Structural Geological Field Guide: Bhuj Area (Gujarat, India)

Nidhi Lohani, Soumyajit Mukherjee, Seema Singh, Aashu Pawar, and Mohamedharoon Shaikh

Abstract The Kachchh offshore being a petroliferous basin of great prospect, knowing the tectonics of the Kachchh offshore as well as the land region is of great attention for geoscientists. The present study put forward a composite picture of various features like faults, local folds associated with faults, shear bands etc. from the Kachchh land area, which is expected to (i) provide insights into the different structural aspects of the most tectonically active segment of Katrol Hill Range Fault Zone (KHRFZ) and, (ii) provide possible mechanism of present day structural set up of the region.

1 Introduction

Tectonics of the W-striking Kachchh Rift Basin (KRB), located in the state of Gujarat on the western continental margin of the Indian plate, has been a place of enormous national and international attention for the geoscientists from academia and industries (Biswas & Khattri, 2002). The KRB rifted in the Late Triassic or Early Jurassic, before India-Africa separation, causing extensional stresses and continual sedimentation until the Late Cretaceous (Biswas, 2016). As a response, the W-striking major faults were activated as normal faults, following the structural trend of the Mid-Proterozoic Delhi-Aravalli fold belt (Biswas, 2016). The rifting of the KRB then ceased during the Late Cretaceous, and the Indian plate began to drift counter-clockwise from the Mid-Jurassic Period onward (Biswas, 2016). Rifting of the KRB was followed by rift

N. Lohani · S. Singh · A. Pawar
Department of Geology, Panjab University, Chandigarh 160014, India

S. Mukherjee (✉)
Department of Earth Sciences, Indian Institute of Technology Bombay, Powai, Mumbai, Maharashtra 400076, India
e-mail: smukherjee@iitb.ac.in

M. Shaikh
Department of Geology, Faculty of Science, The M. S. University of Baroda, Vadodara, Gujarat 390002, India

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inversion since the Late Cretaceous, leading major intra-basinal faults to reactivate as reverse faults (Biswas & Khattri, 2002; Shaikh et al., 2020).

The Nagar Parkar Fault (NPF) to the north and North Kathiawar Fault (NKF) to the south serve as rift shoulders that separate the KRB from the rest of the landmass (Biswas, 2016). The tectonic framework of the KRB is governed by W-striking intra-basinal faults—Island Belt Fault (IBF), Gedi Fault (GF), Allah Bund Fault, South Wagad Fault (SWF), Kachchh Mainland Fault (KMF) (> 1200 m throw) (Padmalal et al., 2019, 2021; Shaikh et al., 2019) and Katrol Hill Fault (KHF) (~732 m maximum throw) (Maurya et al., 2021a). These major faults have formed large-scale uplifts produced by extension during rifting phase of the KRB (Late Triassic to Early Jurassic)—Island Belt Uplift (IBU), Desalpar Uplift (DU), ~60 km long and ~40 km wide Wagad Uplift (WU), ~193 km long and ~72 km wide Kachchh Mainland Uplift (KMU) (Biswas, 1993).The Northern Hill Range Fault Zone (NHRFZ) along the KMF, Katrol Hill Range Fault Zone (KHRFZ) along the KHF, Vigodi-Gugriana Khirasra-Netra Fault System (VGKNFS) and Bhuj structural low are the four structural zones that make up the KMU (Biswas, 1993; Shaikh et al., 2020). Based on recent seismicity data recorded for all the earthquakes that have occurred in the KRB, all the intra-basinal faults can be classified as neotectonically active.

There is another category of structure that can be equally important to the regional structural geology as it is to the seismicity of the KRB. These are the N-, NW-, NE-, NNW- and NNE-striking, m- to km-scale, transverse fault system with dip-/oblique-slip, which affected and segmented the W-striking major intra-basinal faults in the KRB (Biswas, 1993; Maurya et al., 2003, 2021b; Shaikh et al., 2020). Transversse faults are important since (i) prior research has reported periodic reactivation of these faults to accommodate the growing compressive stresses on W-striking faults (Maurya et al., 2003); (ii) they offset and change the structural attitude of many intra-basinal faults, therefore are an integral part of the KRB (Biswas, 1993; Shaikh et al., 2020); (iii) KRB is a petroliferous basin and transverse faults might give rise to various types of petroleum traps (Wilcox et al., 1973).

The KRB and Himalayan mountain belt are the most tectonically and seismically active regions of India, and they fall in the highest seismic risk zone-V. Previous workers have reported transverse faults from the Himalayas: for example, the Siwaliks and the Lesser Himalayas as well as the Sikkim Himalayas (Paul et al., 2015), where they have been related to the displacement of major faults and seismicity. Previous workers have reported transverse faults from various parts of the KRB: for example, Shaikh et al. (2020) documented NW-, NE- and E-striking unnamed transverse faults with dip-slip/oblique-slip in the NW-striking VGKNFS. They extend for tens of meters to a few kilometers before dying out or truncating in the deformation zone of major NW-striking faults (Shaikh et al., 2020). Maurya et al. (2003) reported transverse faults that offset two major intra-basinal faults of the KMU—the KMF and KHF. These faults have been mostly deciphered using field observations, ground-penetrating radar (GPR) surveys, landscape and drainage characteristics. Previous workers have discussed reactivation and subsequent geomorphic expressions of the transverse faults in various parts of the KRB (e.g., Maurya et al., 2003; Patidar et al., 2007; Sohoni et al., 1999; Thakkar et al., 1999). However, very limited structural documentation from field has so far been made (Dasgupta & Mukherjee, 2019).

The primary aim of the present study is to report detailed field-based structural information near the Bhuj city. This site is ideal for carrying out structural studies because: (i) the transverse faults dissect and displace the KHF, which is one of the neotectonically active element of the region; (ii) in a recent study carried out on the basis of quantitative geomorphic parameters and field evidences the KHF, which is dissected into five segments by such transverse faults have been assigned values based on their tectonic activity (Das et al., 2019). The present area of study is one of the most active segments of the KHF.

Another aim of the present study is to carry out sedimentological studies because the selected outcrop consists of sandstone-shale sequences of Lower Cretaceous Bhuj Formation. Such sedimentological studies in conjunction with structural studies shall be helpful in knowing the overall structural disposition and deposition of sandstone units within the Formation.

2 The Study Area

2.1 Structure

The study area is located along the W-striking KHF in the central part of the KMU. Tectonically, KHRFZ lies parallel to one of the most important structural element of the KRB, the W-striking KHF. The KHF is an intra-basinal range-bounding fault that separates the KMU into two divisions– hilly topography of the Katrol Hill Range Fault Zone (KHRFZ) in the south and the low-relief rocky plain to the north comprising Late Cretaceous Bhuj Formation (Biswas, 1993; Maurya et al., 2016). The ~71 km long KHF as first described by and later on by many other researchers (Chung & Gao, 1995; Morino et al., 2008; Singh et al., 2014) is a south dipping, high-angle fault with reverse slip-sense (Biswas, 1993). It has a single, well exposed, sub-vertical fault plane, which forms a sharp boundary between the Jurassic (Jhumara) and the Cretaceous (Bhuj Formation) rocks (Biswas, 2016). The fault strikes $\sim$ E-W but at places it is NWW-SEE due to the effect of several transverse faults that dissect it. Biswas (2016) described KHF as a post-rift fault as it has no direct relation with the syn-rift sediment accumulation. It activated after the inversion phase during Early Eocene (Maurya et al., 2016) along a primordial fault.

Based on detailed field mapping and GPR studies, Patidar et al., (2007, 2008) divided the KHF into four segments. These segments of different lengths show different degree of tectonic activity and are bounded by transverse faults that offset the KHF (Patidar et al., 2007). Out of these four segments, segment 2 and 3, which make up the central part of the KHRFZ are most tectonically active. The eastern delimiting transverse fault of segment 2 is the basis of present study (F2 in Fig. 2c). The exact coordinates of the field location are—23° 14′ 38.228″ N latitude and 69°

Fig. 1 Google earth image of the study area enclosed within the yellow box. Inset image *a:* study area enclosed in a rectangle on the map of India. Red triangle: KodkiDeriwada Ganesh temple

35′ 8.286″ E longitude and it lies near the Bhuj city (Fig. 1). Walid et al. (2021) has studied vein geometries in detail from our study area, but the work seems to have a limited tectonic significance.

2.2 *Seismicity*

The KRB is seismically very active (Zone 5, according to BIS, 2002) and is a high risk potential zone outside Himalayas in India. Inside the KRB, it is reported that the frequency of small (M_w < 4.0) to large (M_w > 6.0) earthquakes occurring near the KHRFZ is higher than the other parts of the KMU (Fig. 2c). A recent major earthquake of Mw ~6.0 recorded along the KHF was the Anjar earthquake of 21 July 1956 (Chung & Gao, 1995) (Fig. 2b). Prior studies have attributed the high seismicity and tectonically active nature of the region to the growing N-S compressive stresses due to the northward movement of Indian plate under the Eurasia. Previous researchers have reported that the E-W trending intra-basinal faults accumulate a major part of the growing compressive stress by vertical movements. In such a case the offsetting of these major faults by transverse faults becomes very significant (Maurya et al., 2016). Several workers suggest that a part of these growing stresses is transferred to these transverse faults and this might be the key reason for the present seismicity of the region (Maurya et al., 2016).

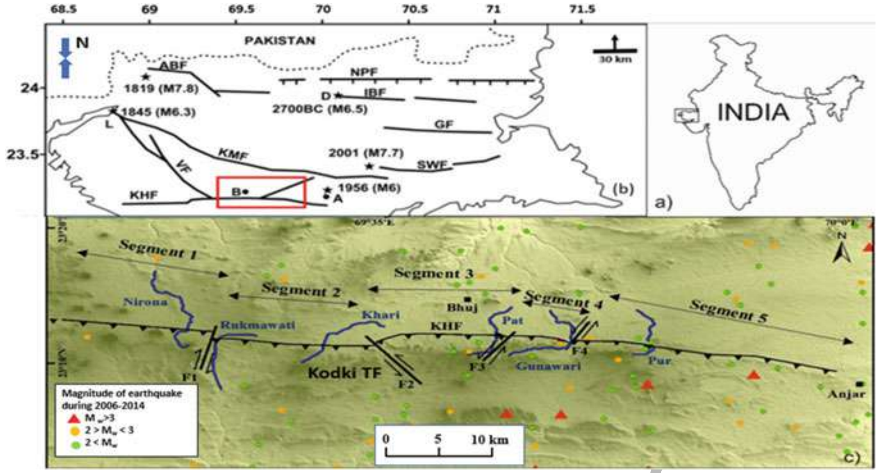

Fig. 2 **a** Map of India shows the study area in Kachchh. **b** Tectonic map of Kachchh showing major faults and associated epicenters of major earthquakes (Rastogi et al., 2014). Red box: study area. Blue arrow at top left: N-S compressive stresses acting in the region (World stress map, 2016). **c** Modified DEM of study area along with major fault segments, drainage and seismicity during the period 2006–2014 (ISR earthquake catalogue) (Das et al., 2019). The Kodki transverse fault (TF) or F2 is the area of present study

2.3 Lithology and Stratigraphy

The entire Mesozoic sequence except the Jhurio Formation is exposed in the Mainland Kachchh along the KHF. Stratigraphy of the Kachchh mainland has been discussed in detail by Biswas (2016) (Table 1).

The present study conforms to a field location where only the Lower Ghuneri Member of Bhuj Formation is exposed, therefore only Bhuj Formation has been discussed in the next section.

2.3.1 Bhuj Formation

The thickness of Bhuj Formation is 815 m and is completely siliciclastic, typical of a rift environment (Biswas, 1993). It deposited in the last phase of rifting of a pericratonic rift basin that originated from the disintegration of Gondwanaland in the Late Triassic (Biswas, 1977, 1987, 2005). The western exposure of Bhuj Formation is unanimously accepted to be of deltaic nature, however the nature of Bhuj sediments in the eastern part of its exposure has been debated. Biswas (1977) suggested a complete fluvial nature. On the other hand, entirely marine nature of sediments was suggested by other group of researchers (Casshyap et al., 1983; Krishna et al., 1983; Rai, 2006); Shukla & Singh, 1990.

Table 1 Updated and modified lithostratigraphic classification of the Mesozoic rocks of Kachchh

Stage	Kutch mainland group	
Tertiary	Formation	Member
Maastrichtian-Danian	Deccan traps	Basalt flows
Albian	Bhuj formation	Upper member: massive sandstones
Aptian		Ukra member: green glauconitic shale/ferruginous bands with fossil
Hauterivian to Barriasian		Ghuneri member/lower member Sandstone/shales/ferruginous bands/shales with plant fossils
Tithonian	Jhuran formation	Katesar member: massive sandstones
Kimmeridgian		Upper member: fossiliferous sandstones, shales, hard calcaereous sandstones
		Middle member: mainly shales, fossilferous with sandstone interbeds
		Lower member: sandstones/shales/arenaceous limestones with fossils
Oxfordian	Hiatus	
Callovian	Jumara formation	Dhosa Oolite member
		Gypseous shale member
		Ridge sandstone member
		Shelly shale member
Aalenian-Bathonian	Jhurio formation	Member G: thin bedded White Lst& Nod. Lst
		Member F: purple sandstones/packstones
		Member E: bedded rusty grainstone with golden oolite
		Member D: grayshales
		Member C: brick red weathering rusty grainstone with golden oolites
		Member B: grayshales
		Member A: thin bedded yellow white limestones, shales, rusty brown limestones with golden oolites Basement

The member written with bold letters constitutes the present area of study (after Biswas, 1977, 1993; Deshpande and Merh, 1980; Furisch et al., 2001; Krishna et al., 2009)

The Bhuj Formation is bounded by Deccan traps of Tertiary age (Biswas, 1977) on its upper side and it sits over an entirely marine Jhuran Formation of Jurassic age. The age of the Bhuj Formation is Lower Cretaceous (Valenginian to Santonian). It is further subdivided into three members: (i) Lower Guneri Member, (ii) Middle-Ukra Member (limited to Guneri-Ukra area) and (iii) Upper Member.

3 Field Studies

The study area comprises sandstone-shale sequences of Lower Cretaceous Bhuj Formation. Normal faults are one of the most common structural features observed in the study area. The entire study revolves around a fault-controlled ridge that has an exposed section of a major NNE-striking transverse fault, which dissects the KHF. It is a high-angle fault of normal slip-sense, which we refer to as Kodki Fault in this study. Figures 3 and 4 depict the fault exposures on the Bhuj-Kodki road.

3.1 Small-Scale Faults

The classic Kodki normal fault has already been reported by several authors (Kundu and Thakkar, 2011; Thakkar et al., 2017).Numerous small-scale normal faults were also observed near the main fault in the Bhuj Formation, which are reported here (Figs. 5, 6, and 7).

Although less common in the study area, few reverse faults in the vicinity of classic transverse fault of normal nature were also noted.

According to Anderson's theory of faulting a conjugate set of faults is X-shaped wherein the maximum compressive stress axis (σ_1) makes an angle of ~30° with the faults. Here, the maximum compressive stress axis bisects the acute angle, and the minimum compressive stress axis (σ_3) bisects the obtuse angle whereas the intermediate stress axis (σ_2) lies parallel to the line of intersection. Figure 8 shows an example of Andersonian conjugate strike-slip faults.

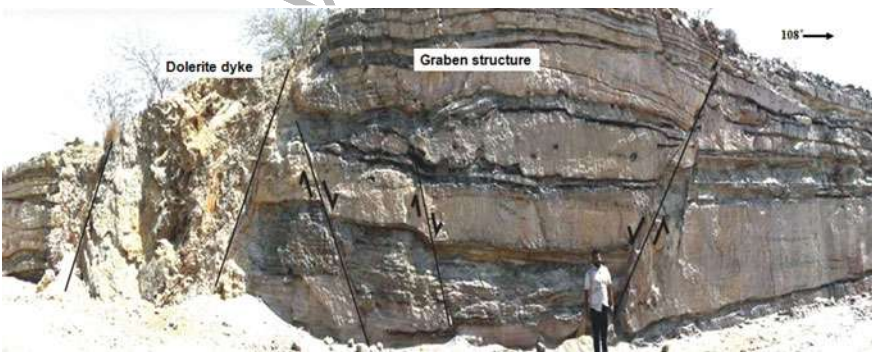

Fig. 3 Vertical section of the Kodki Fault in the Early Cretaceous Bhuj sandstone, depicting agraben structure. Location: 23°14′ 38.228″ N, 69°35′ 8.286″ E

Fig. 4 Vertical section of a normal fault in sandstone-shale sequence of Lower Bhuj succession. S. Mukherjee as scale. Location: 23°14′ 38.228″ N, 69°35′ 8.286″ E

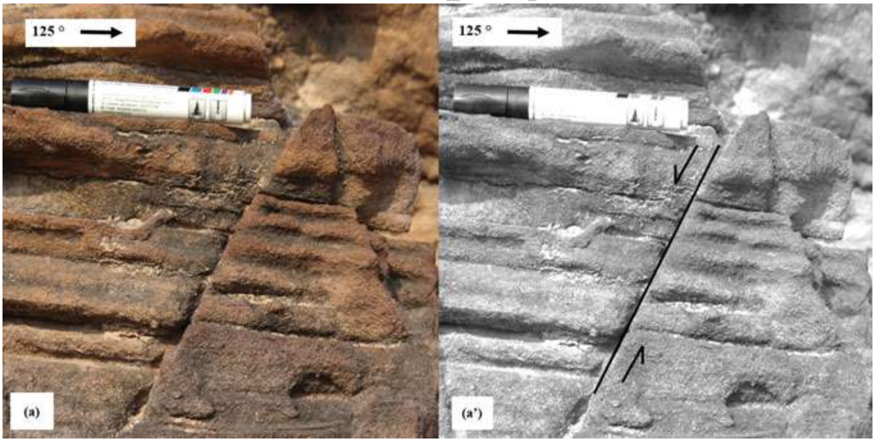

Fig. 5 Uninterpreted (a) and interpreted (a′) images of vertical section of small-scale normal fault in Early Cretaceous sandstone of Bhuj Formation. Marker pen (13 cm) is shown as scale. Location: Road left section from E of Kodki road fault, near Bhuj city, Gujarat, India. Coordinates: 23° 14′ 38.228″ N, 69° 35′ 8.286″ E

Fig. 6 Uniform set of small-scale normal faults as observed in sub-vertical section of sandstone sequence of Early Cretaceous Lower Bhuj succession visible clearly due to the displacement of yellow marker layer on the Kodki road, near Bhuj city, Gujarat, India. Hand is used as marker (15 cm). Location: 23° 14′ 32.6461″ N, 69° 34′ 57.28681″ E

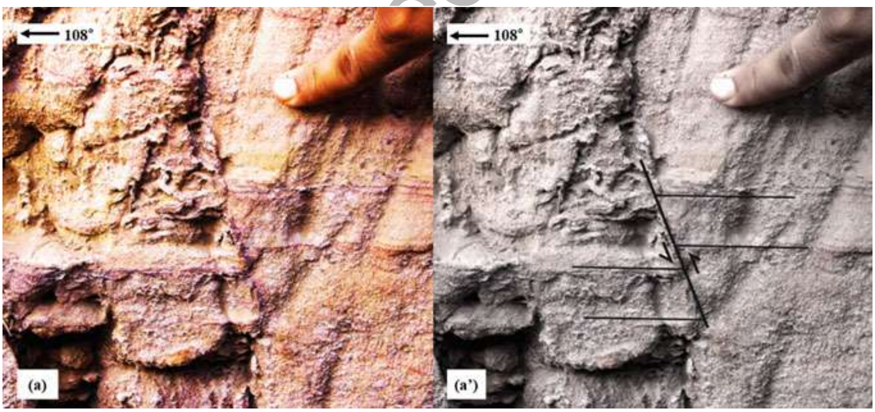

Fig. 7 Uninterpreted (a) and interpreted (a′) images of vertical section of high-angle reverse fault in Early Cretaceous sandstone of Lower Bhuj succession. Finger (6 cm) as marker. Location: 23° 14′ 38.228″ N, 69° 35′ 8.286″ E

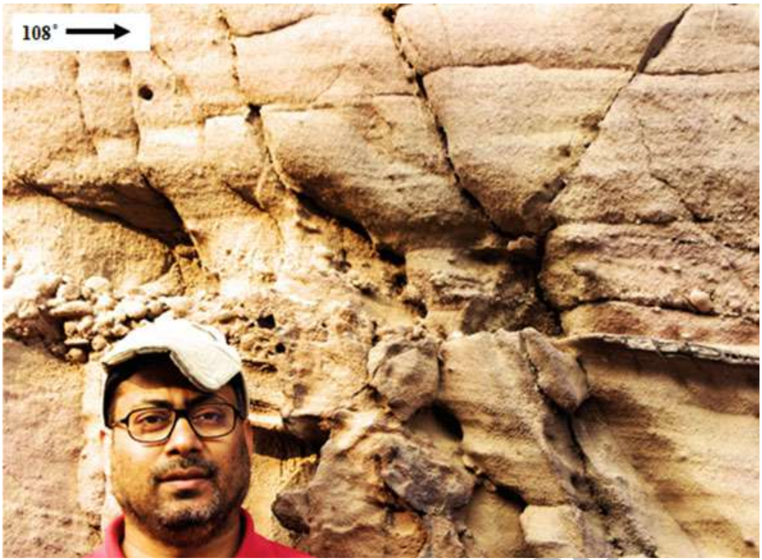

Fig. 8 Mesoscopic conjugate faults within sandstone sequence of early Cretaceous Lower Bhuj succession. The fault plane strikes nearly N-S, and dip steeply ~70°. Slip is greater on the fault towards left of the section. S. Mukherjee is as scale. Kodki road fault, near Bhuj city, 23° 14′ 38.228″ N, 69° 35′ 8.286″ E

Sigmoidal Structures

Numerous sigmoid structures were noted in the field. The shape and inclination of P planes with respect to Y planes have been used to deduce the slip direction conclusively (Figs. 9, 10, 11, 12, 13, and 14).

Fault drag is described as the curved markers adjoining a fault (e.g. Kearey, 1993). Fault drag can be of two types—Normal drag and Reverse drag. Normal drag can be described as the convex deflection of markers in the direction of slip. It is more commonly encountered in the field. Whereas, a reverse drag can be described as the concave deflection of markers in the direction of slip (review in Mukherjee, 2014).

Normal fault with normal drag is a very common case and widely seen in the field.

Reverse faulted normal dragged rock units are widely known and reported profusely in literature. Natural examples of this type have been reported earlier by Passchier (2001), he referred them as 's-Type flanking folds' (Fig. 15).

Reverse fault with reverse drag, a rare variety of reverse fault, was documented from a single place (Figs. 16 and 17).

Fault Gouge

Refracted fault planes (e.g., Bose et al., 2020) are an important structure observed in the area. Most of the faults cut through the Lower Cretaceous sandstone shale sequence of Bhuj Formation. Due to heterogeneous lithology when these faults pass

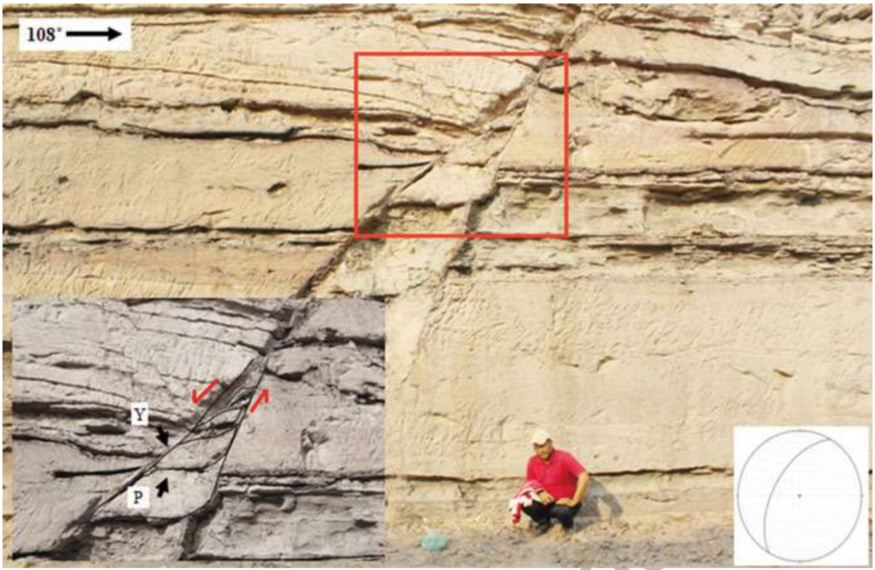

Fig. 9 Vertical section of the Bhuj-Kodki Road Fault in sandstone-shale sequence of Early Cretaceous Bhuj Formation, depicting a normal slip (length of exposed fault plane is ~4.6 m) (210° Strike, 55° Dip, 300° Dip direction) and four sigmoidal structures at the top. The sigmoid structure marked by red box (close-up in inset) shows Top-to-225° sheared P-planes. The Y-planes that bound the curved P-planes are non-parallel. The other inset shows stereo plot of the normal fault plane. S. Mukherjee (1.74 m) is shown as scale. Location: Road right section from E of the Kodki Road Fault, near Bhuj city, Gujarat, India. Location: 23° 14′ 38.228″ N, 69° 35′ 8.286″ E

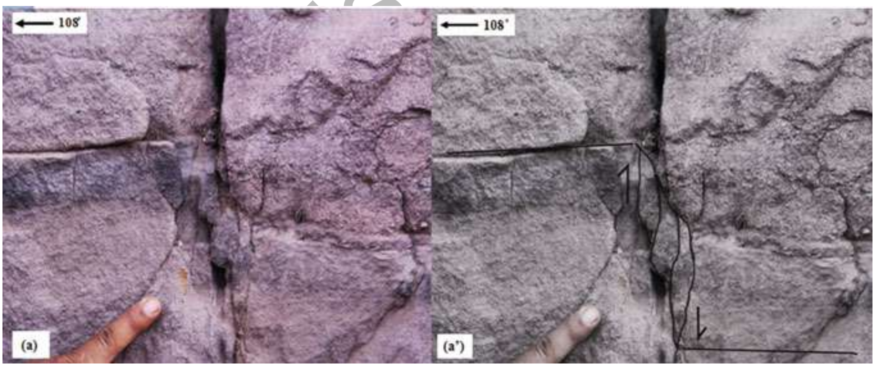

Fig. 10 Uninterpreted (a) and interpreted (a′) images of vertical section of normal fault in marker layer with sigmoidal structures in Early Cretaceous sandstone of Bhuj Formation. The P-planes are almost of equal curvature confined within parallel Y-planes which is not marked. Part of finger (6 cm) as scale. Location: Road section from E of Kodki road fault, near Bhuj city, Gujarat, India. Coordinates: 23° 14′ 38.228″ N, 69° 35′ 8.286″ E

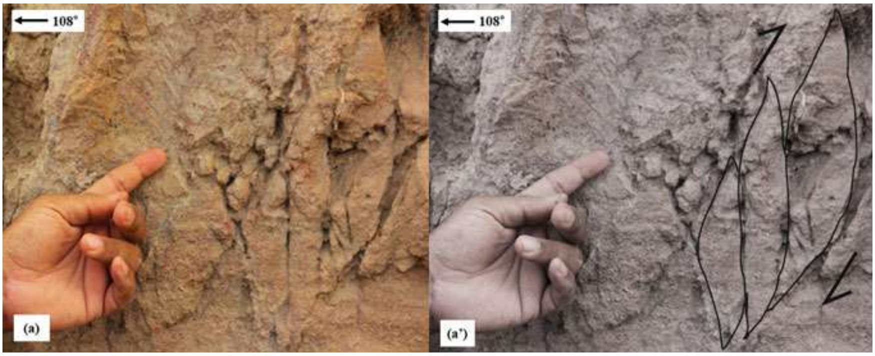

Fig. 11 Uninterpreted (a) and interpreted (a′) images of vertical section of brittle shear Y- and P-planes observed in a vertical section in Early Cretaceous sandstone of Bhuj Formation. Top-to-30° sheared P-planes are bounded by not so clear Y-planes indicate reverse faulting. Finger (8 cm) is used as marker. Location: Kodki road fault, near Bhuj city, Gujarat, India. Coordinates: 23° 14′ 38.228″ N, 69° 35′ 8.286″ E

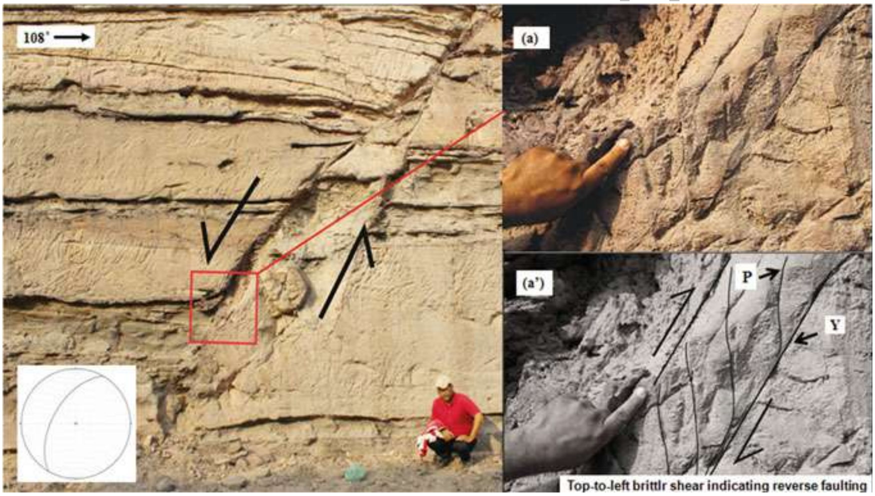

Fig. 12 Vertical section of the Bhuj-Kodki Road Fault in Cretaceous sandstone-shale succession of Bhuj Formation, depicting a normal fault (attitude: 210° strike, 55° dip, 300° dip direction). The red box (close-up in other boxes—Un-interpreted (a) and interpreted (a′)) shows reverse faulting within the normal fault. The top-to-30° sheared P-planes are bounded by parallel Y-planes. Finger (6 cm) as scale. The other inset shows stereo plot of the normal fault plane. S. Mukherjee (1.74 m) as scale. Location: Road section from E of the Kodki Road, near Bhuj city, Gujarat. Coordinates: 23° 14′ 38.228″ N, 69° 35′ 8.286″ E

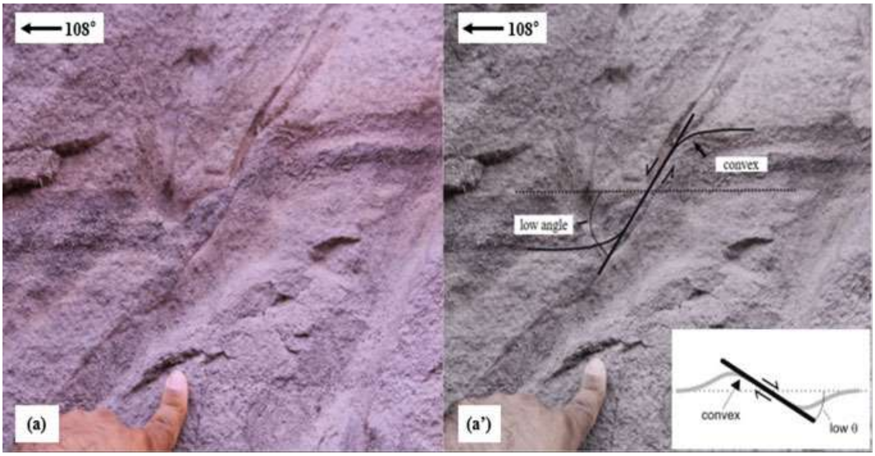

Fig. 13 Uninterpreted (a) and interpreted (a′) images of vertical section of normal fault in marker layer with normal drag in Early Cretaceous sandstone of Bhuj Formation. Low angles favor normal drag (Grasemann et al., 2005). The low angle mentioned here is the acute angle measured from the fault to the undeformed central marker (anticlockwise angles are positive). Part of finger (6 cm) is shown as scale. Location: Road left section from E of Kodki road fault, near Bhuj city, Gujarat, India. Coordinates: 23° 14′ 38.228″ N, 69° 35′ 8.286″ E

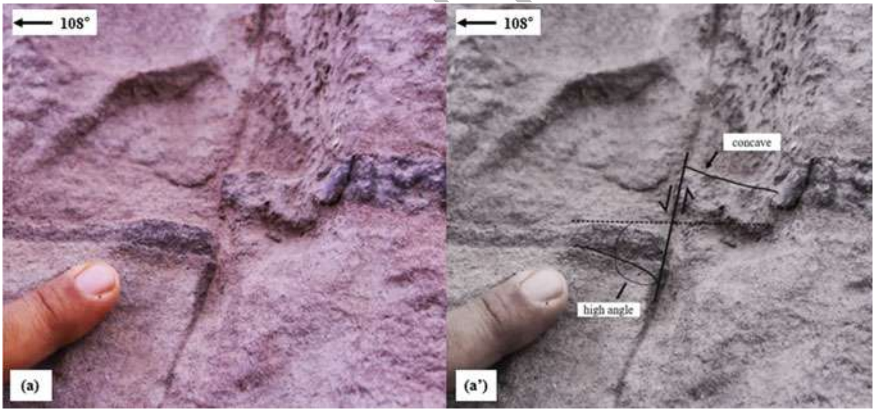

Fig. 14 Uninterpreted (a) and interpreted (a′) images of normal fault in marker layer with reverse drag in vertical section of Early Cretaceous sandstone of Bhuj Formation. Part of finger (3 cm) as scale. Location: Road section from E of Kodki road fault, near Bhuj city, Gujarat, India. Coordinates: 23° 14′ 38.228″ N, 69° 35′ 8.286″ E

through the shale units, they get refracted. Lithological heterogeneity causes fault planes to get refracted (Figs. 18 and 19).

Fault related landforms are crucial as they give indications regarding tectonic activity. Fault scarp is one such landform. Prior workers have given various definitions, in the present work the term ‘fault scarp’ is referred to as the topographic

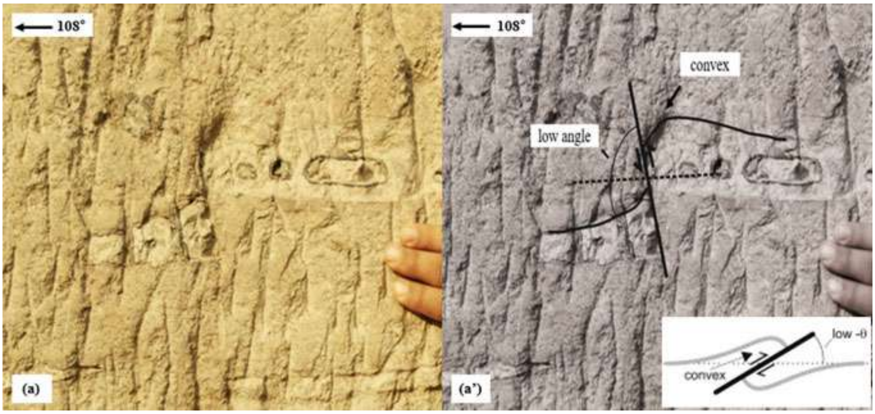

Fig. 15 Uninterpreted (a) and interpreted (a′) images in vertical section of high angle reverse fault in marker layer with normal drag in Early Cretaceous sandstone of Bhuj Formation. Part of finger (5 cm) as scale. Location: Road section from E of Kodki road fault, near Bhuj city, Gujarat, India. 23° 14′ 38.228″ N, 69° 35′ 8.286″ E

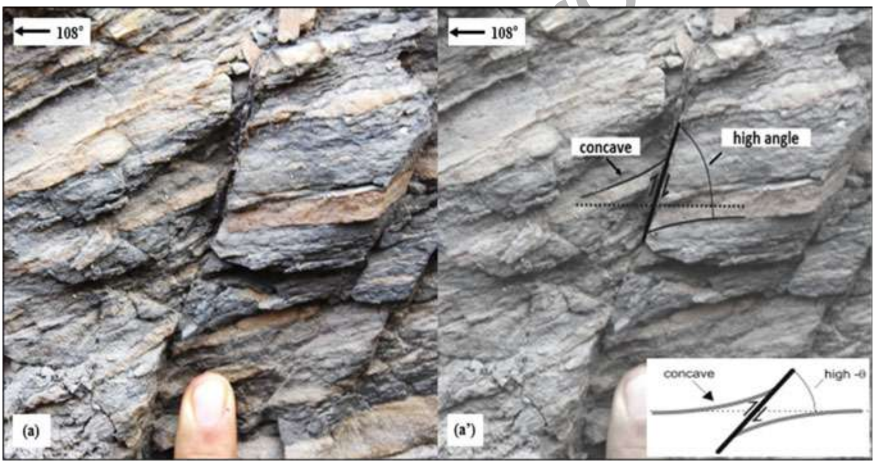

Fig. 16 Uninterpreted (a) and interpreted (a′) images of reverse fault with reverse drag in vertical section of Early Cretaceous sandstone- shale sequence of Bhuj Formation. Part of finger (2 cm) as scale. Location: Road left section from E of Kodki road fault, near Bhuj city, Gujarat, India. Coordinates: 23° 14′ 38.228″ N, 69° 35′ 8.286″ E

expression of faulting which is associated with displacement caused by movement along the fault. It coincides with the fault plane and carries kinematic indicators of tectonic activity. Few characteristics of fault scarps are: (i) they are primarily related with episodic movements which can be due to any type of tectonic displacements like earthquakes and faults of various types, including strike-slip faults; (ii) very prone to erosion because they form due to a sudden uplift along the fault and therefore are

Fig. 17 Vertical section of Network of faults in sandstone shale sequence of Lower Bhuj succession. No scale is used. Location: Kodki road fault, near Bhuj city, Gujarat, India. Coordinates: 23° 14′ 38.228″ N, 69° 35′ 8.286″ E

Fig. 18 Vertical section of a thick white colored fault gouge (attitude: dip amount 70°, dip direction 113°, strike 23°) in Early Cretaceous sandstone of Lower Bhuj succession. Soumyajit Mukherjee (174 cm) is shown as scale. Location: Kodki road fault, near Bhuj city, Gujarat, India. 23° 14′ 38.228″ N, 69° 35′ 8.286″ E

Fig. 19 Subvertical section showing refraction of fault plane due to marker layer in Early Cretaceous sandstone of Bhuj Formation causing decrease in dip angle. Part of finger (3 cm) is shown as scale. Location: Road left section from E of the Kodki Road, near Bhuj city, Gujarat. Coordinates: 23° 14′ 38.228″ N, 69° 35′ 8.286″ E

mineralized and differently colored; (iii) they can be few centimeters to many meters in height. Several segmented fault scarps of variable height ranging from 15 cm up to few meters are present in the study area. Mostly they are NNE-SSW and NW–SE trending and gives indication of dip slip movement. Figure 20 shows one prominent exposure of fault scarp.

The studied fault scarps are comparable with 'fault-fins' structures described by Davis (1990) in Navajo sandstone of Colorado Plateau region in Southern Utah. Like fault-fin structures these fault scarps also give bladed appearance, occur as aligned elements that project upward from a common structural trace and are probably related to deformation band shear zones of tectonic origin.

Deformation bands are primary deformation elements in faults, which are a result of strain localization in highly porous rocks, usually noted in sandstones of high porosity (Fossen et al., 2007; Shaikh et al., 2020). Deformation bands differ from extensional fractures formed in low-porosity rocks as they: (i) increase cohesion and decrease permeability in contrast to extensional fractures, which tends to decrease cohesion and increase permeability; (ii) are associated with strain hardening whereas extensional fractures are associated with strain softening; (iii) are thicker and show low-displacement as compared to extensional fractures. Numerous deformation bands were noted in the study area. They are present as individual bands and in clusters as zones of bands, also reported within slip surfaces (faulted deformation bands). Their occurrence in the study area is important as: (i) prior workers have reported their association with major faults which is the case here as well (Shaikh

Fig. 20 A prominent exposure of a fault with unknown slip-sense(190° strike, 70° Dip and 215° Dip direction) in Lower Cretaceous sandstone of Bhuj Formation. Soumyajit Mukherjee (174 cm) is shown as scale. Location: Kodki road fault, near Bhuj city, Gujarat, India. Coordinates: 23° 14′ 38.228″ N, 69 °35′ 8.286″ E

et al., 2020). The density of deformation bands decreases on both sides as we move away from the Kodki transverse fault; (ii) they result in decreased permeability and increased cohesion and therefore, they act as a barrier to fluid flow (e.g., Pittman, 1981; Sample et al., 2006); (iii) they provide crucial information about their formation (e.g. Aydin & Johnson, 1978; Johnson, 1995) and progression (e.g. Schultz & Siddharthan, 2005; Wong et al. 2004) of faults in porous sandstones (Figs. 21, 22, and 23).

Another interesting feature noted in the area is the large sized honeycomb or boxwork sandstone boulders (Fig. 24). Numerous such boulders were noted in the study area around the fault-controlled ridge. A network of cm-scale deformation band shear zones that intersect each other can be seen. Honeycomb/boxwork structure are formed when the sandstone between these deformation structures weathers out.

Mineralised Fault Plane

Mineralized and differently colored surfaces are generally characteristic of fault planes. Almost all the fault planes were mineralized in the study area. Figure 25 presents an example.

Igneous Intrusion

Maurya et al. (2003) suggested that the formation of transverse faults that offset major E-W trending intra-basinal faults is contemporaneous with the dyke emplacement i.e. it is related with the Deccan trap volcanism in an extensional stress regime.

Fig. 21 Horizontal section of a cluster of deformation bands trending N-S in Early Cretaceous sandstone of Bhuj Formation. Pen (15 cm) is shown as scale. The deformation bands follow the trend of the Kodki transverse fault which we are studying. Location: Kodki road, near Bhuj. 23° 14′ 38.228″ N, 69° 35′ 8.286″ E

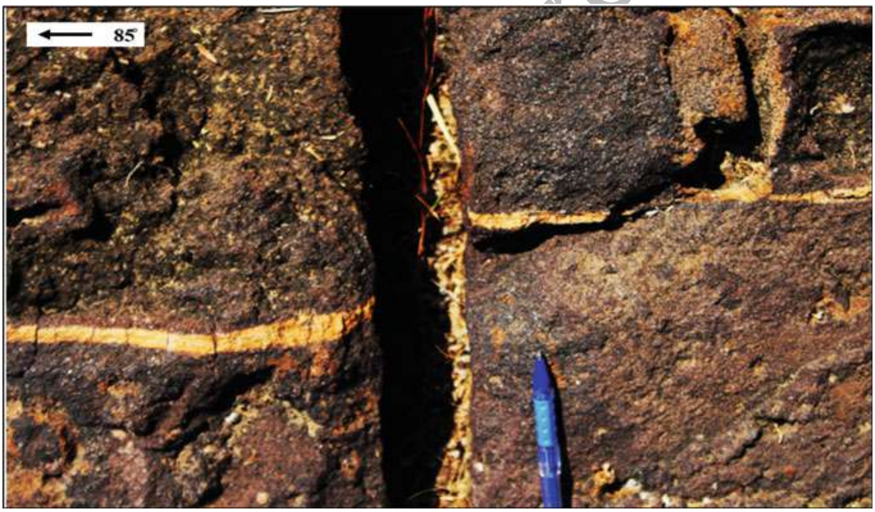

Fig. 22 Subhorizontal view of an almost E-W trending deformation band in weathered sandstone. The band is sinistrally faulted along a N-S trending transverse fault. Pen (15 cm) is used as scale. Location: Kodki road, near Bhuj. 23° 14′ 38.228″ N, 69° 35′ 8.286″ E

He suggested this on the basis of close association of intrusive dykes along transverse faults. One such association was observed in the field as well. A dolerite dyke was noted, which follows the trend of Kodki transverse fault. Figure 27 shows the spheroidal weathering of the dyke (Fig. 26).

Fig. 23 Sub-horizontal section of fractured deformation band in weathered Bhuj sandstone. Coin as scale. Location: Kodki road fault, near Bhuj. 23° 14′ 38.228″ N, 69° 35′ 8.28″ E

Fig. 24 Close-up of a large boulder showing the winnowed boxwork character of the deformation band shear zone in Lower Cretaceous Bhuj sandstone. The Kodki transverse fault ridge is flanked by such structures on its sides. Nidhi Lohani (163 cm) as scale. Location: Kodki road fault, near Bhuj city, Gujarat, India. Coordinates: 23° 14′ 38.228″ N, 69° 35′ 8.286″ E

Fig. 25 A sub-vertical, mineralized and striated fault plane (attitude: 210° strike, 55° dip, 300° Dip direction) in Early Cretaceous sandstone of Bhuj Formation. Lineations indicate dip-slip movement. Finger (6 cm) is shown as scale. Location: Road right section from E of the Kodki Road, near Bhuj city, Gujarat. Coordinates: 23° 14′ 38.228″ N, 69° 35′ 8.286″ E

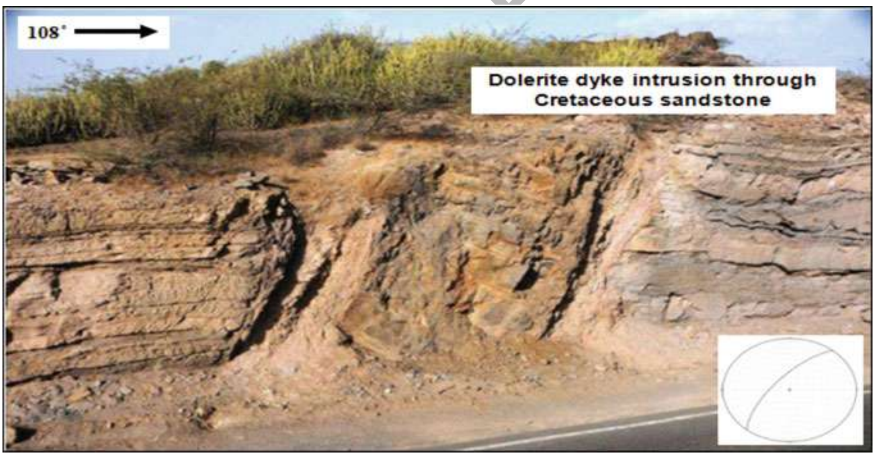

Fig. 26 A vertical section of almost NE-SW trending dolerite dyke (attitude: 220° strike, 70° dip, 310° dip direction) of about 5–6 m width cutting through the thinly laminated sandstone-shale sequence of Early Cretaceous Lower Bhuj succession. The inset shows stereoplot of the dyke. No scale is used. Location: Kodki road fault, near Bhuj city, Gujarat, India. Coordinates: 23° 14′ 38.228″ N, 69° 35′ 8.286″ E

Fig. 27 Subvertical section of a spheroidally weathered dolerite dyke. Rounded features developed. S. Mukherjee (174 cm) is shown as scale. Location: Kodki road, near Bhuj city, Gujarat, India. Coordinates: 23° 14′ 38.228″ N, 69° 35′ 8.286″ E

Folds

Although KHRFZ is reported to have many fold-related structures, not many are noted in the area. Figure 28 shows a drape folding formed due to sagging of a shale layer due to overlying sandstone layers.

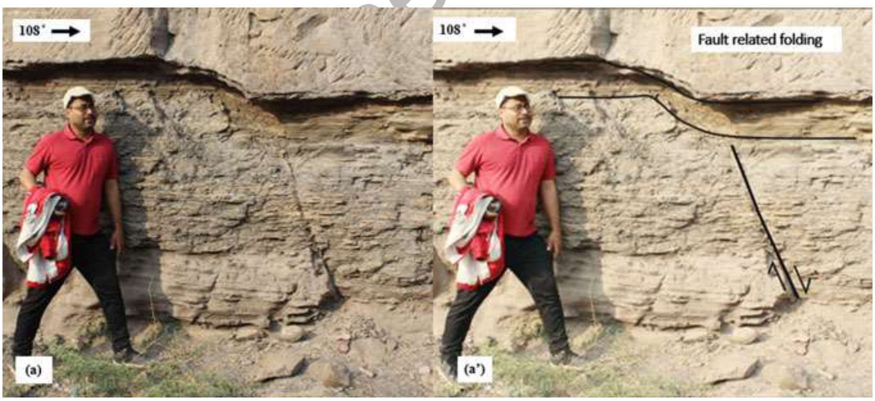

Fig. 28 Uninterpreted (a) and interpreted (a′) images of Dip-slip normal fault and fault-related folding in vertical section of thinly laminated sandstone-shale sequence of Early Cretaceous Lower Bhuj succession. S. Mukherjee (174 cm) is shown as scale. Location: Kodki road, near Bhuj city, Gujarat, India. Coordinates: 23° 14′ 32.6461″ N, 69° 34′ 57.28681″ E

4 Conclusions

Meso-scale normal faults strikingNW-SE to NE-SW is the main observation on the Kodki road. Such faultsarealso accompanied by different drag patterns, local-scale reverse faults, network of faults and conjugate faults, sigmoid shear planes, shear bands etc. Paleostress study from this location can be an important input into the tectonics of the KRB.

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