part exhibits a dendritic drainage pattern, although higher-order streams display rectangular drainage at various locations (Fig. 2). The Chitrod dome demonstrates a radial pattern. On a regional scale, the drainage pattern primarily follows a radial arrangement, indicating a domal shape for the Wagad highland. However, the presence of fault-controlled drainage systems disrupts this pattern. The Chang River and Khari River flow in the WNW-ESE direction, while the Adhoi River and Narelawali River follow the SSW-NNE directions (Fig. 2).

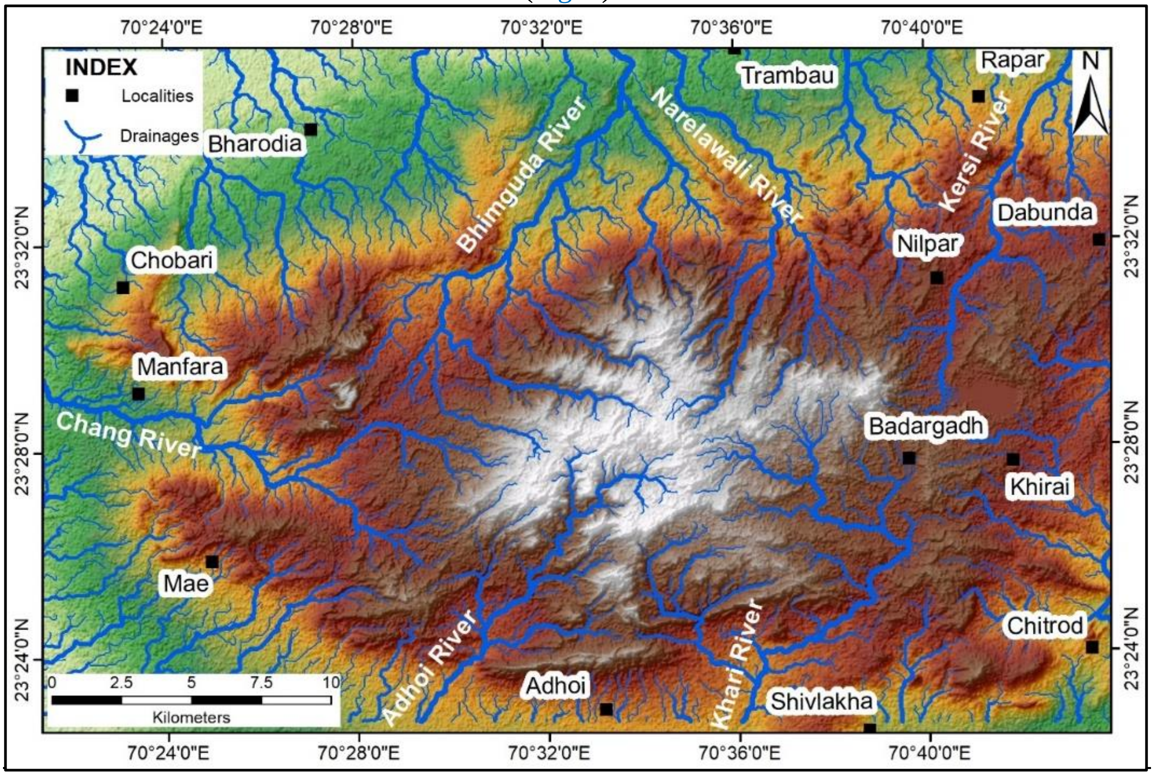

Fig. 2. Drainage map overlaid on SRTM 30-meter hill shade image of the study area (present work).

Methodology

The work utilized the software GEOrient to plot structural data, specifically in relation to joint strikes and stream bearings (Holcombe, 2012). To extract and analyze the streams from the SRTM image, the process was conducted in ArcGIS 10.5 as depicted in Figure 3. Firstly, different order streams were extracted, and their orientations were added to the attribute by using the add geometry tool. Secondly, the stream orientation data were correlated with the joint data that were being collected from the study area. It should be noted that streams are not straight-line features, as their formation is influenced by the topography, structure, and lithology of the study area. To determine the bearing of the streams, the outlet and inlet points of each stream were connected, and their bearings were recorded in an Excel sheet. The stream-bearing calculations were automated using the data management tool within the ArcGIS software, following the described process in Figure 4.

The data, including stream orientation and joint orientation, was exported to an Excel sheet and imported into the GEOrient environment. Rose diagrams were generated using this data, representing the streams. Additionally, joint data collected in the field was also plotted on the rose diagram. The GEOrient software followed a specific data format, as illustrated in the flow diagram (Fig. 4), to ensure accurate plotting of the data. Subsequently, the stream orientation and joint orientation data were correlated, as depicted in Figure 5.

Qualitative analysis of the stream orientation

Stream extraction was performed in the study area using the SRTM 30m resolution image, focusing on medium stream density. In accordance with Figure 3, five orders of streams were generated using ArcGIS. The results of this process yielded a total of 946 first-order streams, 225 second-order streams, 56 third-order streams, 14 fourth-order streams, and a single fifth-order stream. Analysis of the data revealed that the predominant orientation of the first-order stream is 345° (Fig. 5a). For the second, third, and fourth-order streams, the primary orientations were observed to be 015°, 005°, and 335°, respectively (Fig. 5b, c, d). There was only one fifth-order stream with an orientation of 25°.

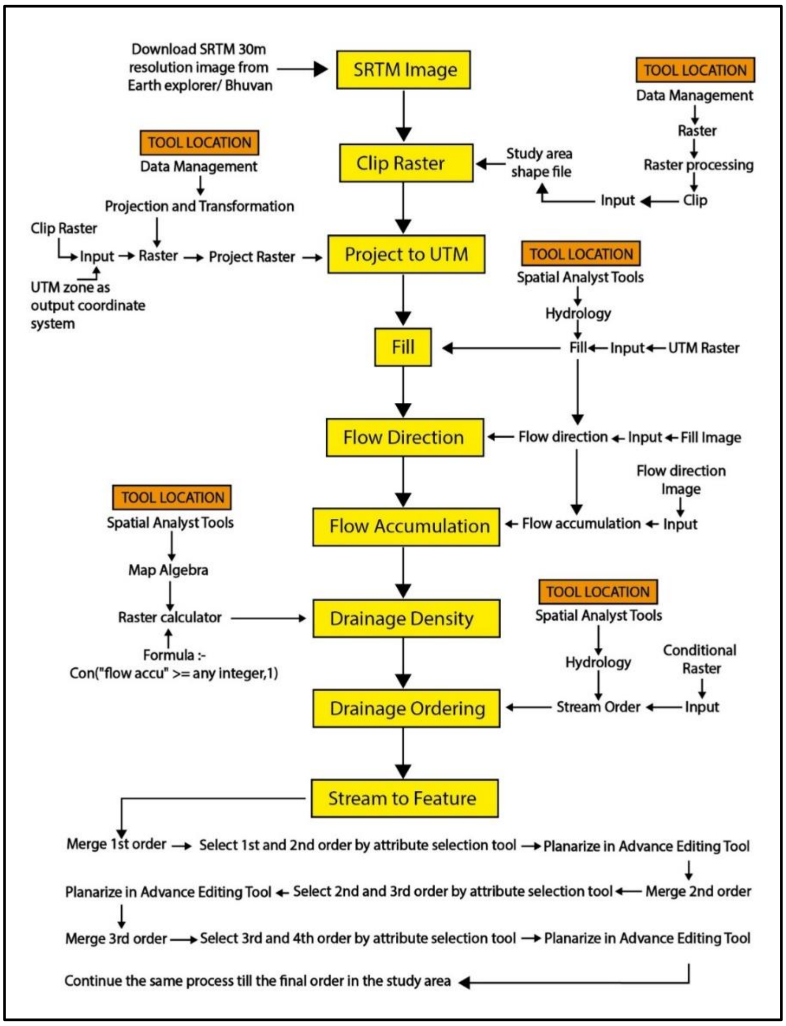

Fig. 3. Diagram showing the process of extraction of a different order of streams from SRTM image in ArcGIS.

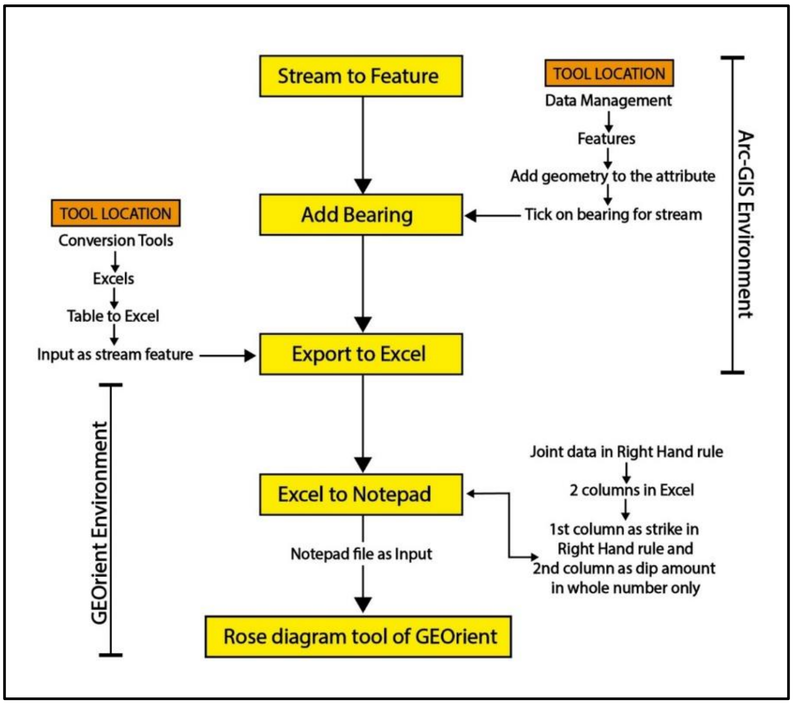

Fig. 4. Diagram showing the process of generating rose diagram from GEOrient software and adding bearing to the streams in ArcGIS.

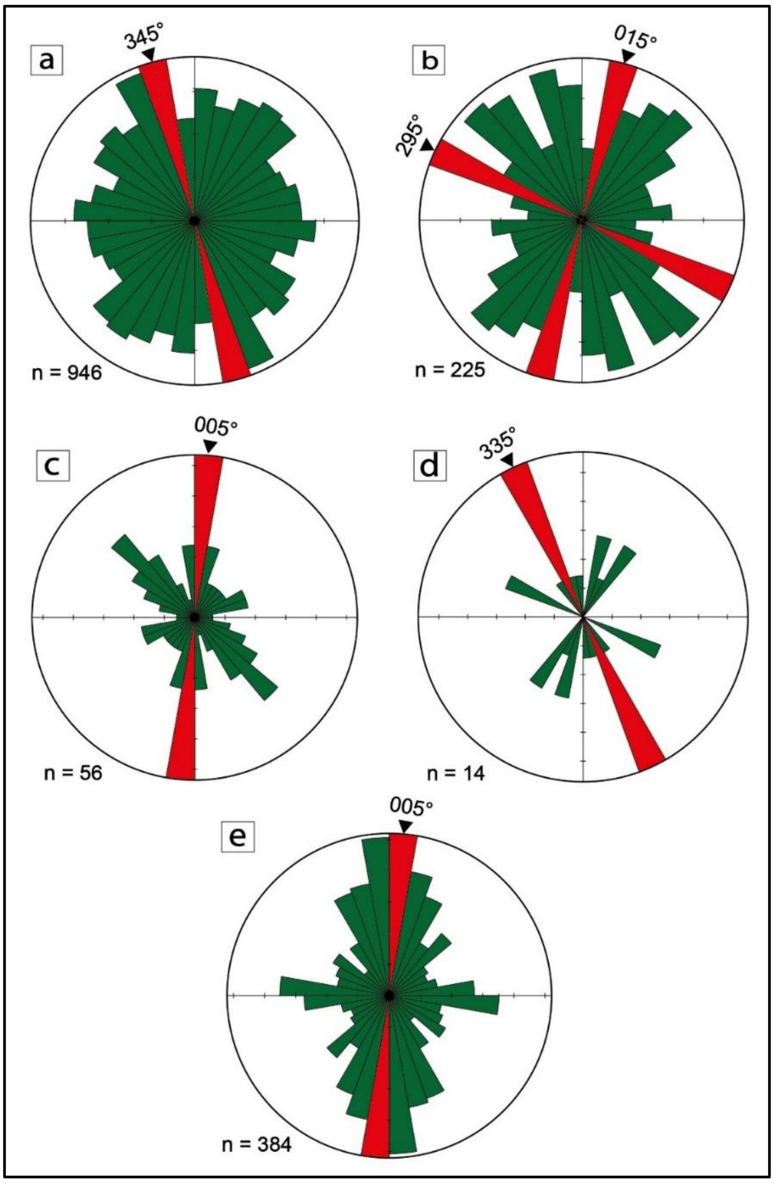

Fig. 5. Rose diagram showing the major orientation of the streams, with red colour showing the major orientation. a) Rose diagram of 1st order stream. b) Rose diagram of 2nd order stream. c) Rose diagram of 3rd order stream. d) Rose diagram of 4th order stream. e) Rose diagram of joints.

Qualitative analysis of the joint orientation and its relationship with streams

The joint data reveals a predominant strike orientation of 005° (Fig. 5e). The orientation of 1st order streams is deviated by 20° from the joint strike. Similarly, one of the orientations of 2nd order streams is deviated by 10°, while the other is 70°. The 3rd order stream aligns with the joint strike. A 30° difference is observed in the orientation of 4th order streams, and the 5th order stream deviates by 20° from the joint strike.

Interpretation

The investigation into how geological structures influence the course of stream flow is most effectively studied in basins devoid of weathering mantles and sedimentary fills (Bannister, 1980). Typically, in a given region, smaller streams align with the orientation of joints (Centamore et al. 1996). However, in the study area, it was noted that all stream orders conform to the predominant joint orientation, i.e., 005°. This suggests that if an area is subjected to recurring earthquakes of moderate magnitude, such as Mw ≥ 4.0, not only will lower-order streams be influenced by the geological structure but higher-order streams as well. Moreover, a noteworthy observation was made that streams falling within a 30° angle on both sides of the 005° joint orientation demonstrate a uniform pattern. This finding further underscores the direct correlation between joint orientation and the direction of stream flow.

Conclusions

Finally, GEOrient and ArcGIS10.5 software were used in this study to investigate the impact of geological structures on stream flow direction. The analysis revealed that in the study area, all stream orders aligned with the prevailing joint orientation of 005°, indicating a direct correlation between geological structures and stream flow. Furthermore, streams within a 30° angle on both sides of the 005° joint orientation exhibited consistent flow patterns, emphasizing the influence of joint orientation on stream direction. These findings highlight the significance of considering geological structures when studying stream dynamics. By understanding the relationship between geological structures and stream flow, this study provides valuable insights into landscape dynamics and stream systems. The findings suggest that moderate-magnitude earthquakes can impact both lower and higher-order streams, emphasizing the need to consider geological structures in hydrological and geological investigations. Further research in different geological settings can expand upon these findings and deepen our understanding of the mechanisms driving stream flow patterns. Overall, this study contributes to our knowledge of the complex interplay between geological structures and stream dynamics, offering implications for various fields, including hydrology and geoscience.

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References

Bannister, E. (1980). Joint and drainage orientation of SW Pennsylvania. Zeitschrift für Geomorphologie, pp.273-286.

Bendick, R., Bilham, R., Fielding, E., Gaur, V.K., Hough, S.E., Kier, G., Kulkarni, M.N., Martin, S., Mueller, K. and Mukul, M. (2001). The 26 January 2001 “Republic Day” earthquake, India. Seismological Research Letters, v.72(3), pp.328-335.

Biswas, S.K. and Khattri, K.N. (2002). A geological study of earthquakes in Kutch, Gujarat, India. Geological Society of India, v.60, pp.131-142.

Biswas, S.K. (1981). Basin framework, paleo-environment and depositional history of the Mesozoic sediments of Kutch basin, western India. Quarterly Journal of the Geological, Mining and Metallurgical Society of India, v.53, pp.56-85.

Centamore, E., Ciccacci, S., Del Monte, M., Fredi, P. and Palmieri, E.L. (1996). Morphological and morphometric approach to the study of the structural arrangement of northeastern Abruzzo (central Italy). Geomorphology, v.16, pp.127-137.

Chakrabarti, B.K. (2016). Geology of the Himalayan belt: deformation, metamorphism, stratigraphy. Elsevier.

Fürsich, F.T., Pandey, D.K., Callomon, J.H., Jaitly, A.K. and Singh, I.B. (2001). Marker beds in the Jurassic of the Kachchh Basin, western India: their depositional environment and sequence-stratigraphic significance. Journal of the Palaeontological Society of India, v.46, pp.173-198.

GSI (2003). Geological Quadrangle Map: Anjar Quadrangle, Gujarat; Geol. Surv. India, Kolkata.

Gupta, H.K., Harinarayana, T., Kousalya, M., Mishra, D.C., Mohan, I., Rao, N.P., Raju, P.S., Rastogi, B.K., Reddy, P.R. and Sarkar, D. (2001). Bhuj earthquake of 26 January, 2001. Geological Society of India, v.57, pp.275-278.

Holcombe, R. (2012). GEOrient, structural geology and mapping software, Holcombe Coughlin and Associates Australia. http://www.holcombe.net.au/software/rodhsoftware_georient. htm.

ISR (2020). Annual Report (2018-19). Indian Seismological Research, Department of Science and Technology, Government of Gujarat.

Mandal, P. and Dutta, U. (2011). Estimation of earthquake source parameters in the Kachchh seismic zone, Gujarat, India, from strong-motion network data using a generalized inversion technique. Bulletin of the Seismological Society of America, v.101, pp.1719-1731.

Mandal, P., Rastogi, B.K., Satyanaraya, H.V.S., Kousalya, M., Vijayraghavan, R., Satyamurty, C., Raju, I.P., Sarma, A.N.S. and Kumar, N. (2004). Characterization of the causative fault system for the 2001 Bhuj earthquake of Mw 7.7. Tectonophysics, v.378, pp.105-121.

Maurya, D.M., Chowksey, V., Tiwari, P. and Chamyal, L.S. (2017). Tectonic geomorphology and neotectonic setting of the seismically active South Wagad Fault (SWF), Western India, using field and GPR data. Acta Geophysica, v.65, pp.1167-1184.

Maurya, D.M., Thakkar, M.G. and Chamyal, L.S. (2003). Implications of transverse fault system on tectonic evolution of Mainland Kachchh, western India. Current Science, pp.661-667.

McCalpin, J.P. and Thakkar, M.G. (2003). 2001 Bhuj-Kachchh earthquake: surface faulting and its relation with neotectonics and regional structures, Gujarat, Western India. Annals of Geophysics, v.46, pp.937-956.

Nath, R. (1932). A contribution to the stratigraphy of Cutch. QJ Geol. Min. Metall. Soc. India, v.4, pp.161-174.

Roy, A.B. and Purohit, R. (2018). The Himalayas: evolution through collision. Indian Shield. Amsterdam: Elsevier, pp.311-27.

Sohoni, P. S. and Karanth, R. V. (2003). Jointing and fracturing characteristics of Central Kachchh Mainland, Kachchh, Western India. Journal of Geological Society of India, v.61, pp.673- 684.

Stoliczka, F. (1871). On some Tertiary crabs from Sind and Kutch. Memoirs of the Geological Survey of India, Palaeontologica Indica, v.1, pp.1–16.

Valdiya, K.S. and Sanwal, J. (2017). Neotectonism in the Indian Subcontinent: landscape evolution. Elsevier.

Waagen, W. (1875). Jurassic fauna of Kutch. Palaeontologia Indica. Geological Survey of India, Memoir, v.9, p.247.

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