

**Landscape response to neotectonic reactivation
of Kachchh Mainland Fault (KMF) and
associated faults in Western Kachchh**

**Synopsis
of the
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by**

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Introduction

Neotectonic deformation in the Kachchh Rift Basin (KRB) comprises dominantly of vertical movements along the E-W trending faults due to compressive stresses, however, future earthquake nucleation is most likely to be in the zones where the E-W trending faults intersect with the transverse faults. The KHF and KMF show highest intensity of neotectonic activity followed by IBF, SWF and GF which broadly correlates with the observed level of historic seismicity and the post-2001 aftershock activity. The data generated suggests that the KHF and KMF are capable of generating high magnitude seismic events, while the possibility of the high magnitude events occurring along the SWF and GF is low. A basement controlled fault model of the basin which are currently undergoing differential uplift under compressive stresses. The anomalous seismic activity of the Kachchh basin on the passive western continental margin of India is attributed to thermo-mechanically weak upper crust sandwiched between the rigid Saurashtra horst in the south and the Aravalli basement block to the north and favourable orientation of the faults.

Approach and methodology

The literature survey including the available published data on the structural and seismotectonic aspects of the KRB are critically studied and evaluated to understand its regional geological setting. Special emphasis has been given to the previous work on aspects related to surface and shallow subsurface deformation, Quaternary history and tectonic set-up of the region. Survey of India (SOI) topographic sheets on 1:50,000 scale and Google Earth imageries are used to delineate the regional-scale geomorphic set-up of the study area including the deformation zones of the KMF, Vigodi and Gugriana faults. The tectonic landforms and various geomorphic features located in the deformation zone are mapped in detail. The influence of tectonic disturbances over drainage pattern has been evaluated. Digital Elevation Models (DEMs) of study area containing the fault damage zones are generated using USGS SRTM (Shuttle Radar Topography Mission) of 90 m resolution and qualitative and quantitative geomorphic analysis has been performed. Various tectono-geomorphic features, Quaternary landforms, structural observations and collection of fault-slip measurements are done. The fault-lines are precisely mapped after intensive field studies and various deformation events are inferred to delineate the morphostratigraphic evolution of the fault zones. After the intensive field studies, sites are selected to carry out the Ground Penetrating Radar (GPR) with a view to map the blind faults. The field observations and GPR results are combined together

for precise mapping of the KMF, Vigodi and Gugriana faults. The sense of slip, shallow subsurface nature of the faults has been inferred. In order to better understand the kinematic evolution of western part of the KRB, paleostress analysis of the fault system at regional-scale are carried out. The data generated through field studies and GPR surveys are synthesized to reconstruct the neotectonic evolution of western part of the Kachchh Mainland Uplift (KMU).

Regional geological and structural setup

The Kachchh basin, located on the western continental margin of India, is well known for several large magnitude earthquakes in historical times. The basin is recognized as one of the best examples of Stable Continental Region earthquakes and has been compared with the New Madrid seismic zone. The region is characterized by multiple seismic sources as various intra-basinal faults are found to be responsible for moderate to high magnitude earthquakes in historical times. However, tectonic evolutionary history of these faults, particularly, in Late Cenozoic and consequent landscape evolution is not known. This has resulted in a general lack of geological database on the fault zones that includes precise fault maps, geomorphologic setting, long-term and short-term slip rates. Tectono-geomorphic Studies are essential to resolve the above geological issues which are critical for seismic hazard estimation and mitigation in the Kachchh basin. The Kachchh basin is located in the hyper-arid belt of NW India that includes the Thar Desert to its north resulting in a highly rainfall deficit climatic regime. As a consequence, various rivers show dry channels for the most part of the year with insignificant episodic water flows, lasting for few days during monsoon season. Also, there are no historical records of extreme discharges or floods during historical times, however, several prolonged spells of drought have been common. This together with a long history of devastating earthquakes points to tectonics as the major geological factor in the geological evolution of the Kachchh basin. The present article deals with the KMF zone encompassing two major flexures – the Jumara and Jara domes in the upthrown block. This part of the NHR is geomorphologically significant as it comprises the spectacular Jaramara scarp that is parallel but considerably higher than the KMF scarp. Studies on the tectonic geomorphology of fault zones have been found useful for delineating fault characteristics and neotectonic. A fundamental aim of the tectono-geomorphic studies is to establish the link between tectonic forces and geomorphological processes in shaping the landscape of the areas that have undergone significant deformation during the Cenozoic Era. In this sense, tectonic geomorphology provides critical data on understanding long-term deformation based on

identification and mapping of geomorphic landforms to provide the sequence of morphostratigraphic evolution which can serve as a reference frame for further seismotectonic and paleoseismic studies.

Kachchh Mainland Fault (KMF) and Northern Hill Range (NHR)

The northern margin of the Kachchh mainland uplift is marked by an E-W trending structurally controlled hill range called Northern Hill Range that is bounded by the KMF on its northern side. The range extends from Lakhpat in the west to the area around Devisar in the east. The hill range displays a rugged mountainous topography developed in the Mesozoic rocks which form asymmetrical domes and anticlines of various sizes. The chain of various structures from the west comprises the Karanpur dome, Ghuneri dome, Mundhan anticline, Jara dome, Jumara dome, Nara dome, Keera dome, Jhura dome, Habo dome, Wantra dome and Devisar anticline in addition to several smaller domes. The domes expose rocks belonging to the Jhurio, Jumara, Jhuran and Bhuj Formations that range in age from Middle Jurassic to Late Cretaceous and represent deposition in rift environment. The formations comprise well compacted and hard sedimentary rocks of various lithologies like sandstones, shales and limestones. The domes are asymmetric in the sense that the northern limb of the domes is steeper as a consequence of the tectonic movements along the KMF that truncates the northern margin of the hill range, while the southern limbs show gentle dips. The KMF is the largest intrabasinal fault of the Kachchh palaeorift basin that originated during Mesozoic time. The fault is traceable for more than 150 km as a steep north facing discontinuous scarp delimiting the Northern Hill Range in upthrown block. It is an E-W trending fault parallel flexure zone comprising asymmetric domal, anticlinal structures and drape folds which form a linear chain of hills. The northern downthrown block comprises Holocene sedimentary basin of the Banni-Great Rann. In the westernmost part, from Lakhpat to Mundhan, the strike of the KMF changes from NNW-SSE to E-W as it is laterally displaced by several NNE-SSW trending transverse faults mostly located in the interdomal saddle zones. Several large magnitude earthquakes have occurred along the KMF viz. 2001 Bhuj earthquake (Ms 7.9), 1956 Anjar earthquake (Ms 6.1) and 1819 Allah bund earthquake (Mw 7.7-8.2).

Tectonic influence on fluvial system

The drainages of the study area comprise north-flowing rivers incising through the rocky landscape and disappearing into the flat Rann surface after cutting through the KMF

scarp. The drainage density is very high which strongly contrasts with the hyper-arid desertic climate of the region. In fact, the streams of the area rarely witness the consistent flow of water even during the monsoon season due to hyper-arid climatic regime. The main drainage divide is not formed by the Jaramara scarp, instead, the rugged hilly topography of the Ukra intrusive that occupies a large part of the back slope of the scarp, forms the main drainage divide. From the intrusive, several streams originate that flow southward into the rocky plain further south. The study area is drained by north flowing rivers which show remarkable correspondence with the structural setup of the area. The drainages flow northward in anti-dip direction, dissecting through the rugged hilly topography of the NHR suggesting a strong component of long-term tectonically induced erosional processes. Deeply incised bedrock channels and knickpoint generation are conspicuous features of the various rivers. Each structural sub-domain of the area shows a strong influence on the drainage network superimposed over it. The Jumara and Jara domes show a prominent radial drainage pattern which is conformity with their structure. The Jaramara scarp does not form a prominent drainage divide, however, several streams originate at the base of the scarp which flow northward along their structurally controlled courses through the Jumara and Jara domes. Only two rivers, the Jara river and the Jumara stream originate on the back slope, just behind the crest of the. These two rivers, particularly the Jara river has developed a spectacular gorge as it flows northward through the scarp and further incising through the low hilly topography of the Jara. The river shows three prominent knickpoints within the gorge. The Gandi river shows the most interesting course that circles around the southwestern and western margin of the Jara dome. It originates from the western part of the Ukra intrusive on the back slopes of the Jaramara scarp and flows in a northwest direction following the swerving strike of the Mesozoic strata and takes a sharp turn to flow northward through the western fringe of the Jara dome. The channel reach of the Gandi river from north of Lakhapar is deeply incised. The river shows three prominent knickpoints, out of which the middle one formed in the rocks of Ukra intrusive is ~25 m. This knickpoint formed at the western fringe of Jara dome is the biggest in the entire study area. The Jara river, as described earlier, forms a deep gorge across the Jaramara scarp and shows a deeply incised channel all throughout its course on the eastern fringe of the Jara dome. A parallel stream to the west of Jara river that originates at the base of the Jaramara scarp also shows a deeply incised channel at the eastern margin of the Jara dome. Similarly, there are streams that follow structurally controlled channels but with significantly less incision, at the eastern as well as the western margin of the Jumara dome. A neotectonic component of tectonic uplift is implicit from the seismically active nature of the area and youthful nature of the drainages.

Tectonic control on landform development

The rugged youthful landscape of the area shows the cumulative effect of the long-term erosion through the Cenozoic in response to sustained uplift along the KMF and other faults. As it is obvious from the foregoing description, the KMF is the main causative fault that has impacted the formation of the asymmetrical domal structures and continued erosion over a prolonged period of time. The geomorphic diversity of the landscape is attributed to the structural complexity of the area as major morphotectonic landforms conform to the structural sub-domains, in the present case, these are the Jumara and Jara domes, the Jaramara scarp, the KMF scarp and the Ukra intrusive. The prominent and precipitous Jaramara scarp is anomalous in the sense that there is no other comparable scarp in the entire length of the NHR. The formation of the scarp is therefore intriguing but nevertheless linked to the long-term structurally controlled erosion due to tectonic uplift.

The most dominating landform of the area is the vertical and almost undissected north facing Jaramara scarp. The scarp formation is primarily attributed to the hard arenaceous lithology of the upper part of Jhuran Formation. The north facing scarp is formed over the gently south-dipping strata of Jhuran Formation. The Jaramara scarp dies out beyond the confines of the Jumara and Jara scarp and no comparable scarp exists further on either side of the study area. The formation of the scarp is therefore primarily controlled by the structural complexities of Jumara and Jara domes. Our studies reveal that the prime reason for the formation and preservation of the Jaramara scarp is the Ukra intrusive on the backslope of the scarp. The intrusive extends in E-W direction and shows discordant contacts. This contrasts with the extension of the intrusive especially towards the west where it changes over to thick sills as seen in Gandi river.

Geomorphic Evidence of Neotectonic Uplift

Almost complete absence of Quaternary deposits in the study area is a strong indicator of prolonged uplift induced erosion due to tectonic activity along the KMF during the Quaternary. Continuous uplift led to constant erosion and negligible Quaternary depositional activity. All sediments generated by extensive erosion were carried away and deposited in the basin to the north of KMF which is presently identified as the Great Rann sub-basin. The Great Rann is a large E-W trending sub-basin bounded by the KMF in the south and the Nagar parker Fault (NPF) in the north. The basin preserves a huge thickness of Quaternary fluvial and

shallow marine sediments. The maximum thickness of the Quaternary sediments of ~300 m is found closer to the KMF and comprises shallow marine Holocene sediments at the top with fluvial sands below. The Quaternary sediments are underlain by full sequence of marine Tertiary and Mesozoic Formations. The maximum thickness of Quaternary sediments together with the subsurface fluvial sediments was primarily facilitated by tectonic activity along the KMF. This resulted in continuous uplift of the upthrown block leading to erosion in the uplifted block and deposition of eroded sediments in the downthrown block i.e. the Great Rann sub-basin. This explains the occurrence of deeply incised bedrock channels, Jara river gorge, large knickpoints and the absence of Quaternary sediments in the Jumara and Jara domes. The role of tectonic uplift as a major factor in the formation of erosional landscape of study area is corroborated by the paleoclimatic studies from the Thar Desert which show that large scale aridity existed in the region for most part of the Quaternary Period and continues at present. A strong component of Quaternary uplift is obvious from the one to one correspondence of structural elements with the topography, the youthfulness of the KMF scarp and the Jaramara scarp. All rivers show structurally controlled courses. Prominent control of domal structural setup on drainage configuration also points to sustained uplift that continued during Quaternary. The presence of the knickpoints, both small and large, along the rivers also suggest that the drainages are in a state of continuous rejuvenation. The ~25 m knickpoint in Gandi river and the Jara river gorge over the Jaramara scarp provide evidence of Quaternary tectonic activity.

Long-term morphotectonic evolution

The study area provides a perfect example of long-term landscape evolution in response to uplift induced structurally controlled erosion due to differential movement along faults. The various E-W trending faults of the Kachchh basin including the KMF were active during the rift sedimentation in Mid-Late Mesozoic time. The sedimentation was followed by an extensive phase of pre-Deccan Trap intrusive activity.

Though there is very little published information of the nature and phases of magmatic activity, a linkage between the structural pattern and evidence of pre- and post-Deccan Trap intrusive activity is obvious. The pre-Deccan Trap intrusive activity along the fault zone led to the doming of the overlying Mesozoic sequence. Offshoots of the intrusive flared out as dykes and sills. The Ukra intrusive, the largest of the intrusive also occurred during this time (Santonian to pre-Deccan Trap). Being a large intrusive body and its offshoots, both concordant

and discordant contacts are observed. This was followed by inversion of the basin in reference to compressive stresses induced by the collision of the Indian plate further to the north. Continued tectonic uplift of the flexure under compression and further along the KMF is known through Tertiary and Quaternary times led to the formation of the present structurally controlled landscape. The hyper-arid climatic regime also points to dominant role of tectonic uplift in the formation of rugged erosional landscape. The Jumara and Jara dome with the differential erosion of the lithologies induced and intruded by tectonic activity. The Quaternary deposits are confined to the north of KMF scarp in the Great Rann sub-basin which forms the downthrown block. Our study of the landscape of Jumara and Jara dome shows that the two domes are possibly two intrusive controlled enclosures within the larger anticlinal flexure. The Jumara scarp forms the southern gentle limb of this large anticline in phases in the post-Deccan Trap inversion phase culminated in the present landscape. In the initial phase, the intrusive activity occurs which includes both the intra-domal and the Ukra intrusive, concordant with faulting along the KMF and transverse faults.

The Jaramara scarp attained its current position during Middle Pleistocene as evidenced by the aeolian miliolite deposited in front of the scarp and on the back slopes of the scarp. The miliolite deposits in the Jara river gorge striding the Jaramara scarp face are incised by ~25 m which is a reflection of the amount of uplift of the area along the KMF in the post-miliolitic time. This is well supported by the ~25 m high knickpoint along the Gandi river that is formed over the Ukra intrusive. The deeply incised courses of the stream and several knickpoints and the Jara river gorge testify to the neotectonic component of uplift induced erosion of the landscape. The precipitous Jaramara scarp is the remnant of a retreated KMF scarp and currently occurs ~4 km away from the actual KMF fault line. The ~4 km distance of the Jaramara scarp from the KMF is the cumulative amount of retreat that has occurred during the Cenozoic. Since then the inversion of the basin began in the post Deccan Trap time. The scarp appears to have been preserved till present mainly because of the wide Ukra intrusive which comprises a more resistant lithology than the Mesozoic rocks. However, the preservation of the scarp is also attributed to the hard and compact arenaceous lithology of the upper part of the Jhuran Formation that makes up almost half of the scarp height. The relatively softer lithologies of the lower part of Jhuran Formation and the underlying Jumara Formation suffered more erosion and formed low dissected structurally controlled topography developed over the Jumara and Jara domes. The present KMF scarp, which is of considerably lower height than the Jaramara scarp, attained most of its present elevation due to post-Miocene uplift along the KMF.

Ground Penetrating Radar (GPR) studies along the KMF

The precise shallow subsurface mapping of western part of the seismically active KMF using Ground Penetrating Radar (GPR) and geological field mapping techniques is done. No neotectonic studies have been carried out so far from its western part even though the eastern half has been investigated in detail to understand the Quaternary tectonic evolution. The study is intended to provide precise details on near-surface trace and shallow subsurface nature of the KMF from Lakhpat to Mundhan forming the westernmost part. The study has implications for understanding neotectonic and seismic hazard estimation along the KMF. The GPR has been proved as the most promising geophysical technique to image and detect the buried active faults and document the related subsurface deformational structures in varying geological settings. Previous studies using GPR combined with field data along other faults in the Kachchh basin have led to a significantly improved understanding of their nature and neotectonic history.

GPR surveys were carried out at several locations with a view to map the continuity of the KMF trace and its shallow subsurface nature. Radargrams from six survey sites are presented and interpreted in terms of the near-surface fault properties of the KMF. The sites include southeast of the Karanpur dome, between Karanpur and Ghuneri dome, at western and eastern flanks of Ghuneri dome, Sahera and western flank of Mundhan anticline. In almost all locations, the fault is buried under thin alluvial cover.

Raw GPR data were processed using a standard processing scheme in order to obtain the best visual representation of radargram to appreciate and interpret the geological features under investigation. The post-survey processing of acquired GPR profiles was done in RADAN (v.7) software by GSSI Inc. Preprocessing of raw GPR radargram is required as the data is affected by different noises, instability of the equipment and vibrations during survey operations. The basic processing steps followed are - time-zero correction, topographic correction, horizontal scale normalization (stretching), background removal, band-pass filtering and gain restoration. The vertical position of radargram was adjusted by using time-zero correction to remove the delay time and to match the surface position. After this step, appropriate 2D background removal filter was applied to suppress the strong low-frequency background noise. Vertical and horizontal band pass filters were applied using Finite Impulse Response (FIR) and Infinite Impulse Response (IIR) Filters to exclude very low and high-frequency noise which improved signal/noise ratio significantly. After applying band-pass

filters, gain restoration function was applied to remove the gain applied during profile acquisition and normalizing the gains for each scan. As the profiles were taken on flat terrain, there was no need to perform the topographic correction except the profile acquired to the north of Mundhan anticline. A 10 scan IIR horizontal low pass filter was applied to further smooth the radargram and to remove high-frequency vertical noise. At last, range gain function was applied to artificially increase the amplitudes of radar signals and to offset the attenuation caused by some processing methods like background removal and improve the visibility of reflectors. The unnecessary information at the beginning and end of radargram (occurs when the antenna is stationary and running in continuous mode) were removed by selecting and cutting undesired blocks. Finally, the CMP profiles were used to determine the subsurface velocity for time-depth conversion during post-processing. Subsurface radar velocities obtained from CMP surveying revealed a relatively constant velocity of 0.12 m/ns.

High resolution GPR imaging along the western part of the KMF in Kachchh palaeorift basin has provided critical data for shallow subsurface fault mapping and fault geometry in contemporary seismotectonic setting. Based on the GPR studies, it is inferred that the KMF is mostly a vertical fault at Mundhan anticline, Ghuneri dome and Sahera which becomes steep southward dipping reverse fault near Karanpur dome. The tendency of the fault plane to become reverse is because its presence in the vicinity of the transverse faults. Thus, the GPR studies along the western part of the KMF are in good agreement with our field geological studies. The data presented shows the need for further structural mapping to understand variations in strike direction and near surface fault geometry.

GPR studies along the Vigodi and the Gugriana Faults

The 2D GPR surveys are carried out with a view to map the continuity of the Vigodi Fault (VF) and the Gugriana Fault (GUF) buried below patchy alluvial cover, to reveal their shallow subsurface nature and to further strengthen our field observations indicating the changing slip sense. The high-resolution 2D GPR radargrams recorded from three selected survey sites are presented and interpreted in terms of the near-surface fault properties of the VF and the GUF.

The VF can be identified at 7.5 m horizontal distance in the radargram. The characteristic signatures of locating a fault plane are identified such as, truncation, thinning and dip change of the radar reflector facies across the fault plane as can be observed in the derived instantaneous phase attribute. Also, small hyperbolic diffraction at the tip of the fault plane can

be observed at 7.5 m horizontal distance. Further, reflectors are dipping due SW in the upthrown block. The position of the VF is further confirmed by the marker given manually during survey when the antenna crossed the strike of surface exposure of the VF. The reverse dip-slip is exemplified as the SW dipping reflectors in the hangingwall are displaced upward with respect to the almost horizontal reflectors in the footwall. Almost horizontal, high amplitude, thick radar reflections throughout the depth of profile at 16–17 m horizontal distance are due to manmade utility buried underground.

The processed radargram shows presence of SW dipping GUF at 11 m horizontal distance that correlates well with the nearby surficial exposure of the GUF. At 5-10 m horizontal distance, the sub-horizontal, high amplitude, thick reflectors of host Bhuj sandstone (devoid of deformation bands) in the footwall are truncated along the GUF. In the hangingwall, at 11-15 m horizontal distance, $\sim 40^\circ$ dipping thin reflectors of Bhuj sandstone are displaced upward with respect to the thick reflectors in the footwall indicating reverse dip-slip along the WVF. They are then covered by loose, sandy alluvium at 0-37 ns depth. The GPR survey also pick the hard, compacted, cluster of deformation bands (dies out in the damage zone of the GUF) as their subtle dielectric contrast with the host, friable Bhuj sandstone. In the radargram, the deformation bands cluster is marked by closely-spaced, sub-parallel, thin, $25-45^\circ$ dipping reflectors. It has to be noted that each, wavy, undulating reflector pattern within the package may/may not mark the individual strand of the deformation bands cluster. The instantaneous phase attribute based on Hilbert transform clearly shows the lateral break in the continuity of the sub-horizontal, high amplitude reflectors marked by offset and dip change of the continuous reflectors.

Paleostress analysis along the Vigodi and the Gugriana Faults

In order to better understand the kinematic evolution of western part of the KRB, detailed structural analyses of the fault system at regional-scale are carried out. The paleostress analyses on the collected fault-slip data is performed. The fault-slip data includes attitudes of fault planes and slickenside lineations, and the sense of slip along the fault plane determined by observing various kinematic indicators. Spatially or temporally varying stress regime may work on the same fault plane. Temporally, the fault may be reactivated multiple times preserving multiple slickenside orientations superimposing one another or the fault may show spatial variation in the stress conditions. Such fault-slip data are called heterogeneous. Multiple stress states are required to explain heterogeneous fault-slip data. The fault-slip data is called

homogeneous if a single stress state explains the whole fault-slip dataset. To accurately compute the paleostress state belonging to distinct tectonic event, to minimize the uncertainties and to cross-examine and increase the reliability of the results, several algorithms are used. Two types of brittle structures in the paleostress inversion procedure are included: fault planes with slickenside lineations and deformation bands with striated, principal slip surface. In the fault damage zone, it is assumed that the tilting of the beds is synchronous to the faulting.

The similar paleostress states are grouped together and two major, distinct deformation events – older D1 and younger D2 are defined that correspond to the regional tectonic events. The older D1 deformation event is further divided into two sub-groups – older D1A and younger D1B. Each sub-group should be considered as sub-type of the major deformation event owing to their similarity with the far-field stress conditions. The deformation phases defined here are multi-phase as the orientation of principal stress axes remains constant during the individual sub-type of the major deformation events. Furthermore, they cannot be considered as progressive in the sense that they are neither immediately preceding/following deformation phases nor showing gradual changes in stress orientations that may give rise to progressive deformation. The deformation events are derived from the consistency among the deduced paleostress tensors from multiple paleostress inversion programs. The age of faulted formations, attitude of principal stress axes, orientation of S_{Hmax} and S_{Hmin} and the governing stress regime are the parameters used to interpret the paleostress tensors belonging to the same deformation events.

The D1 deformation event is characterized by paleostress tensors belonging to the extensional kinematics and is preferentially dominated by ~NW directed extension. W, NW, NNW and NE trending S_{Hmin} directions are observed in each of the sector belonging to NW trending major faults as well as NE oriented unnamed normal faults of local occurrence that terminate against the major fault system. The D1 deformation event is most favorably represented by NE trending normal faults that could not reactive in later times due to their unfavorable orientation, parallel to the ongoing compression stress direction. The younger D2 deformation event characterized by the compressive stress regime is the predominant structural style since the Late Cretaceous in response of far-field stress generated due to India-Eurasia plate collision in the east. It is characterized by NNE compression and is the most dominant and best-fitted stress regime to the present-day stress conditions. The paleostress regimes in the study area involves three major compressions – NNE, NE and E and are related to ongoing compression in response of far-field stresses generated due to post Indian-Eurasian plate convergence.

Inferences

The major inferences drawn from the present study are as follows:

- The youthful topography of the NHR evidenced by deep bedrock incision with several large knickpoints, gorges, the imposing Jaramara scarp and KMF scarps is attributed to multiple phases of tectonic uplift along the KMF during the Cenozoic.
- The deformed Eocene and Miocene rocks along the KMF indicate post-Eocene and post-Miocene tectonic activity under compressional stress regime during the inversion phase.
- Geomorphic evidence from the Jara and Jumara domes suggest tectonic uplift and continued gorge formation during pre- and post-miocene time.
- Field mapping and GPR data show that the uplift bounding fault- KMF is a vertical dipping to high-angle normal fault, while the intra-uplift faults- Vigodi and Gugriana faults are largely high angle reverse faults.
- The paleostress analysis results show that the pure compressive stress regime prevailed with NNE-SSW oriented SHmax along both the intra-uplift Vigodi and Gugriana faults.
- A large part of the compressive stresses were accommodated in the intra-uplift faults zones of the Vigodi and Gugriana faults as evidenced by the reverse nature of the faults and the relatively higher elevations with youthful landscape.