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Implications of transverse fault system on tectonic evolution of Mainland Kachchh, western India

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The tectonic evolution and seismic phenomenon of Kachchh region have been attributed to differential movement along the E-W trending master faults. However, a NW-SE to NE-SW transverse fault system also exists which cuts across the E-W tectonic fabric of Kachchh. The present study attempts to delineate the role of transverse faults in pre-Quaternary and Quaternary tectonic evolution of Mainland Kachchh based on a regional scale geomorphic study. Significance of these transverse faults in the tectonic evolution of Kachchh is obvious as they laterally displace the large E-W faults and the domal structures associated with them. The Kachchh Mainland Fault (KMF) and the Katrol Hill Fault (KHF) are the two major E-W trending master faults of Mainland Kachchh which show distinct offsets along transverse faults. Geomorphic evidences of strike slip movement along the transverse faults affecting the KMF and KHF are seen in the form of displacement of major fault scarps, beheaded/deflected or offset drainage, sags, shutter ridges and pressure ridges. The observed amount of offset along the transverse faults ranges from a few hundreds of metres to several kilometres, which includes a pre-Quaternary as well as a Quaternary component. It is suggested that a part of the stresses being accumulated on the E-W trending faults is being possibly transmitted to the NW-SE to NE-SW transverse faults, which may account for the present seismic phenomenon in Kachchh. However, detailed mapping of the transverse fault system, followed by detailed geomorphic and palaeoseismic studies are needed to understand the role of transverse faults in generating seismic activity in Mainland Kachchh.

THE lack of understanding of the seismic phenomenon of the Kachchh region as a whole can partly be attributed to inadequate data on fault systems and Quaternary tectonic activity along them. In general, the seismic instability of the area has been attributed to the E-W trending fault system, which includes among others, the Kachchh Mainland Fault (KMF) and the Katrol Hill Fault (KHF; Figure 1 *a* and *b*). The KMF and the KHF are the two major E-W trending faults which control the present tectonic framework and overall geomorphic configuration of the Mainland Kachchh[1,2]. These faults are not continuous, but appear to be laterally displaced by several NNE-SSW to NNW-SSE trending transverse faults. The role of these transverse faults in the tectonic evolution of Mainland Kachchh is not yet known. Here, we present some evidence on the possible implications of the transverse faults on tectonic evolution and seismicity based on a regional-scale geomorphic study carried out along the KMF and the KHF. The study reveals that tectonic activity along the transverse faults is intricately linked with the tectonic evolutionary history of Mainland Kachchh in pre-Quaternary and Quaternary times as well.

The KMF is a significant tectonic feature with a long history of reactivation closely connected with the tectonic evolution of the Kachchh basin[1,2]. The general trend of the fault is E-W while in the western part, it trends in WNW-ESE direction (Figure 1 *a*). The fault forms a spectacular geomorphic feature with north-facing steep fault scarps that separate the Banni-Rann region to the north and a highly rugged topography of the Mainland Kachchh to

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the south. The drainage of KMF zone comprises north-flowing rivers which follow deeply incised courses. The KMF has been an important zone of accumulation of compressive stresses evidenced by the association of several anticlines, half anticlines, synclines and domal structures with the fault[3]. This narrow zone, known as the Northern Hill Range, has steep slopes towards north, while the southern slopes are gentle and almost concurrent with the dip of the beds. The major domal structures associated with this fault are Habo, Jhura, Keera, Nara, Jumara, and Jara (Figure 1 *a*). The domes consist of a thick sequence of Mesozoic rocks which have been divided into Jhurio, Jumara, Jhuran and Bhuj Formations[4]. The southern limbs of the domes are gently inclined, as little as 5–10° towards south, while the northern limb is steeply dipping towards the north or is vertical. At places, the northern limbs are seen overturned, with steep dips due south. The core portions of the domes are occupied by basaltic intrusive rocks[3]. The eastern and western limits of the domes are marked by N-S transverse faults. The N-S and NW-SE to NE-SW trending faults and fractures are occupied by basic igneous dykes. The dykes mostly occur in the vicinity of faults or along the faults, suggesting syntectonic nature of the intrusive rocks[5].

The E-W trending KHF divides the Mainland Kachchh into northern and southern parts (Figure 1 *a*). The KHF marks the northern edge of the Katrol Hill Range with the rocky plain in the north. The geomorphic expression of the KHF is similar to the KMF, with the north facing scarps separating the Katrol Hill Range comprising mostly of Jhuran Formation in the south and the rocky plain consisting of Bhuj Formation to the north[3]. The Katrol Hill Range comprises a narrow zone of domal hills[3] along the KHF, as observed in the KMF. The KHF scarps also display remarkable shifts along the NNE-SSW and NNW-SSE trending transverse faults. Apart from the faults, the

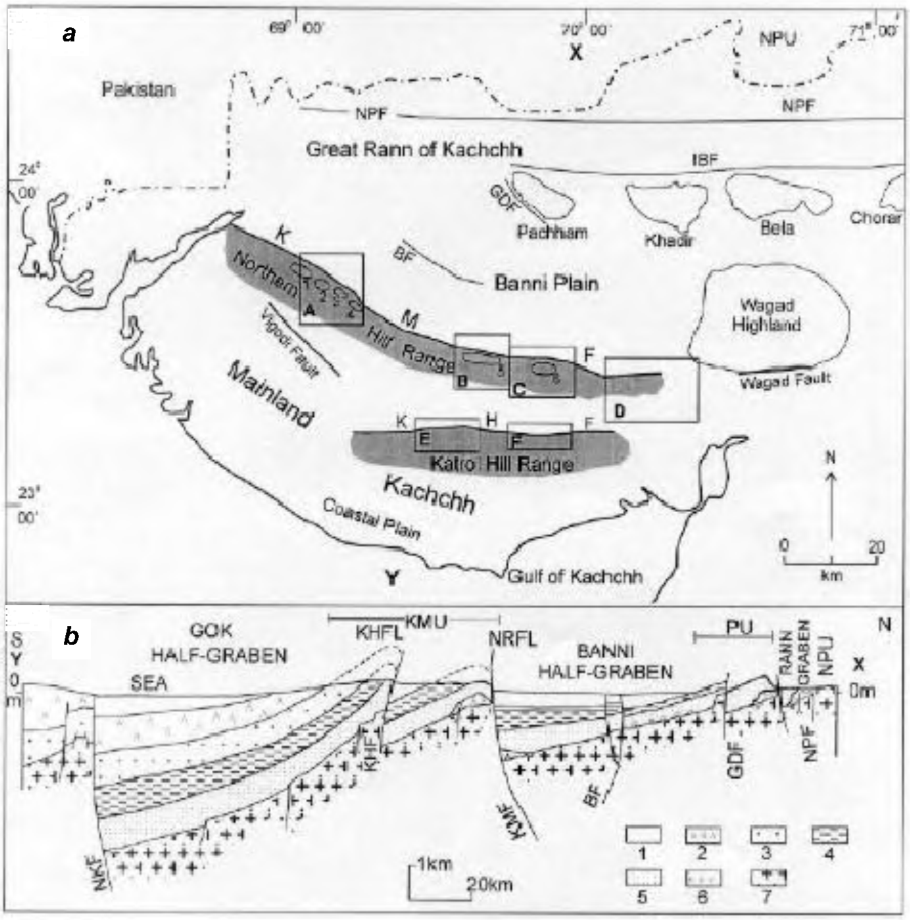

Figure 1. *a*, Generalized tectonic map of Kachchh showing major faults (based on Biswas and Khattri[12]). Enclosed areas (squares) indicate maps in Figures 2 and 3. 1, Jara dome; 2, Jumara dome; 3, Nara dome; 4, Keera dome; 5, Jhura dome; 6, Habo dome. X–Y is the section alignment of ***b***, N-S geological cross-section across Kachchh (after Biswas and Khattri[12]. NPU, Nagar Parkar Uplift; NPF, Nagar Parkar Fault; IBF, Island Belt Fault; PU, Pachchham Uplift; GDF, Gora Dongar Fault; BF, Banni Fault; KMF, Kachchh Mainland Fault; KHF, Katrol Hill Fault; NKF, North Kathiawar Fault; GOK, Gulf of Kachchh; KHFL, Katrol Hill Flexure Zone; NRFL, Northern Range Flexure Zone; KMU, Kachchh Mainland Uplift. 1, Quaternary and Tertiary; 2, Deccan Trap; 3, Lower Cretaceous; 4, Upper Jurassic; 5, Middle Jurassic; 6, Lower Jurassic and Upper Trias and 7, Precambrian.

transverse trend is also well brought out by several dykes. The dykes are present to the north as well as to the south of the KHF. However, none of the dykes appears to cut across the KHF. Though the KHF and KMF zones are structurally similar, they differ in one respect that the KMF marks the southern limit of the Banni-Rann sedimentary basin, which has witnessed sedimentation until Late Holocene, while no such Quaternary basin is present to the north of KHF. However, the KHF shows other Quaternary deposits like colluvium, alluvial fans, miliolites and other fluvial channel deposits[6].

The transverse faults trending in N-S, NE-SW and NW-SE have caused lateral shifts in the fault scarps of the KMF (Figure 2 *a–d*). The fault planes of these transverse faults are either vertical or steeply dipping (60 to 70°). In general, the fault planes dip towards the domes. The lateral movement along these faults in the form of horizontal shifting of rocks and the E-W trending faults are conspicuous in the field and also significant. Palaeontological and stratigraphic studies indicate lateral displacement of lithological units of the various domes along transverse faults[7–10], though detailed structural investigations on these faults have been lacking.

However, the most impressive aspect of the topography of the KMF and the KHF is an assemblage of tectonically-produced landforms associated with strike-slip movement along transverse faults. These landforms are offset fault scarps of the KMF, beheaded/deflected or offset drainage, sags, shutter ridges and pressure ridges (Figure 2 *a–d*). A significant feature observed is that all major transverse faults displacing the KMF and truncating the domes are occupied by a high-order river channel debouching into the Banni plain. The Nara river flows along a transverse fault at the eastern end of the Nara dome, while the faults affecting the Keera dome are occupied by the Panjorawali and the Khari rivers. The Kaswali river and an unnamed high-order stream follow the trends of transverse fault in the Habo dome, while the Kaila and Khari rivers flow along these faults within the Jhura dome (Figure 2 *a–d*). These rivers exhibit deeply incised channels and features like entrenched meanders, drainage offsets and small sags/depressions filled with alluvium, which can be related to lateral movement along transverse faults. The Nara, Panjorawali, Khari and Kaswali rivers show these features at several places along their fault-controlled courses. In the eastern flank of the Nara dome, the river Nara shows many depressions and ponding along its course. Several pressure ridges oriented along the transverse faults are also present (Figure 2 *a*). These ridges show either unusual variation in dips of the strata or extremely shattered rocks or both. The pressure ridges along the Khari river to the north of Bhuj show unusual variation

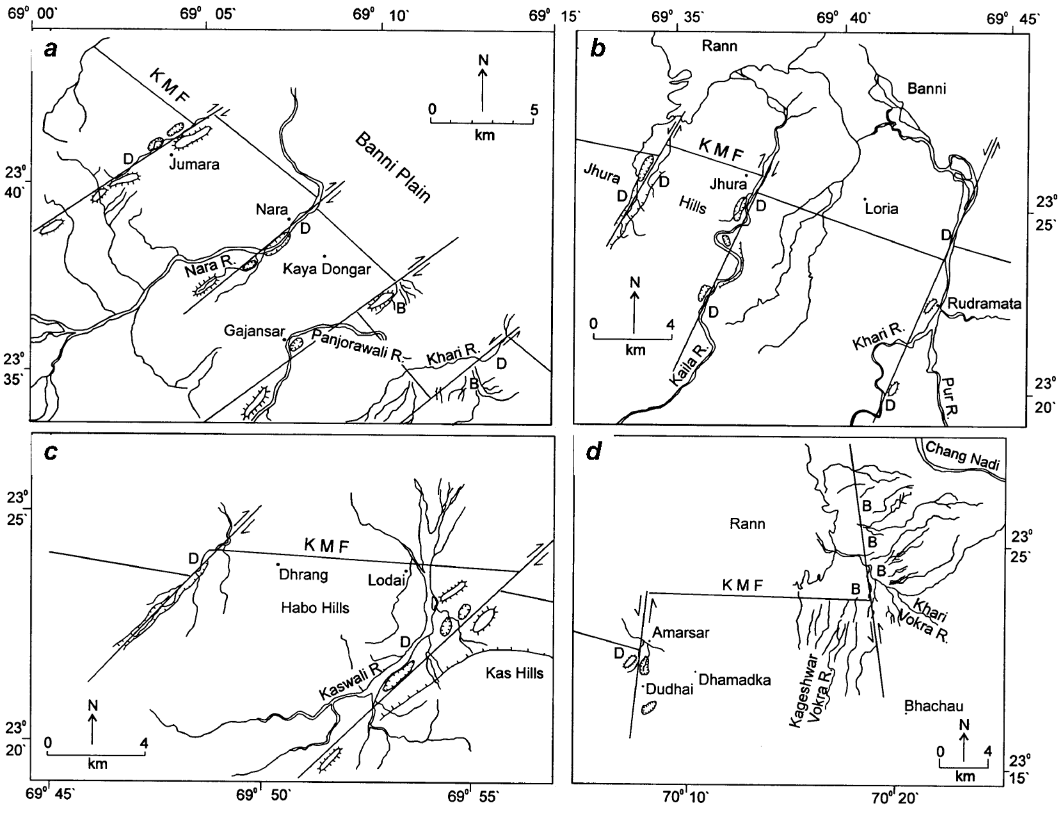

Figure 2. Maps showing landforms associated with strike-slip movement along transverse faults in selected segments of the KMF. Locations of individual maps are shown in Figure 1. Legend is the same as given in Figure 3.

in dips in the beds of Jhuran Formation. Large-scale shattering and shearing is seen in the rocks comprising pressure ridges along the Nara river.

The KMF truncates along a major N-S trending fault north of Bhachau. The geomorphic expressions of this fault are not as spectacular as those of other transverse faults and the KMF. Evidence which points to the existence of a N-S fault hidden below the alluvial cover includes termination of the KMF, Wagad Fault and the rocks of the Mainland Kachchh, straight eastern margin of the Wagad highland and abrupt termination of a number of westward-flowing streams along the fault (Figure 2 *d*). The epicentre of the earthquake of 26 January 2001 was located in this region. The NNW-SSE-oriented Manfara Fault located in close vicinity[11] is further evidence of a major fault along this trend in the area. Right-lateral strike-slip motion along the Manfara fault has been reported. A similar fault trending NNW-SSE and showing lateral displacement is reported[11] near Bharodia. This zone has now been identified as a highly stressed zone based on the clustering of several earthquake epicentres[12].

The KHF also shows distinct offsets of the E-W trending fault scarps along the various transverse faults (Figure 3). The trends of the transverse faults cutting across the KHF vary from NNE-SSW to NNW-SSE. The transverse faults show steeply dipping fault planes and are marked at several places by NNE-SSW to NNW-SSE trending escarpments and ridges. The faults show dextral as well as sinistral slips (M. G. Hardas, unpublished, Ph D thesis). Lateral movements along the transverse faults have produced landforms associated with strike-slip movements as observed in the KMF zone. These include offset scarps of the KHF, deflected streams, sags, shutter ridges and pressure ridges (Figure 3). The transverse faults along the KHF have affected the domal structures in a similar way as seen in the KMF zone. Movements along the transverse faults have horizontally shifted the lithological contacts by several kilometres (M. G. Hardas, unpublished, Ph D thesis). Thakkar *et al.*[5] noted the exceptionally fresh nature of the fault scarps of the transverse faults. They also noted that these faults are continuous and are never found to cut across by other faults, unlike the KMF and the KHF, which are divisible into several segments by faults cutting across them. The transverse faults along the KHF differ from those of the KMF zone in one significant aspect. Most of the transverse faults along the KMF have a major river flowing along them; however, this is not the case with the transverse faults along the KHF. Here, none of the transverse faults shows a major river flowing along it (Figure 3). The reason for this is that the KHF marks the main drainage divide, which defines the drainage of Mainland Kachchh into north-flowing and south-flowing drainages, whereas the KMF does not form a drainage divide. Several rivers originating in the Katrol Hill Range flow northwards and cut across the Northern Hill Range along the weak zones of the transverse faults, before disappearing into the Banni plains. The N-S trends of the drainages of the Mainland Kachchh suggest the significance of the transverse trend in landscape[13].

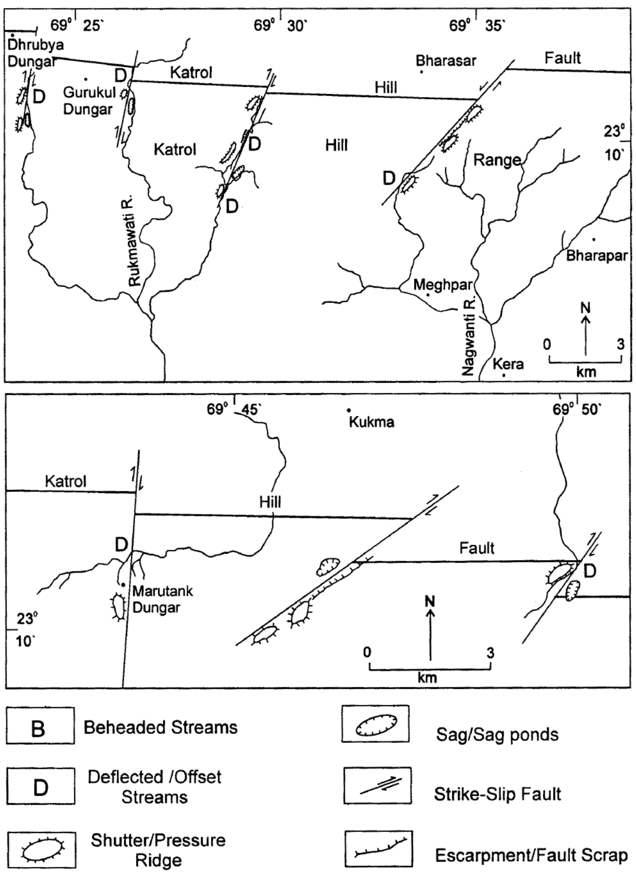

Figure 3. Maps showing landforms associated with strike-slip movement along transverse faults in selected segments of KHF shown as squares E and F in Figure 1.

Apart from the major transverse faults offsetting the KHF scarps, several other faults showing similar trends occur within the Katrol Hill Range. These faults do not extend up to the KHF; however they display remarkable effects on geomorphology and drainage, which points to their tectonically active nature (Figure 4). A N-S trending reverse fault is seen 1 km north of Kundanpar, where a small stream meets the left bank of Rudrani river, a tributary of Nagwanti river. The fault cuts across the stream exactly at the confluence. The fault scarp with well-preserved slickensides is exposed within the river channel (Figure 4 *b*). Reverse movement along this fault has uplifted the bed of the stream by 3 m, resulting in the formation of a fluvial hanging valley (Figure 4 *a*). Another steeply-dipping N-S trending fault was observed near Bharapar, which cuts across one of the small streams. Normal faulting along this fault has displaced the river bed by about 2 m along the fault plane (Figure 4 *c*). On the upthrow side, a narrow gorge has developed. Similarly, differential uplift along three closely-spaced N-S trending faults has led to drainage reversal near Meghpur along a E-W trending tributary of the Nagwanti river (Figure 4 *d* and *e*). Interestingly, the fault scarps mentioned above are well-preserved within the river channel, a least favourable site for the preservation of fault scarps. These evidences clearly point to the continuing tectonic deformation of Mainland Kachchh along N-S trending faults, much of which is dominantly coseismic.

The Kachchh region marks the site of an intracratonic palaeo-rift graben whose evolutionary history dates back to the Mesozoic times[1,2]. The Kachchh basin evolved in two major stages[12]. The first one is the rift stage, which includes formation of rift during the extensional phase of the break-up and separation of Indian plate in Late Triassic–Early Cretaceous time followed by syn-rift sedimentation. The second is the inversion stage[12] in Late Cretaceous, when the rifting was aborted and the basin uplifted by basement-involved upthrusts along the existing master faults like the KMF and the KHF. The period of tectonic upheaval in post-collision compressive regime following the cessation of Mesozoic sedimentation is responsible for the complications in the structural set-up of the area, which is manifested in the present landscape[12].

The NNW-SSE, NW-SE, NE-SW and NNE-SSW transverse faults displacing the KMF and the KHF have been periodically reactivated during the post-rift tectonic evolution of the Mainland Kachchh. The structural features of the KMF and the KHF suggest multicyclic tectonic activity involving reactivation of the major E-W and transverse faults, dyke emplacement, eruptive volcanic activity and formation of domal structures. Earlier studies have indicated that the intrusives, with the exception of plugs, belong to a pre-Deccan Trap phase[5]. The close association of the

Figure 4. ***a***, View of uplifted valley floor of a tributary stream of the Rudrani river due to reverse movement along the N-S trending fault shown by dashed line (location 2 km north of Kera). ***b***, Close view of fault plane of the fault shown in (***a***) exposed within the river channel. Note the slickensided fault plane dipping away from the viewer, indicating reverse movement. ***c***, Photograph showing displaced valley floor of a small stream along a N-S trending normal fault (location 1 km north of Bharapar). ***d***, Downstream view of a stream (which appears like an upstream view due to drainage reversal) near Meghpur. Arrow marks the zone of river-bed uplift along three closely-spaced N-S trending faults which are exposed in the river channel. ***e***, Diagrammatic section (not to scale) of the uplifted river bed (shown in (***d***)) showing the faults responsible with inferred relative movements as indicated by the fault planes exposed in the channel. Approximate length of the river bed covered in the section is about 150 m.

transverse fault trends and the intrusive dykes suggests that the formation of these faults and the emplacement of dykes are roughly contemporaneous events. These events took place sometime after the deposition of Bhuj Formation (Late Cretaceous), but before the onset of Deccan Trap volcanic activity. This was followed by a major diastrophic cycle, which accompanied the main trappean volcanic activity[4] which peaked around ~ 65 Ma (ref. 14). This phase gave rise to several domes and flexures along the KMF and the KHF, as suggested by the presence of volcanic plugs related to the eruption of trappean lavas[5] in the central portions of the domes. The formation of domes, folds and flexures is thus the result of intricate interplay of localization of compressive stresses in fault zones and simultaneous volcanism. The major uplift zones of the area came into existence as a result of differential uplift along the E-W faults during this phase[12]. This phase of tectonic upheaval ceased before the onset of Tertiary, as evidenced by the gently dipping Tertiary rocks which overlie the eroded Mesozoic folds in E and SE part of Mainland Kachchh[1].

The strata in the various domes show lateral displacement along the transverse faults. This suggests another phase of reactivation of transverse faults with dominantly strike-slip movement, as evidenced by the horizontally displaced fault scarps of the KMF and the KHF sometime during Tertiary. This event is possibly related to Stage 5 of the drift history of the Indian plate[1], which constitutes the final welding of Indian and Eurasian plates during Eocene–Oligocene period[15] resulting in slowing down of the northward drift and anticlockwise rotation of about 9°. The abrupt slowdown of the Indian plate after a rapid northward movement and the anticlockwise rotation possibly realigned the tectonic stresses and reactivated the transverse fault system resulting in strike-slip movement. The transverse faults remained tectonically active throughout the Tertiary period by accommodating part of the compressive stresses accumulating along the major E-W trending faults in response to the northward-moving Indian plate.

Quaternary tectonic activity in Kachchh is poorly understood. The first-order topography of the area together with the recurrent seismic activity point to tectonic instability of the area during Quaternary[6,16]. Neotectonic uplift along various faults has been responsible for the present landscape of the area. Recent studies[6,13] have indicated that the Quaternary tectonic uplift took place in two major phases. These two phases are separated by the depositional phase of miliolites. The pre-miliolite phase took place in Early Quaternary[6], while the post-miliolite phase occurred during Late Pleistocene and Holocene which is continuing at present[6,17]. The Early Quaternary tectonic activity took place along the E-W trending faults, while the Late Pleistocene phase took place along the NNE-SSW to NNW-SSE trending transverse faults[6]. The E-W trending faults were more active during Early Quaternary as evidenced by the miliolites overlapping the colluvial deposits along the Katrol Hill Fault[6]. The Early Quaternary physiographic set-up has been modified by the Late Pleistocene–Holocene tectonic activity along transverse faults. Late Pleistocene tectonic activity along transverse faults is evidenced by the faulting in the Late Pleistocene fluvial deposits, tilting of sheet miliolites in the vicinity of these faults, a youthful fault scarp morphology and N-S-oriented drainage configuration[6,13]. The present study indicates that the compressive stresses accumulating on the E-W latitudinal faults of Mainland Kachchh due to locking up of the Indian plate in the NE are being transmitted to the NNE-SSW and NNW-SSE transverse faults after being transformed to tear movements along these strike-slip faults. The zones where the KMF and the KHF are cut across by transverse faults are, therefore, the most likely ones of stress release and could thus be potentially seismogenic.

As discussed above, multicyclic tectonic movements along the transverse faults have played an important role in the tectonic evolution of Mainland Kachchh. The transverse faults were periodically reactivated due to the accommodation problem caused by the compressive stresses accumulating on the E-W faults. The formation of the transverse faults is related to the pre-Deccan Trap phase of dyke emplacement. This was followed by the formation of domes as a result of trappean volcanic activity and localization of compressive stresses along the KMF and the KHF. A major phase of reactivation of transverse faults is possibly related to the collision of the Indian plate during Eocene–Oligocene, which displaced the E-W trending KMF and KHF and the domal structures as well. Evidence of Late Quaternary reactivation of these faults has also been recorded[6,13]. However, at present no unambiguous relationship can be discerned between the transverse faults along the KMF and the KHF and the available epicentral maps of the earthquakes in Kachchh. This may be due to the incompleteness of the historic record of the earthquakes. Secondly, detailed tectonic maps showing the various transverse faults are not available. Multidisciplinary studies on tectonically-generated landforms and palaeoseismic signatures along transverse faults should be a priority to fill in the gaps in available knowledge of tectonic set-up and past seismic events. This is essential, as detailed studies on discontinuous faults elsewhere have shown that the transverse faults may show clustering of earthquakes and also significantly affect the aftershocks and earthquake swarm activity[18–22]. It requires accurate mapping of transverse faults in the E-W trending fault zones already identified as seismically vulnerable. This is essential as the present study indicates that the transverse fault system perhaps holds the key to understanding the recurrent seismic activity of Kachchh region. Detailed studies of landforms associated with strike-slip faulting along the various faults of Kachchh can prove extremely helpful to evaluate the palaeoseismicity of a particular fault or section of a fault.

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Reproductive biology of *Gentiana kurroo* Royle

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Reproductive biology studies in *Gentiana kurroo*, an important endangered medicinal plant of temperate/subtemperate regions, revealed its flowers to be dichogamous due to protandry. The stigmatic lobes remain adpressed till almost complete anther dehiscence. The stigma becomes receptive to pollen germination about 6 days after initiation of anther dehiscence. The flowers are cross-pollinated and about 70–75% seeds germinated.

GENTIANA kurroo (family Gentianaceae), occurring in temperate regions, is valued as a bitter tonic, antiperiodic, expectorant, antibilious, astringent, stomachic, anthelmintic, blood purifier and carminative[1,2]. The drug plant, heavily extracted from its natural habitat is an endangered medicinal plant. Hence, the Ministry of Commerce, Government of India has put it in the negative list of exports vide Notification no. 2 (RE-98) 1997–2002 dated 13 April 1998. A perusal of the literature reveals that no information regarding its breeding system is available. The present study was undertaken to understand its breeding behaviour, which, to a large extent, determines the degree of variability expected in a population[3]. An understanding of the breeding system is fundamental to the establishment of cultivation, undertaking any genetic improvement for higher yield attributes, disease resistance, etc.

Plants of this species occur in some pockets in District Sirmour, Himachal Pradesh at an altitudinal range of 1700 to 2000 m at mean sea level. Morphological studies were carried out on both wild as well as field-grown plants, while pollination studies were conducted on field-grown plants only (in our university campus). Controlled pollination was done at stigma-receptive stage (stigma lobes in open condition) and between 8 and 10 am, using fresh pollen. In bagging and controlled selfing, buds that were about to open were covered with paper bags. While in the former the buds/flowers were left as such till fruit formation, in the latter, after flower-opening, the bag was removed, stigma hand-pollinated with pollen from the same flower and rebagged, repeating the process for 3–4 days. In open cross and controlled cross, buds about to open in next couple of days were carefully emasculated.

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