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Remote sensing in lineament identification: Examples from western India

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Abstract

Remote sensing satellite images are studied visually in identifying different lineaments and to interpret therefore the tectonics. The identified lineaments from imagery should be validated (at least partially) by field data. Variation of drainage pattern and vegetation trends can also indicate presence of different structures like domes, synclines etc. as well as certain lineaments. Digital elevation model images provide better idea regarding topographic elevation and thus help in delineating geological structures. After launch of Google Earth, high resolution satellite images are freely available, thus researchers can use those for different purposes: pre-field reconnaissance survey, lineament identification in remote areas, virtual fieldwork etc. Here we analyse satellite images from different intra and peri-cratonic basins of western India. Towards the end of the chapter, few problems have been presented related to lineament identification from Google Earth Pro satellite imagery. The solutions are given in the Appendix.

Keywords: (1) Lineaments, (2) remote sensing, (3) Google Earth, (4) Indian Space Research Organisation, (5) dykes, (6) Barmer basin, (7) Kutch basin, (8) Deccan trap

Introduction

Academic and industry geoscientists acquire significant knowledge from on-job learning or learning-by-doing and through outcrop-based studies in various terrains. Laboratory experiments (Mukherjee et al. 2012), software-based modelling (Bose et al. submitted), analytical modelling (Mukherjee 2012a), microstructural studies (Mukherjee 2012b), seismic studies (Misra and Mukherjee 2018a) and fieldworks (Mukherjee 2013) are some of these methods. Fieldwork is an excellent way of learning structures, tectonics, geomorphology etc. It helps in understanding the formation of different structures (e.g., folds, faults, joints, boudins and primary sedimentary structures) sometimes in 3D sense also. Understanding tectonic structures is an important aspect of geological map interpretation (Bose and Mukherjee 2017), which helps in planning exploration programs such as acquisition of seismic and geochemical data, site selection for drilling wells in hydrocarbon exploration etc. (Stone 1999; Marjoribanks 2010; De Donatis et al. 2012). Detail structural analyses helps in interpreting and finding geneses of different structures. Thus fieldwork is the most direct technique to get true geological data, which can be used in understanding, assessing and developing exploration in rifted, intra-cratonic and/or peri-cratonic basins in extensional and/or compressional settings (Marjoribanks 2010; De Donatis et al. 2012; Racey et al. 2016; Dasgupta and Mukherjee, 2017; Dasgupta, 2018a, b; Dasgupta and Maitra, 2018; Misra et al., 2018a, b; Misra and Mukherjee 2018b). Now-a-days digital pen supported laptops and tablets with GPS application are available, which not only benefits field geologists in acquiring more accurate data but also to store and interpret the field data and keep a track of the implemented processes (De Donatis et al. 2012). During past few decades remote sensing techniques are being extensively used in large-scale geological mapping and to identify different structural features with support of field work for ground truthing (Gupta, 2003; Lageson et al. 2012;

Tewksbury et al. 2012; Misra et al. 2014; Prost, 2014; Abdunaser, 2015; Dasgupta and Mukherjee, 2017). Geological mapping practices have further improved with integrating of geographical information systems (GIS) with remote sensing data and fieldwork outputs (Bonham-Carter, 1994; DeDonatis et al. 2012; Prost, 2014; Abdunaser, 2015).

Lineament analyses is the key element to interpret regional to sub-regional scale structures from remote sensing imagery (O'Leary et al. 1976; Karnkowski and Ozimkowski, 1999; Gupta, 2003; Fisher et al. 2012; Lageson et al. 2012; Tewksbury et al. 2012; Prost, 2014; Misra et al. 2014; Abdunaser, 2015; Rahmati Kamel et al. 2015; Rana et al. 2016; Babar et al., 2017; Kaplay et al., 2017a,b). Any natural linear feature on the Earth surface related to extension/compression/strike slip or as a result of igneous or metamorphic activity is termed as a lineament (Karnkowski and Ozimkowski, 1999; Prost, 2014). There are different types of lineaments, which include shear zones, faults, dykes, mineralized veins, fold hinges, uplifted topography or contacts between rock types, elongated fractures, fault-related traps, linear sink holes, fault bound elongated valleys etc. (Gupta 2003; Prost 2014). Other than lineaments, drainage patterns in many cases indicate the trend/type of subcrop structures (Prost 2014). For example, on a flat terrain the drainage pattern is normally dendritic; however, domal structure is generally accompanied with radial and concentric drainage (Gupta 2003; Prost 2014). There are several other structurally controlled drainage patterns such as orthogonal drainage, barbed drainage, compressed meanders, double drainage etc. (Doeringsfeld and Ivey, 1964; Prost 2014). Even variation/trend of vegetation cover may also indicate presence of certain lineaments or some other subcrop structures (Prost 2014).

Remote Sensing Technique and its Application

Remote sensing technology guided by satellite imagery data is very convenient to identify geological structures, as well as varied type of landforms and drainage patterns. Thus is immensely helpful in mineral and hydrocarbon exploration and geological mapping (Campbell 2002; Gupta 2003; Prost 2014; Rahmati Kamel et al. 2015). Satellite imagery comes in the form of digital image data, in raster form, which consist of numerous pixels arranged in rows and columns (Gupta 2003). Each of these pixels reflects a particular area on the Earth surface and possesses a numerical value/digital number (Drury and Drury, 2001; Gupta, 2003; Rahmati Kamel et al. 2015).

Image processing is a key step in remote sensing. A number of filtering processes (like noise filter, blur filter, high-pass filter, low-pass filter, band-pass filter etc.) are applied on the satellite derived digital image in order to distinguish the object of interest with greater confidence (Gupta, 2003; Rees 2013; Prost, 2014; Rahmati Kamel et al. 2015). Principal component analysis is also applied to different bands of satellite data to minimise duplicate data or perplexing elements like topography effect, shadow and effect of sun rays falling at an angle on the Earth surface (Ayday and Gümüşlüoğlu, 2008; Rahmati Kamel et al. 2015). Thus remote sensing technique is a rather easier process to explore potentially widespread areas. Better satellite image resolution is now available, both spatially as well as in different bands, with advent of advanced satellite sensors and data processing techniques (Soille and Pesaresi, 2002; Rahmati Kamel et al. 2015). With enhanced resolution, the scale of an image also increases, which is an important factor (Prost,2014) for detail mapping and analyses of structures. 3D topographic models of an area are also available from digital elevation model (DEM) images for better delineation of geological structures (Alaa, 2006; Prost, 2014; Kaya, 2013).

To delineate a particular topographic feature, the direction of sun-ray and its subsequent shadow is used as a tool in the DEM images, thereby giving a better idea about the topographic elevation. Variation in slope of a topographic feature in a DEM image results in change in brightness, in relation to sun illumination direction, and thus helps in identifying the dip direction (Tewksbury et al. 2012). Several countries have their Earth observation satellites having different sensors and instrument systems used for specific non-military purposes such as weather monitoring, observation of sea level changes, air pollution, land mapping etc. Some countries conduct joint venture projects as per requirements. Few examples of satellite programs (Prost 2014) conducted by various countries are: Landsat series (1, 2, 3, 4, 5, 6, 7 and 8) of United States of America, *System Probatoire d' Observation de la Terra* (SPOT) series of France, IRS and Cartosat series of India.

The Google Earth: Applications and Uses

Previously researchers used satellite imageries of Landsat, ASTER, MODIS SRTM etc. having image resolution ranging between ~15 m (Landsat 7 ETM+) to 250 m (MODIS). For high resolution images, one has to purchase them from commercial dealers such as Digital Globe, GeoEye etc. With launch of Google Earth (2005 onwards, Bailey et al. 2012; Fisher et al. 2012), we can view, track and access any remote areas on the Earth's surface free of cost. It has now become one of the most convenient and powerful tool for geoscientists aimed at observing and analysing geological features (Google Inc., 2011; Bailey et al. 2012).

The Google Earth algorithm constitutes surface based satellite imagery integrated with a DEM that replicates the Earth's surface (Bailey et al. 2012). Initially Google Earth used

freely available Landsat 7 data having ~ 15-30 m resolution along with Shuttle Radar Topography Mission (SRTM) digital elevation models having 30 m or 90 m resolution (Farr et al. 2007; Fisher et al. 2012). Now a days Google Earth comprises of wide range of true-colour visible spectrum satellite imagery obtained from different public domain Landsat imagery (7 and 8), and high resolution data available from commercial vendors like Digital Globe™ (www.digitalglobe.com), GeoEye™ (www.geoeye.com), and SPOT™ (www.spot.com) (Tewksbury et al. 2012; Fisher et al. 2012). The image resolution ranges < 1 m to ~ 15 m globally (Fisher et al. 2012; Tewksbury et al. 2012). With incorporation of Keyhole Markup Language (KML) in Google Earth platform (in 2004-05) and later adoption by Open Geospatial Consortium (OGC, in 2008), data files of Google Earth can be opened and viewed in other mapping and geographic information software such as ArcGIS, QGIS (Bailey et al. 2012; Tewksbury et al. 2012). A KML file includes both symbols and data, which can be imported and exported from Google Earth (Guth, 2012). Thus it facilitates digitisation of geological maps incorporating various data like coordinate information, lineament plots etc. from Google Earth.

The updated and advanced version of Google Earth is known as Google Earth Pro, which is now available free of cost. Google Earth/Google Earth Pro enables a vivid 3D visualization of the Earth's landscape (Lageson et al. 2012). It is of immense use in pre-field planning and reconnaissance survey in order to identify key outcrop locations as well as link remote areas with outcrops validated by field data. Moreover, it is a very useful tool to study structural elements in remote and war-torn or politically disturbed regions. One can even carry out a virtual field tour using Google Earth/Google Earth Pro (Lang et al. 2012; Lageson et al. 2012; Tewksbury et al. 2012). However like other software tools, Google Earth too has some limitations (Fisher et al. 2012). It is known that Google Earth/Google Earth Pro uses SRTM

DEM data as elevation profile amalgamated with Landsat and other satellite imagery data. In some areas, it even uses ASTEM DEM and Lidar data (Perroy et al. 2010; Slater et al. 2011), but to what extent the new elevation data are integrated in Google Earth is indeterminate (Fisher et al. 2012). Also, in many terrains having considerable relief, shadowing effect (due to particular incidence angle direction of sun ray path) may mask/obscure few structural and geomorphic features. Similarly there is lesser chance of getting lineament and other geomorphic landform data in areas having thick vegetation cover (Fisher et al. 2012).

Other than Google Earth/Google Earth Pro, some other open source software applications are also available, which provide virtual tour of the Earth's landscape (Prost, 2014), e.g., NASA World Wind, Open Web Globe and *Bhuvan* of the Indian Space Research Organisation (ISRO). *Bhuvan* uses merged/fusion satellite imagery data provided by ISRO's Resourcesat-1, LISS – IV, Cartosat-1 and Cartosat-2 series, with image resolution ranging 1-15 m (www.bhuvan.nrsc.gov.in; www.isro.gov.in).

Lineament Interpretation procedure from Western Indian Terrain

In the following paragraphs different lineament guided structural features and the method to distinguish them would be discussed, using remote sensing satellite imagery obtained from Google Earth Pro from western India. Three locations are identified: (a) northern part of Barmer basin, Rajasthan, (b) Kutch basin, Gujarat and (c) western Deccan region of Maharashtra (Fig. 1).

[Insert Fig 1 here]

(a) Northern part of Barmer basin, Rajasthan

Tectonics: The Barmer basin in W Rajasthan, India, is a narrow (~ 50 km) oblique intracratonic failed rift basin, which initiated during Early Cretaceous and continued up to Tertiary (Dolson et al. 2015; Dasgupta and Mukherjee, 2017). The basin extended non-coaxially twice: (a) along NW-SE, during E Cretaceous, and (b) along NE-SW during Late Cretaceous to Early Tertiary (Bladon et al. 2015). These link with two tectonic episodes viz., oblique separation of Madagascar from India, and break-up of Seychelles micro-continent from the Indian plate respectively. The Late Proterozoic Malani Igneous Suite/Malani Rhyolites (Bhushan 1999; Sharma 2005) constitute the basement rock for this basin. This basement rock consists of Late Proterozoic ~N trending rift fractures, indicating that the Malani Igneous Suite probably evolved through these rift fractures (Sharma 2005). The basin shallows up towards N where it is bound by the Fatehgarh Fault or the Devikot-Fatehgarh Ridge (Misra et al. 1993; Compton 2009) and extends ~200 km up to Sanchor in S. The Malani Rhyolites expose along the isostatically uplifted W margin. The Cretaceous sequence expose in the E margin near the Sarnoo village along a set of uplifted hillocks (Compton 2009; Bladon et al. 2014; Dolson et al. 2015; Dasgupta and Mukherjee, 2017). A few Late Proterozoic equivalent rift fractures reactivated during Late Cretaceous–Early Tertiary along the E margin of the Barmer basin (Torsvik et al. 2001; Sharma 2005). Cross-cut relationship between NE trending faults of first phase of extension followed by NW trending faults of second phase of rifting is documented from outcrop studies (Dasgupta and Mukherjee, 2017 and unpublished works by these authors).

The rift faults in N and E part of the basin is dominated by transfer zones as depicted by the sub-surface fault map (Bladon et al. 2015). This indicates that the pre-existing tectonic

fractures of the Malani Igneous Suite have most likely guided the main phase of Barmer rifting during Late Cretaceous to Early Tertiary (Dasgupta and Mukherjee, 2017). Reactivation and uplifted hillocks of Tertiary sediments are seen only in the N boundary along the Fatehgarh Fault (Compton 2009). A number of reverse faults exist in the W and E rift shoulders which are likely to be linked to isostatic uplifts (Dasgupta and Mukherjee, 2017). Intrusion of precursor of Deccan volcanics is present near Sarnoo and Tavidar village along the E margin (Roy 2003; Sharma 2007; Compton 2009; Vijayan et al. 2015). These pre-Deccan volcanic sills are displaced by NW trending faults in the E rift shoulder indicating that the main phase of Barmer rifting occurred after the pre-Deccan volcanics emplaced (Dasgupta and Mukherjee, 2017). Few small, outcrop-scale dykes exist in and around Sarnoo area in eastern margin and also in Dhorimana and Jasai villages in the western margin, which are related to the Late Proterozoic Malani magmatism and the Pre-Deccan volcanics of Late Maastrichtian (Pandit et al. 1999; Vijayan et al. 2015; Dasgupta and Mukherjee, 2017). Thus the Barmer basin is affected by multiple tectonic phases. The latest one is the N bounding reactivated Fatehgarh Fault, which is due to neotectonics related to the Himalayan collision orogeny (Compton 2009; Kelly et al. 2014).

[Insert Fig 2 here]

Case Study: The Fatehgarh fault trend or the Devikot-Fatehgarh ridge extends as disconnected hillocks for ~ 20-30 km, associated with uplifted Tertiary sedimentary sequence moderately dipping towards S/SE (Dasgupta and Mukherjee, 2017). These ~ NE/ENE trending discontinuous hillocks consist of Fatehgarh Sandstone of Paleocene at the bottom overlain by volcanic ash bed of Bariyada Member (Paleocene-Early Eocene) and silty

mudstone of Dharvi Dungar Formation (Eocene), exposed along the N/NNW facing fault scarp (Compton 2009; Dasgupta and Mukherjee, 2017). Hence, this reactivated ridge is not a full grown fault having reverse slip. Rather, it can be explained as a disconnected fault system that is associated with transfer zones (Dasgupta and Mukherjee, 2017; also see Peacock and Sanderson, 1991; Fossen and Rotevatn 2016).

The Google Earth Pro satellite imagery depicts these relay structures in the eastern segment of the fault trend (Fig 2; Dasgupta and Mukherjee, 2017). Although the hillocks are of low elevation, the N/NW facing fault scarp is still identified from the Google Earth Pro satellite imagery considering the illumination difference between the darker fault scarp and the brighter S/SE dipping slopes of the hillocks (Fig. 2). These transfer zones or relay structures are in general synthetic approaching to overlapping type (Morley et al. 1990; Dasgupta and Mukherjee, 2017). In these cases the vertical displacement of the adjacent ridges, dipping in same direction, tends to decrease while they approach each other. This has been identified in field as well as in Google Earth Pro imagery (Fig. 2a'; Dasgupta and Mukherjee, 2017). The synthetic overlapping transfer zones are normally soft-linked by relay ramps (e.g. Dasgupta and Maitra, 2018), while some of the synthetic approaching types are hard linked and are commonly associated with tectonic fractures (Fig. 2a'; Dasgupta and Mukherjee, 2017). The tectonic fractures ($\text{dip} > 45^\circ$) has been identified in outcrop study and are often associated with carbonate cementation (Dasgupta and Mukherjee, 2017) These hard linked transfer zones are known as breached relay ramps or transfer faults (Fossen and Rotevatn 2016).

(b) Kutch basin, Gujarat

Tectonics: The peri-cratonic Kutch rift basin of Gujarat, India, originated during Late Triassic Gondwana fragmentation guided by reactivation of pre-existing ~E trending faults of Proterozoic Delhi fold belt (Biswas 1982, 1987, 2005; Roy et al. 2017). This rift basin is bound by a set of sub-parallel reactivated faults of which the Nagar Parkar fault is the northern limit and the N Kathiawar fault acts as the southernmost bounding fault (Biswas 2005). The Mesozoic sequence are aligned along these reactivated faults (namely the Katrol hill fault, Kutch Mainland fault, South Wagad fault, Island Belt fault and the Nagar Parkar fault) in the form of rugged uplifted hillocks (Biswas and Khattri, 2002; Biswas 2005). Overall the basin slopes towards S to SW and sediment thickness varies from < 500 m in N to > 4000 m towards S (Biswas 2005).

The Precambrian basement is exposed towards N along the Nagar Parkar fault. Overall the Kutch rift basin evolved in broadly three tectonic episodes: (a) rift phase during Late Triassic to Cretaceous related to break-up of Gondwanaland, (b) late rift phase of drifting and strike-slip movement from Late Cretaceous onwards associated with post-Deccan Trap related inversion, and (c) Post rift phase of reactivation and strike slip movement during collision of Indian plate with Asia. A number of neo-tectonic activities along these ~E trending reactivated faults, mainly the Kutch Mainland fault (KMF) and Katrol Hill fault (KHF), occurred during Himalayan orogeny and continue to present day due to dextral strike slip movement along these faults (Chandra 1977; Chung and Gao, 1995; Biswas 2005; Patidar et al. 2008; Maurya et al. 2017). These neo-tectonic activities have affected the river drainage system in the basin (Patidar et al. 2007; Maurya et al. 2017) significantly. Furthermore a number of magmatic activities have occurred along these faults during different geological time mainly during Marion and Reunion plume activity in the form of plutonic intrusion as well as volcanic flows (Biswas 2005; Roy et al. 2017).

[Insert Fig 3 here]

Case Study: The Older Mesozoic sequence along the Katrol Hill Range is highly deformed to dome/anticline, truncated against the Katrol Hill Fault (KHF) as a result of tectonic inversion (Maurya et al. 2017). The KHF marks the boundary between the Older Mesozoic in S and the Cretaceous Bhuj Formation towards N (Biswas 2005; Patidar et al. 2008). The Deccan Trap overlies the Mesozoic sequence towards further S of the KHF (Biswas and Deshpande, 1973). The study of Google Earth Pro derived satellite imagery of the KHF area, with support from published literatures, suggests that the geomorphic landform consists of fault-controlled topography with N-facing fault scarp and fault controlled drainage system associated with incised gorges (Figs 3, 4b; Patidar et al. 2007, 2008; Maurya et al. 2017). The N facing fault scarp is identified from Google Earth Pro satellite imagery based on variation in brightness of the scarp and the dip slope (e.g. fig 5; Tewksbury et al. 2012). The lateral extent of the KHF is segmented by a number of transverse faults (Figs. 3a', 4b; Patidar et al. 2007). Here transverse is referred with respect to that of the ~E trending KHF. Many of the recent drainage systems are guided by these transverse faults (Fig. 3). Some of the Older Mesozoic domes in southern part of KHF produce radial drainage pattern (Fig. 3a and a'). A number of Deccan-equivalent dykes, trending NW, N and NE, are observed in the southern part of KHF cutting across the Older Mesozoic (Figs. 3a', 4b; Patidar et al. 2007). A few dykes are displaced by the transverse faults as seen in the Google Earth Pro imagery, possibly indicating faulting after the Deccan volcanism (Figs. 3a', 4b). Normally, the transverse/transfer faults promote stress transfer along a typical normal rift-related fault (Fossen 2016; Fossen and Rotevatn, 2016). However in case of inversion of the normal faults

due to regional or far field tectonic forces, the earlier transverse faults may act as stress barriers, thereby producing compressive structures and seismic activity close to them. Similar type of scenario, inverted structures related to compressive stress regime and earthquake activity, exists close to the transverse faults S of the KHF (Maurya et al. 2017, Patidar et al. 2007). A few Deccan-equivalent dykes are displaced by the transverse faults (Fig. 3a'; Patidar et al. 2007, 2008). Moreover some issues still remain unclear. These are: (i) whether these NW-N-NE trending dykes have evolved along older transfer faults/tectonic fractures, and (ii) the tectonic relation between earlier fractures and the transverse faults. Detailed structural fieldwork and paleostress analysis could resolve them.

[Insert Fig. 4 here]

The Kutch Mainland Fault (KMF) also depicts a similar type of geomorphic landform like that of the KHF, as observed from the Google Earth Pro imagery (Figs. 3b,b'). Areas close to the KMF consists of steep N-facing scarp and is also segmented by a number of NNW to NNE trending transverse faults (Fig. 3b'; Maurya et al. 2003, 2017), with respect to that of KMF. A number of domal structures of Mesozoic rocks having distinct radial drainage pattern are observed along the southern part of KMF (Figs. 3b,b'). The channels flowing north cuts deep incised gorges in the fault scarp zone (Maurya et al. 2017). These domes are developed in between the transverse faults along the W-E trending KMF, with their elevation gradually decreasing towards E (Biswas 1993; Maurya et al. 2017). The drainage patterns are strongly guided by the transverse faults similar to that of KHF (Figs. 3a',b'). In the Kutch basin, the reactivated faults of KHF and KMF are of more pronounced and matured type as against the disconnected fault system linked by relay structures of Fatehgarh Fault in N

Barmer basin, having gentler sloping fault scarp (Figs. 4a,b). The Katrol hill range and the domes and anticlines along the KMF have much higher relief with the rivers cutting deep incised valleys (Patidar et al. 2007; Maurya et al. 2017) as compared to that of Fatehgarh Fault trend.

(c) Western Deccan region of Maharashtra

Tectonics: The Deccan Trap or the Deccan Large Igneous Province (DLIP) covers a significant part of western peninsular India, in states of Maharashtra, Goa, and Gujarat and to some extent in Madhya Pradesh and southern Rajasthan (Misra and Mukherjee 2015; Misra and Mukherjee, 2017; Mukherjee et al. 2017). The DLIP is marked by voluminous flow of flood basalt closely related to drifting of Indian plate over the Réunion plume during which the Seychelles micro-continent separated from the Indian western continental margin. It is widely agreed that, on the basis of outcrop studies and geochronology data from dykes and other alkaline felsic rocks, that most the flood basalts emplaced (~ 65–68 Ma) prior to India–Seychelles break-up during ~ 63–64 Ma, the rifting of which initiated much earlier ~ 80 Ma (Collier et al. 2008; Ganerød et al. 2011; Misra et al. 2014). Numerous dykes that crops out around Mumbai region and along the coastal Maharashtra, trends NW -N – NE, the ~N striking dykes being the most numerous one (Misra et al. 2014; Misra and Mukherjee, 2017; compare with Babar et al. 2017; Kaplay et al. 2017a,b). The dykes have intruded various brittle shear Y- and P-planes. Several dykes have been cut across or displaced by brittle shear planes, as observed in field as well as in remote sensing imagery (Misra et al. 2014; Misra and Mukherjee, 2017). The dyke and brittle shear relationship and paleostress analyses suggest that the rifting between India and Seychelles has not been perfectly orthogonal but rather oblique in nature trending ~NE (Misra et al. 2014; Misra and Mukherjee, 2017).

[Insert Fig. 5 here]

Case Study: The Deccan Trap exposures are seen in and around Mumbai, along coastal areas and other parts of interior Maharashtra, in the western part of Western Ghat. These dykes appear as linear elevated features, sometimes protruding up from lakes and sea water, while some are seen as narrow linear depressions in outcrops (Misra et al. 2014; Misra and Mukherjee, 2017). In many cases these dykes are concealed by vegetation cover. However, while interpreting dykes from remote sensing images, validation from field data is required as many of the identified lineaments could be related to faults or other brittle shear structures (as in Misra et al. 2014). The Google Earth Pro satellite imagery from western Maharashtra depicts dykes within the Deccan Trap trending NNE – NE – to - ~E (Fig. 5). These dykes have been validated from fieldwork (Misra et al. 2014, Misra 2015, Misra and Mukherjee, 2017). Note that the dykes around the Tansa lake, ~80-90 km NE of Mumbai, protrudes up from the lake water and is vegetative covered (Figs. 5a,a'), with cross-cut relationship. While the smaller-scale NE trending dykes, in the rocky beach near Murud, are manifest as narrow linear depressions (Figs. 5b,b').

Problems

Now that we have an awareness regarding different type of lineament identification on satellite imagery and the chosen study areas, let us solve some problems related to them.

1. Identify the type of lineament seen in Fig. 6. What does the dark shadow zone in the middle of the figure indicates? Annotate the different features of the lineament. Also mention the significance of the drainage pattern.

[Insert Fig. 6 here]

2. Identify the type of lineaments seen in Fig 7. Mark the nature of displacement (if any), along some of the lineaments, identified from the Google Earth satellite imagery.

[Insert Fig. 7 here]

3. Mark the different lineaments as seen in the Google Earth satellite imagery of Fig. 8. What does the drainage system signify? If possible create a rose diagram of the lineament trends.

[Insert Fig. 8 here]

Conclusions

Present day public domain remote sensing imagery provided by Google Earth/Google Earth Pro and some other sources such as ISRO's Bhuvan, are good enough to identify and interpret different structural features in a regional-scale as well as tens of meters/meso-scale. Google Earth Pro also provides historical imagery data from past years in order to understand

the changes in geomorphic landforms due to present day erosion and/or deposition and the impact of human activity.

In this study, the Google Earth Pro imagery from various parts of western India depicts different type of lineaments, and the technique to recognize them. It also illustrates how to identify and differentiate a mature fault from a disconnected fault system linked by transfer zones (as described in Barmer and Kutch basins). Lineaments to be designated as dykes are also critical to specify from remote sensing imagery, until it is supplemented by field data. This work also points out that the intensity of the dykes has increased on traversing ~ 1000 km towards S along the western margin of India (i.e., Barmer to Kutch to western Maharashtra). Lineament analysis from open source satellite imagery data (e.g. Google Earth/Google Earth Pro) is of great help to study the regional tectonic frameworks. It is also a guiding tool for understanding the tectonic linkage between adjacent basins. Nevertheless, it is always better to have ground truth data from fieldwork to validate the findings from remote sensing imagery.

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Appendix

Solutions of Figs. 6, 7 and 8 are given in Appendix Figs. 1, 2 and 3, respectively.

[Insert Appendix Figs. 1-3 here]

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List of Figs.

Fig. 1. Maps presenting major tectonic elements from three different regions of western India. (A) Barmer basin, Rajasthan; (B) Kutch basin, Gujarat; and (C) W Deccan region, Maharashtra, India. Black box/circle highlighted in maps: locations from where satellite imagery data from Google Earth Pro were taken for lineament study, as shown in Figs. 2-5. Modified from Patidar et al. (2008), Misra et al. (2014), Dasgupta and Mukherjee (2017), and Maurya et al. (2017).

Fig. 2. Uninterpreted (a) and interpreted (a') Google Earth Pro satellite images of disconnected fault system linked by transfer zones in the NE part of Fatehgarh Fault having north facing scarp (shadow zone). Location: ~ 110 km NE of Barmer town in the eastern side of National Highway-15 (refer Fig. 1A). Two types of relay structures observed: (i) synthetic overlapping (a'), and (ii) synthetic approaching, which is likely hard linked by transfer fault (a'). Note that the seasonal drainage pattern is modified by the fault system. Also, the drainage pattern is guided by the relay structure. Inset: synthetic transfer zones, examples from figs. 4 a,b of Morley et al. (1990).

Fig. 3. Uninterpreted (a,b) and interpreted (a',b') Google Earth Pro satellite images of part of Katrol Hill Fault (KHF; a and a'; refer Fig. 1B) and Kutch Mainland Fault (KMF; b and b'; refer Fig. 1B) depicting well matured reactivated fault system cut across by transverse faults (yellow dotted line). In the southern part of KHF, the transverse faults have displaced the Deccan equivalent dyke (a'). Most of the dykes are towards S of the KHF (also see Patidar et al. 2008; Maurya et al. 2017). Also the drainage pattern modified by the transverse faults (a'

and b'). Blue dotted line in a': the region across which the drainage pattern changes due to varied geomorphic landform. A domal structure is observed immediately below the KHF, in between the displaced dyke at W and the transverse fault at E (a'). The domal structure (Jhura dome; Maurya et al. 2017) south of KMF is more pronounced with distinct radial drainage pattern (b').

Fig. 4. Comparison of two types of fault system, (a) disconnected fault system linked by relay structures along the Fatehgarh Fault in the northernmost part of Barmer basin, Rajasthan, India, and (b) mature/advance fault system of the KHF segmented by transverse faults. Note: Both of these faults have reactivated as reverse dip-slip faults as a result of compressional forces related to Himalayan orogeny (Chung and Gao, 1995; Biswas 2005; Compton, 2009; Patidar et al. 2008; Kelly et al. 2014, Dasgupta and Mukherjee, 2017). Inset: Disconnected fault systems in early stage can get linked by the effect of underneath pre-existing basement structures forming matured faults in advanced stage (fig. 4c in Fossen and Rotevatn, 2016).

Fig. 5. Uninterpreted (a,b) and interpreted (a',b') Google Earth Pro satellite images from western Deccan region, Maharashtra, India. Figures (a) and (a') are from Tansa lake area, ~80-90 km NE of Mumbai (refer Fig. 1C), depicting cross cutting relationship of ~ N-NE and ~ E trending dykes. Note that the dykes protrude up from the water and have thick vegetative cover. Figures (b) and (b') are from a rocky beach near Murud (refer Fig. 1C), consisting of smaller dykes with narrow linear depressions.

Fig. 6. Satellite imagery obtained from Google Earth Pro from N of Barmer basin, Rajasthan, India (refer Fig. 1A).

Fig. 7. Satellite imagery obtained from Google Earth Pro from NW of Kutch basin, Gujarat, India (refer Fig. 1B).

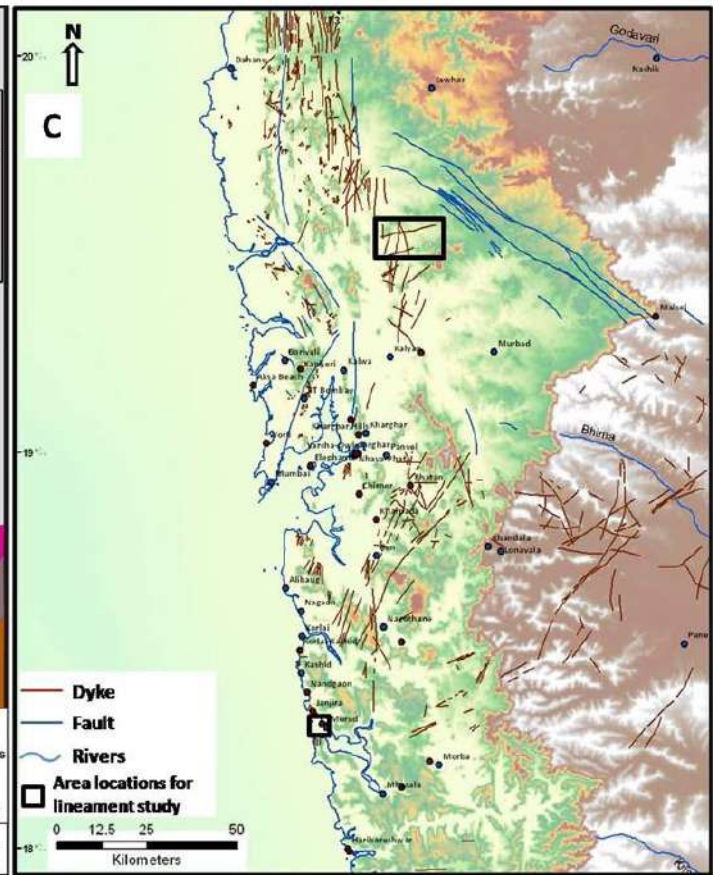
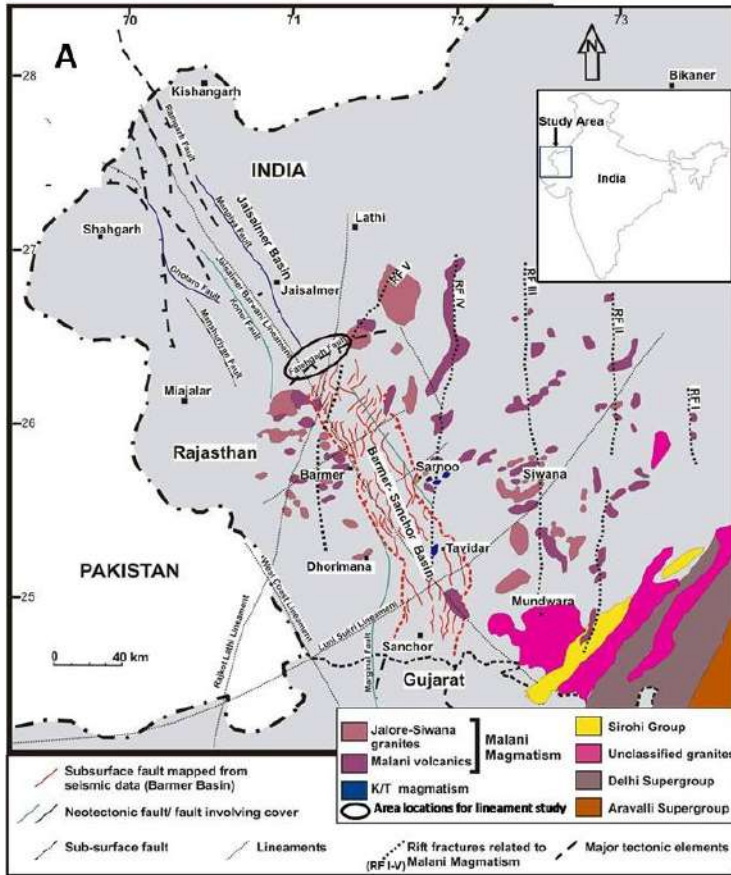
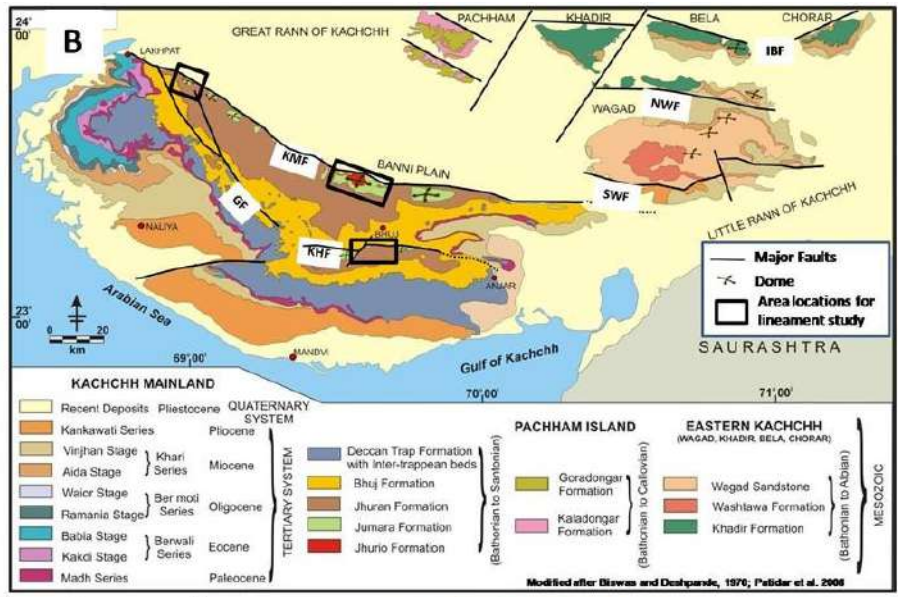
Fig. 8. Satellite imagery obtained from Google Earth Pro from SE of Saurashtra basin, Gujarat, India, about 65 km SW of Bhavnagar city.

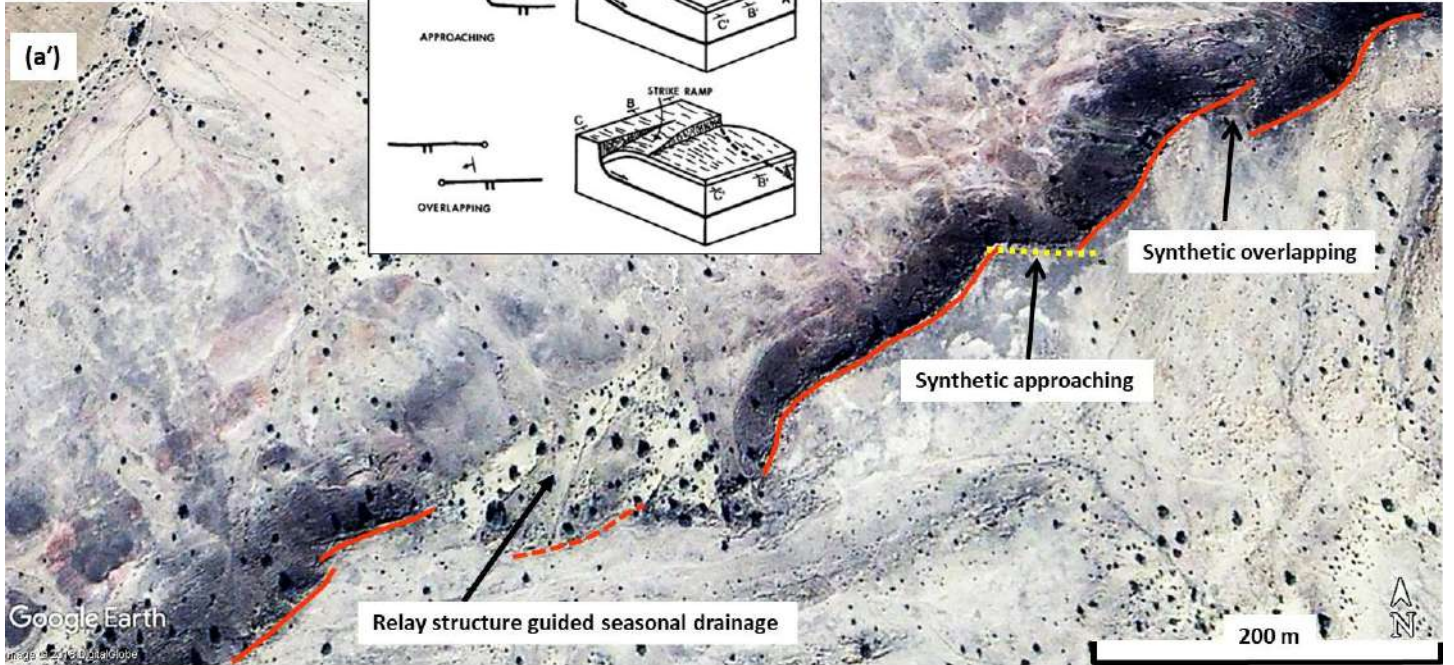
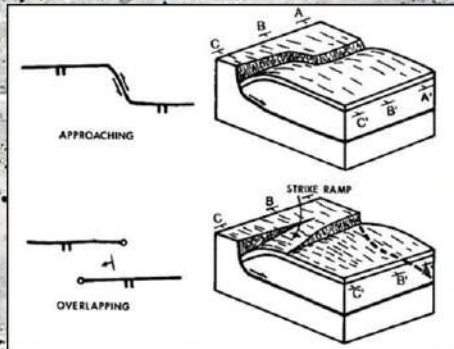
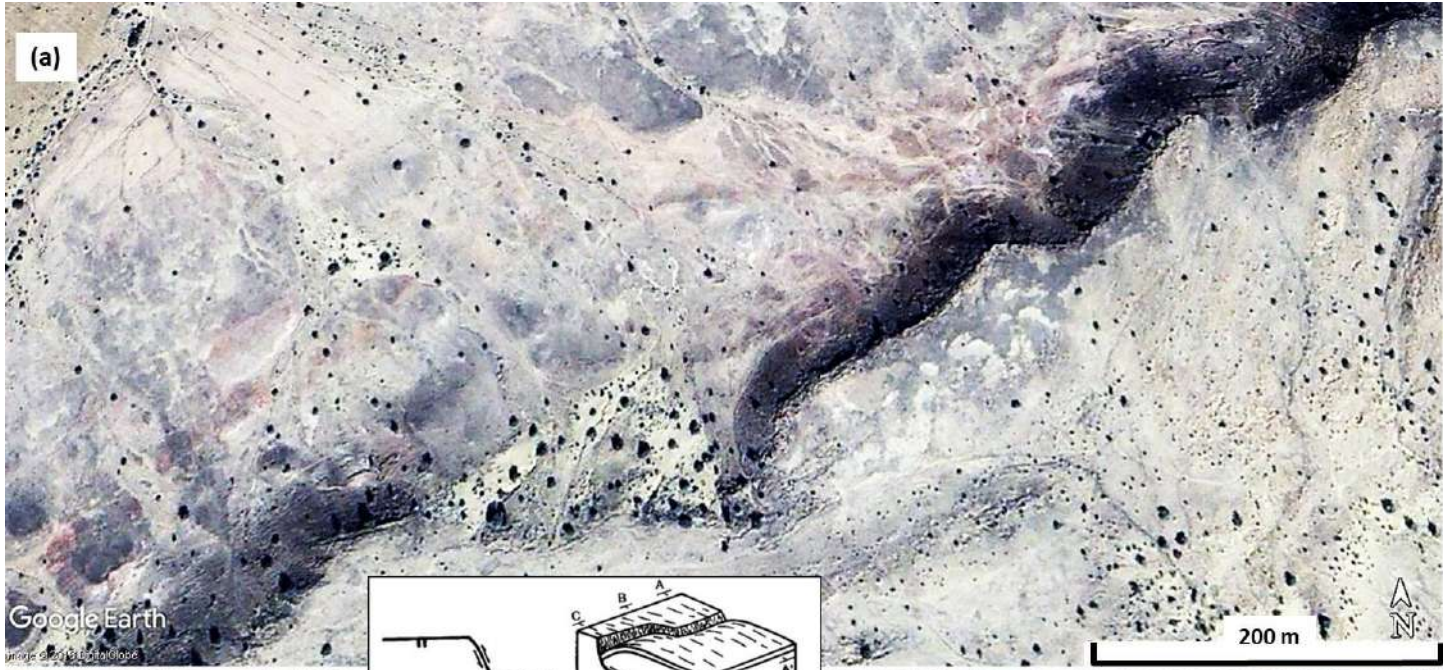
Appendix Fig. 1. Google Earth Pro satellite image from NE part of Fatehgarh Fault, ~ 110 km NE of Barmer town (refer Fig. 1A). The image depicts disconnected fault system trending ~ NE, linked by transfer zones with N to NW facing scarp (shadow zone). Two types of relay structures observed: (1) synthetic overlapping, and (2) synthetic approaching, which is likely to be hard-linked by the transfer fault (Dasgupta and Mukherjee, 2017). Note that the seasonal drainage pattern is modified by the fault system; also, the drainage pattern is guided by the relay structure. Inset: Synthetic transfer zones, examples from figs. 4 a,b of Morley et al. (1990).

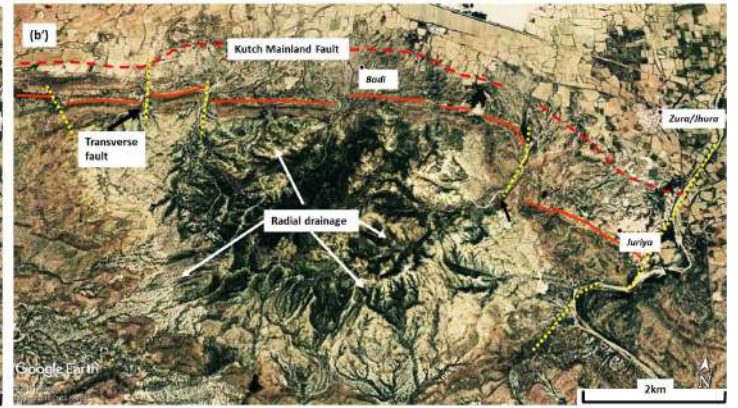
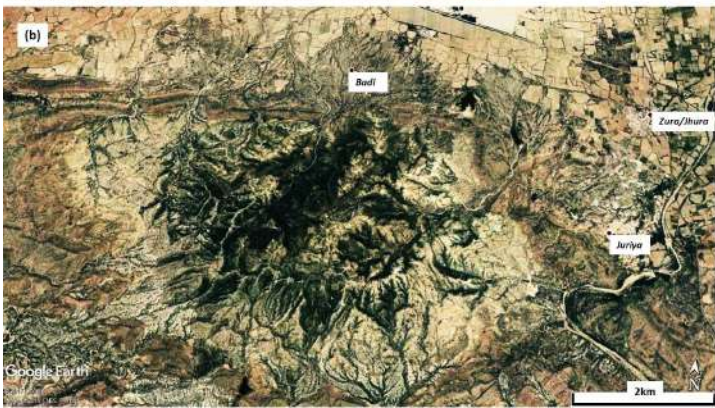
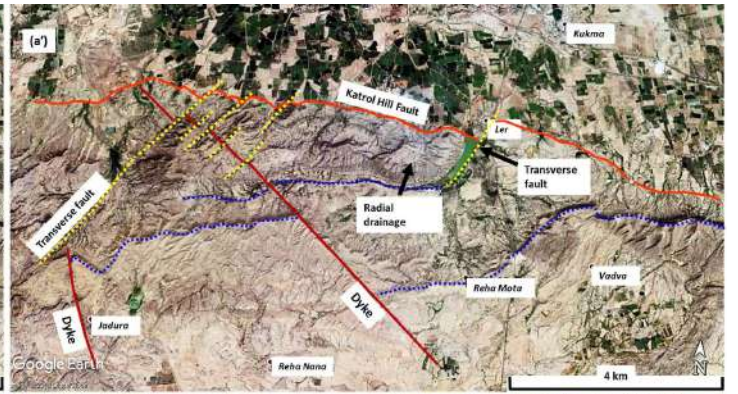
Appendix Fig. 2. Google Earth Pro satellite imagery from NW Kutch basin, near Lakhpat, Gujarat (refer Fig. 1B). The image depicts a partly eroded dome juxtaposed against the ~E trending fault (dotted red line) towards N designated as the Kutch Mainland Fault (KMF, Biswas 2005; Maurya et al. 2017). The dome is displaced by a number of faults transverse to

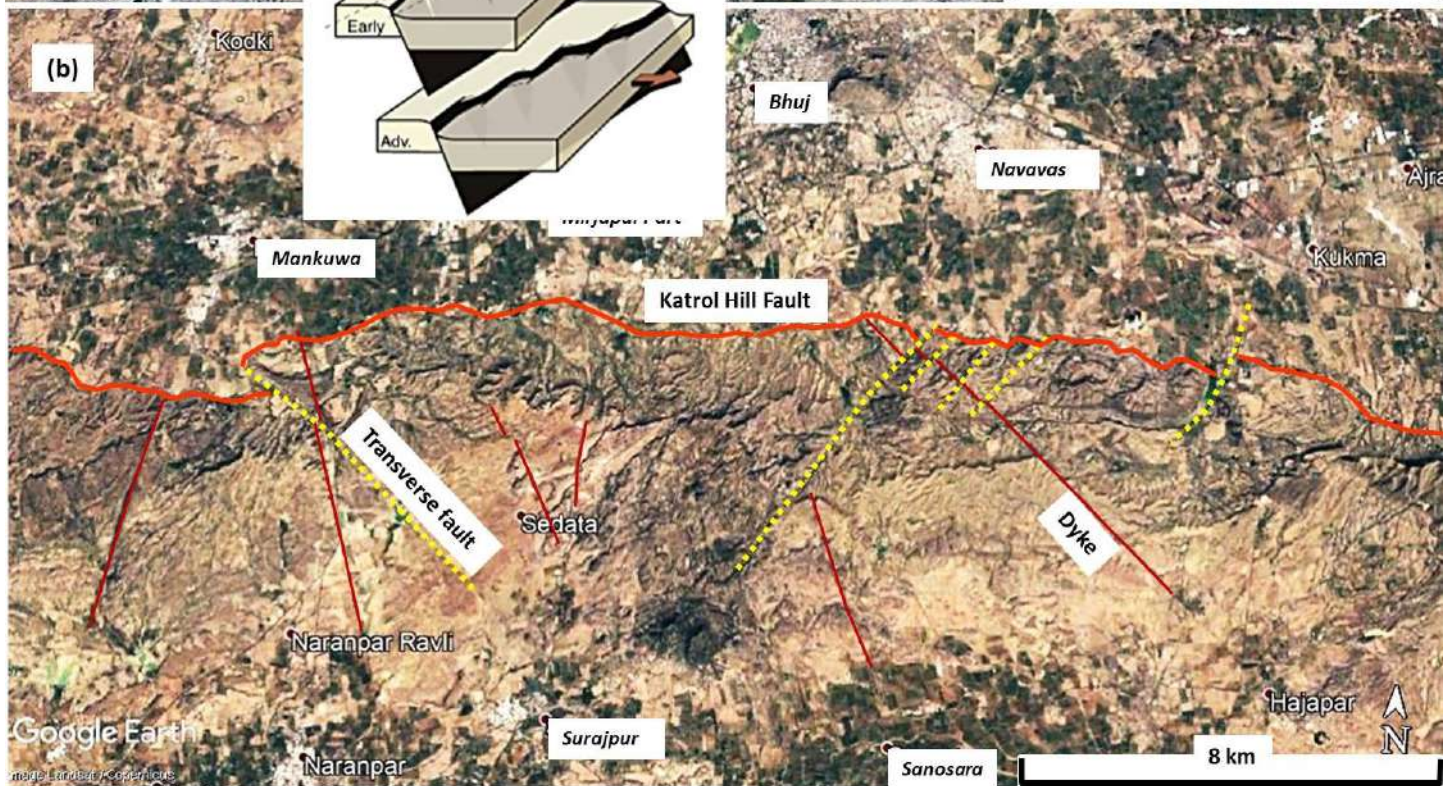
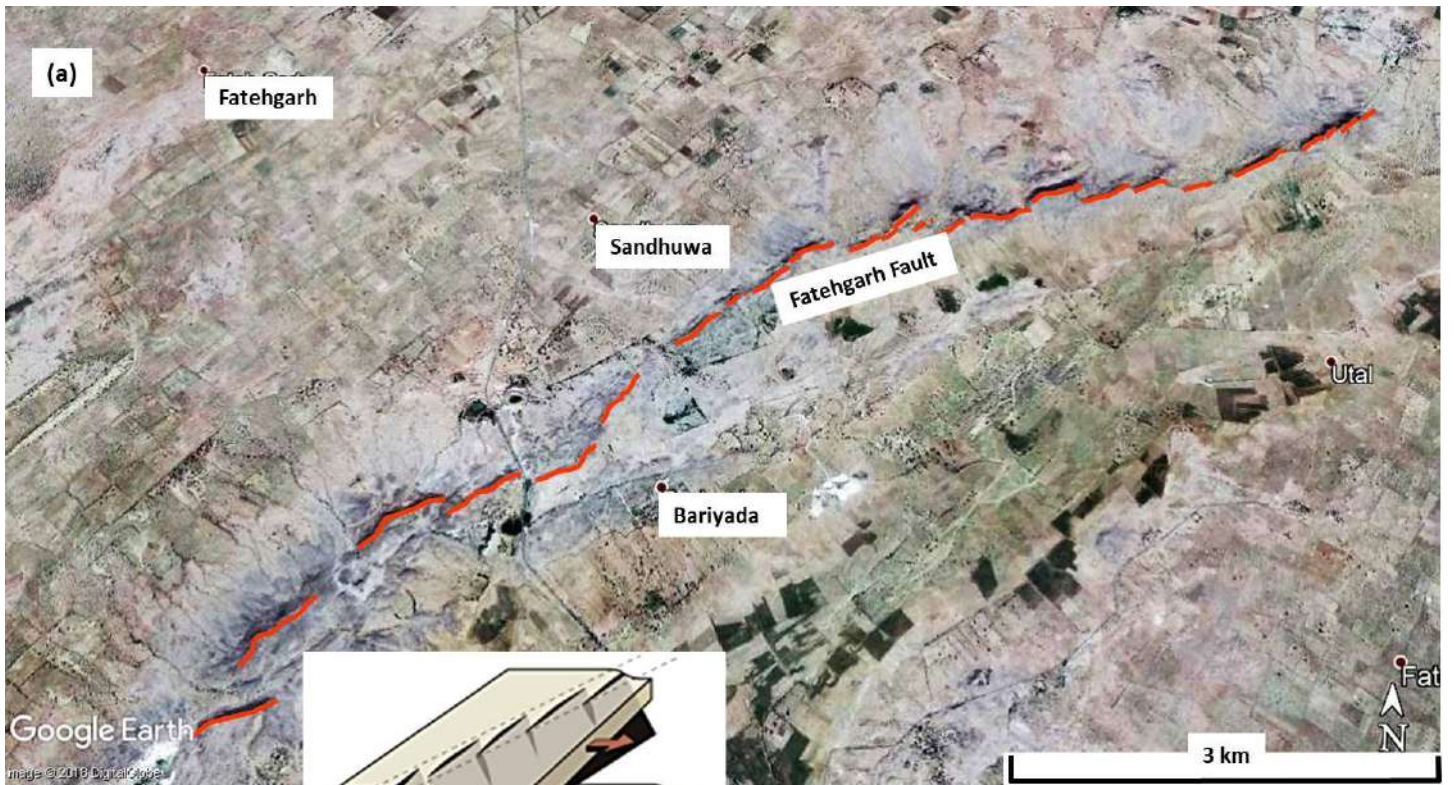
the KMF trending NW (yellow dotted line) with dextral slip. Red line: a probable disconnected fault system trending ~E/ENE sub-parallel to KMF is observed at N, immediately S of the KMF. Some NNE trending lineaments (red line) is seen towards bottom left (SW) of the figure, which are probably dykes.

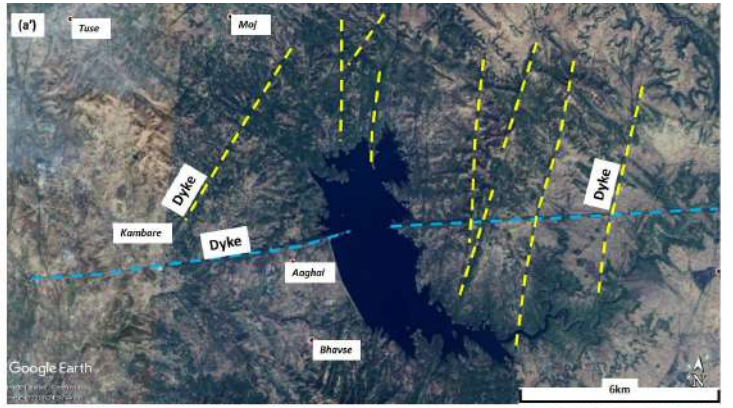
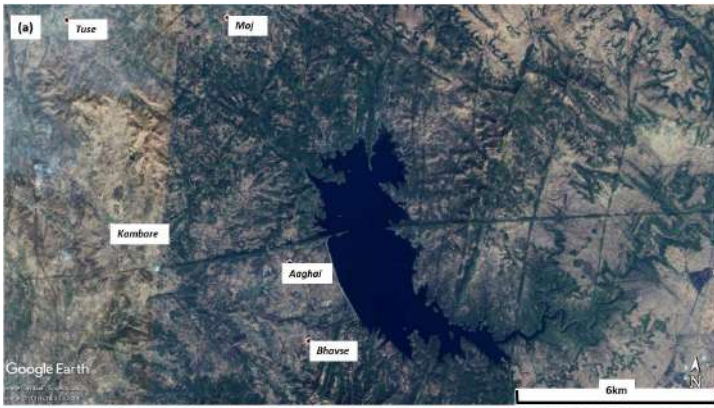
Annexure Fig. 3. Google Earth Pro satellite imagery from SE Saurashtra basin, ~ 65 km SW of Bhavnagar city, Gujarat. The image depicts a number of lineaments trending ~E - ENE – NE – NNE – NNW. Many of these lineaments are likely to be dykes related to the Deccan volcanism (as in Vanik et al. 2018). A rose diagram of the lineament plot (inset) shows that the ~ENE trending lineaments are most common. These lineaments are likely to be guided by the pre-existing basement structures of the Precambrian Delhi-Aravalli trend (Vanik et al. 2018). Also note that the drainage pattern is strongly guided by the lineaments.



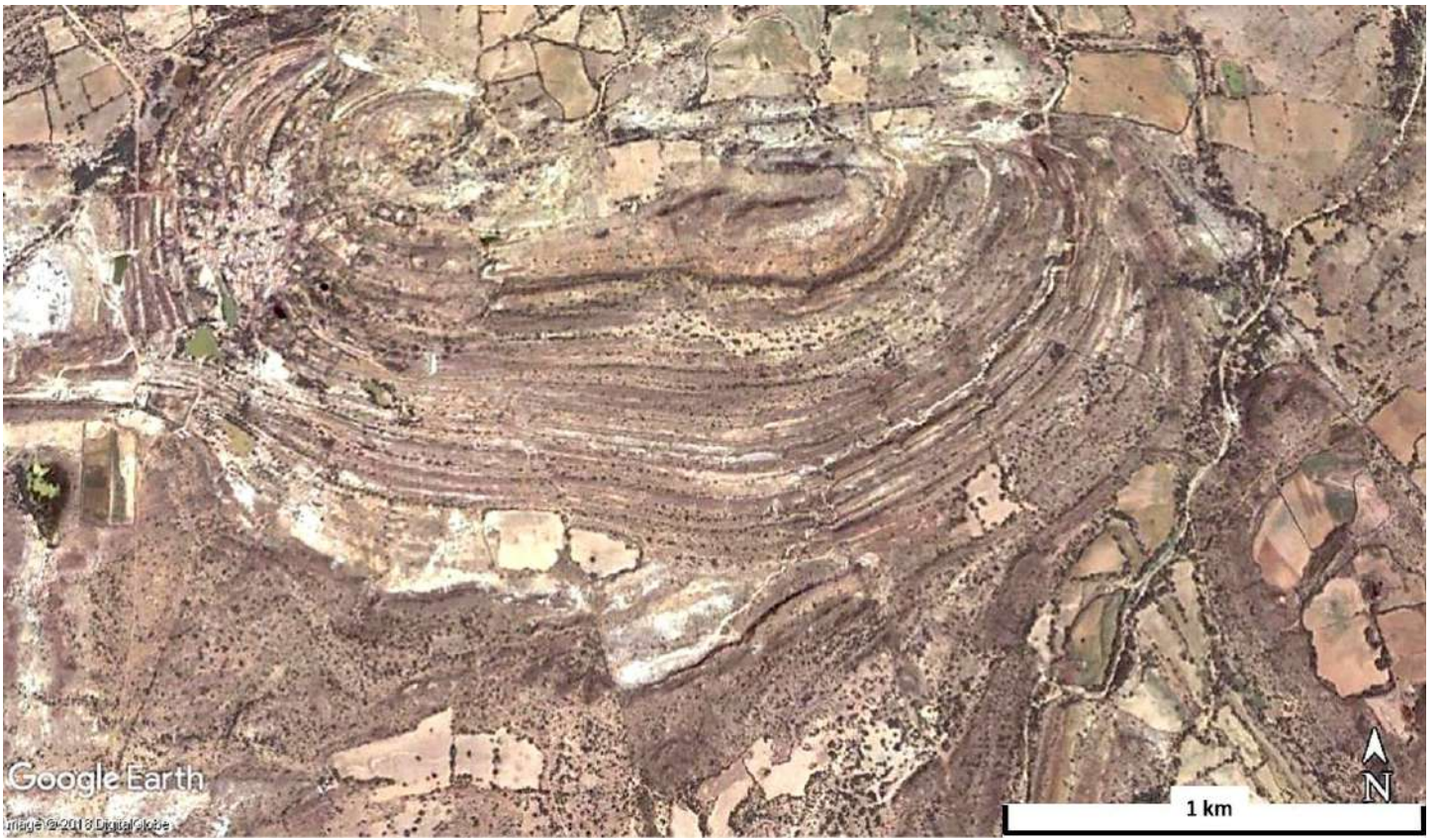




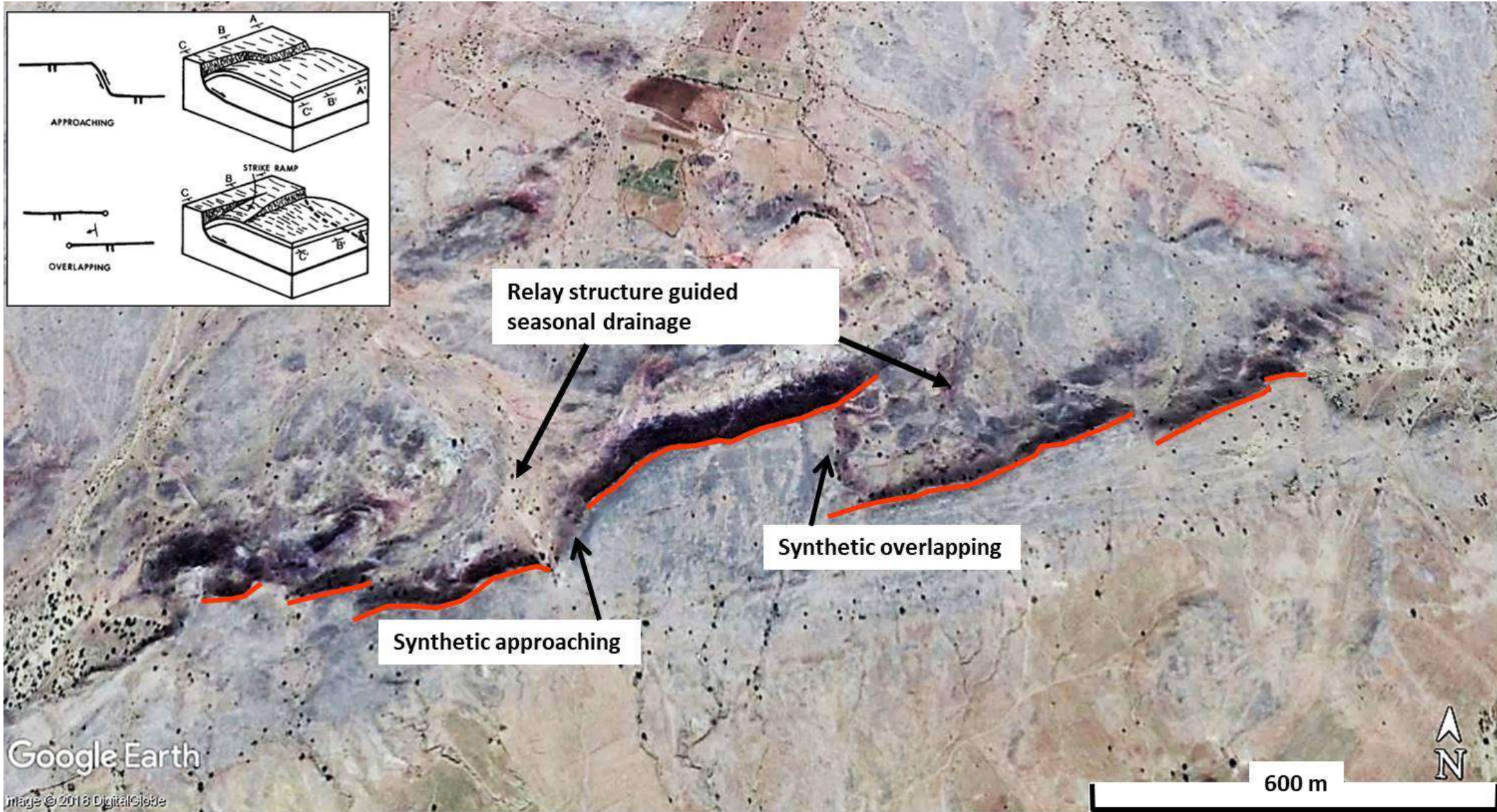
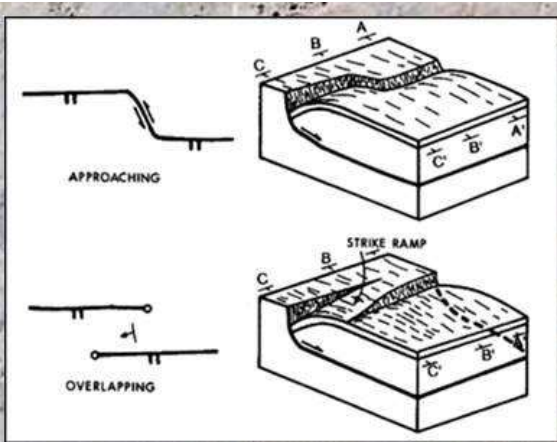






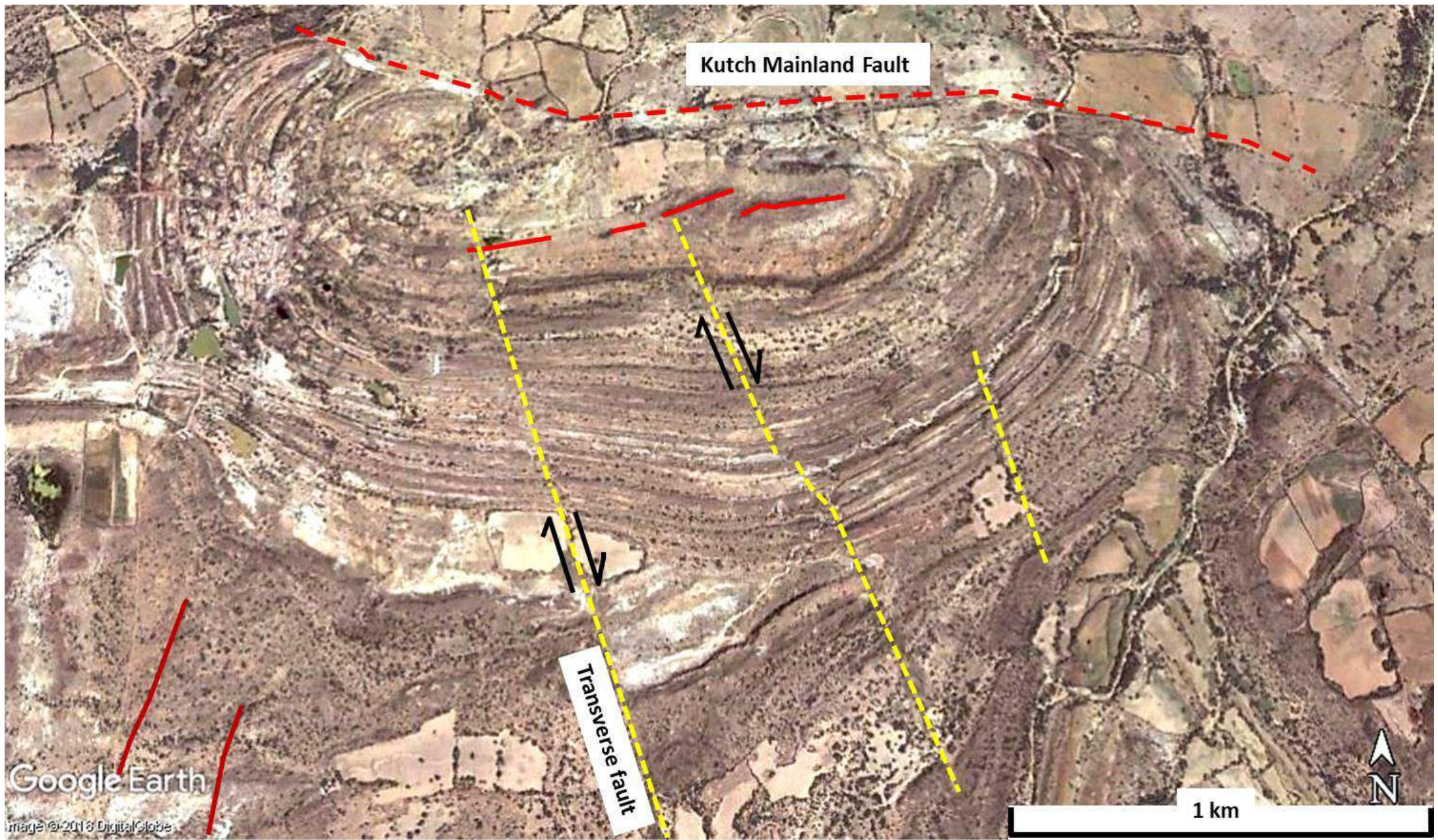






Google Earth

Image © 2016 DigitalGlobe



Kutch Mainland Fault

Transverse fault

Google Earth

Image © 2018 DigitalGlobe

1 km



