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Extremely fast Holocene coastal landscape evolution in the Kachchh Upland (NW India): Clues from a multidisciplinary review

Eshaan Srivastava ^a, Javed N. Malik ^a, Nicolò Parrino ^b, Pierfrancesco Burrato ^c, Nayan Sharma^a, MahendraSinh Gadhavi^d, Attilio Sulli ^b, Cipriano Di Maggio ^b and Maurizio Gasparo Morticelli ^b

^aActive Tectonics and Paleoseismology Laboratory, Department of Earth Sciences, Indian Institute of Technology Kanpur, Kanpur, Uttar Pradesh, India; ^bDipartimento di Scienze della Terra e del Mare, Università degli Studi di Palermo, Palermo, Italy; ^cIstituto Nazionale di Geofisica e Vulcanologia, Rome, Italy; ^dCivil Engineering Department, L. D. College of Engineering, Ahmedabad, Gujarat, India

ABSTRACT

The coastal landscape of the Kachchh Upland (KU) region (NW-India) changed over the last few thousand years from a shallow marine gulf to a salty desert (1–4 meters asl). In this area, bordered to the south by the Northern Hill Range (NHR), the tectonic-climatic interaction triggered the sea level fall from +2/4 m circa (6000–2000 BP) to zero. An ancient river pattern deposited a tidally regulated delta area during the sea level fall that stopped 2000–3000 years ago due to tectonic activity and a dry climate.

Deltaic-alluvial fans (DAF) in front of the NHR suggest that the KU's tectonic activity led to fast landscape evolution. We explored such drastic changes by integrating scientific information from a multidisciplinary literature review, identifying terraces and DAFs, and inferring faults through landform recognition, quantitative morphometry, and field surveys. Our interpretation, summarized in a map, provides new information on active processes along the NHR.

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Kachchh; coastal landscape evolution; tectonic-climatic interaction

1. Introduction

Several authors described the tectonic and climate-driven coastal landscape evolution of Kachchh (NW-India), which evolved from an enclosed sea gulf to the current intertidal environment using different approaches (Malik et al., 1999a; Gaur and Vora, 1999, 2003; Gaur et al., 2013; Makwana et al., 2019, 2021; Sharma et al., 2020). The geo-archaeological evidence of the Harappan civilization ruins on the northern portion of the KU highlighted that the salty mudflats labelled Banni plain was navigable from 5000 BC to 1900 BC (Possehl, 2002; Cleuziou and Tosi, 1993; Kenoyer, 2003; Gaur and Vora, 1999). Beyond that date, due to frequent earthquakes and sea level shifts, this area became uninhabitable, causing the disappearance of such civilization (Burnes, 1834; Sivewright, 1907; Gaur and Vora, 1999; Bisht, 2011; Gaur et al., 2013).

Geochemical, sedimentological, and geochronological studies provided further evidence of the KU coastal landscape evolution since the Last Glacial Maximum (LGM), describing the formation and dropout of Banni plain deltaic fans as a result of the post-LGM sea-level (SL) decline (Gupta, 1972, 1975; Malik et al., 1999b; Makwana et al., 2021; Kale and

Rajguru, 1985; Hashimi et al., 1995; Gaur and Vora, 1999, 2003; Bhatt and Bhonde, 2006; Pillai et al., 2017, 2018; Makwana et al., 2019, 2021; Sharma et al., 2020).

As witnessed in several regions of the world, even in the Kachchh region, the tectonics also controlled the coastal configuration along with the climate (Pirrotta et al., 2022; Parrino et al., 2022a; Parrino et al., 2022b). The 1819 Allah Bund morphogenic seismic event, north of NHR, formed a roughly 90 km long, 6–9 m high fault scarp. The coseismic event deformation caused the cut-off of some rivers from the Arabian sea, the ponding condition north of the scarp, and the sea flooding in the fault southern block (Bilham, 1999; Malik et al., 1999a; Malik et al., 1999b; Rajendran et al., 2001). A similar influence of the tectonic activity on the coastal configuration, occurred after the 2001 Bhuj Earthquake, which coseismic deformation shifted 5 km north the inundation area of high tides and monsoons (Gahalaut and Burgmann, 2004; Figure 1).

Despite these several studies, a detailed characterization of the uplifted deltaic-alluvial fans of the Banni plain and the entire NHR landforms has not yet been produced. To contribute to filling this gap in knowledge and draw a better understanding of the

CONTACT Javed N. Malik javed@iitk.ac.in Active Tectonics and Paleoseismology Laboratory, Department of Earth Sciences, Indian Institute of Technology Kanpur, Kanpur, Uttar Pradesh, India

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landscape evolution of the coastal landscape of Kachchh, we:

1. Mapped the coastal landforms of the NHR formed from the interaction between the region's longest active fault, the KMF, and the eustatic SL change.
2. Reviewed the most relevant papers to draw out a better outline of the landscape evolution of the NHR and its adjacent flat terrain.

2. Geological setting

The geological evolution of the E-W trending Kachchh peri-cratonic basin started in the late Triassic – early Jurassic during the rifting stages of the Gondwana breakup (Biswas, 1987; Merh, 1995). The Indian subcontinent's northward drift started in the late Cretaceous-Early Tertiary, which led to the collision with the Eurasian Plate, causing the uplift of the Himalayan Mountain chain and the tectonic inversion of the Kachchh basin (Biswas, 1982, 1987; Merh, 1995). Such positive inversion partially reactivated the pre-existing normal faults flanking the Kachchh basin as thrust faults (Biswas, 1987; Karanth and Gadhavi, 2007; Figure 1).

Three different deposits characterize the syntectonic Tertiary deposits outcropping along the flank of the Mesozoic structural highs (see the Lithological Map of Kachchh in the main map): the lower lavas of the Deccan Traps, deposited during the passage of the Indian-subcontinent over the Reunion Hotspot, the middle transgressive marine deposits rich in marine micro and vertebrate fossils (foraminifera, plant fossils, whales, sea cows and fish) and the upper fluvial deposits testifying a general regression (Biswas, 1987; Merh, 1995; Johnston, 1994; Biswas, 2005; Catuneanu and Dave, 2017).

The Kachchh, elongating E-W with an area of more than 45,674 km² in the western Indian subcontinent, has a diversified landscape, marked by five ca. E-W trending zones: (1) the coastal zone – delimiting the southern of Kachchh, (2) the Uplands – comprising the outcrops of the Mesozoic succession, (3) the quasi flat Banni-Plain, a basin filled with alluvial and mud deposits, with an elevation ranging between 2-12 m (4) the Island belt – an E-W chain of islands viz., Pachham, Khadir, Bela and Chorar, and (5) the saline-waste land that is usually inundated during high tides and Monsoon, namely the Great Rann in the N-NW and the Little Rann in the E, divided by the Wagad topographic high (Biswas, 1987; Malik et al., 2000). Major E-W south or north dipping faults bounds these physiographic units across the basin. The Katrol Hill Fault (KHF) outcrops south of the KU. The E-W striking, S-dipping KMF, separates the KU from the Banni Plain and the Great Rann to the

north. The S-dipping Island Belt Fault (IBF) borders to the north the isolated highs of the island belt region. The northern portion of the Kachchh basin is bounded by the N-dipping Allah Bund Fault (ABF). Lastly, the Wagad Upland (WU), located NE of the KU, is supposedly bounded by the North Wagad Fault (NWF) and South Wagad Fault (SWF) along the northern and southern sides, respectively (Biswas, 1987; Biswas, 2005; Malik et al., 2017a, 2017b; Srivastava et al., 2021; <https://earthquake.usgs.gov/earthquakes/eventpage/usp000a8ds/executive>; Figure 1)

3. Seismotectonic setting

In the past 500 years, moderate to large magnitudes, historical and instrumental seismicity of the area (6.0 M to 7.8) occurred within the E-W trending faults bounding the Kachchh basin, such as the 1668 Indus-Delta and the 1819 Allah Bund earthquakes (Mw 7.8 and Mw 7.8, respectively) and 1956 Anjar event (Mw 6.0) located near the KHF (Oldham, 1883; Johnston and Kanter, 1990; Chung and Gao, 1995; Malik et al., 2001; Bilham et al., 2007; Figure 1). Sohoni and Malik (1998), based on small-scale folding, micro-faulting, pseudo-sand blow, sand dike, and craters, hypothesized late Quaternary seismic events. Paleoseismological research along the KMF and SWF supports this finding highlighting at least three paleo-earthquakes that may have occurred before 5080 BCE, between 4820 and 2320 BCE, and between BCE 1230 and BCE 04, two of which most likely caused significant harm at the Harappan site (Morino et al., 2008; Malik et al., 2008; Malik et al., 2017a).

The fault plane solutions and the maximum horizontal stress orientations highlight that a general N-S shortening characterizes the whole Kachchh area and that the eastern part is subjected to a roughly NNW-SSE oriented compression (Dziewonski et al., 1981; Ekström et al., 2012; Heidbach et al., 2019). In the same area, the geomorphic features of the rocky uplands of the Kachchh region suggest a tectonically driven uplifting landscape evolution, such as the faults scarps bounding KU and WU. These features include paired Quaternary fluvial terraces, gorges, truncated paleo-channels, ponding areas, incised alluvial fans, etc. (Malik et al., 2000, 2001). According to GNSS data, the ongoing deformation occurs at a rate of 4-5 mm/yr around the faults bounding the basin. The stress map and thrust faults both support that most of this N-S compression is released seismically, with a minor strike-slip component (Gahalaut et al., 2019; Figure 1)

4. Archaeological setting

The archaeological sites of the Kachchh region are considered promising indicators for determining the

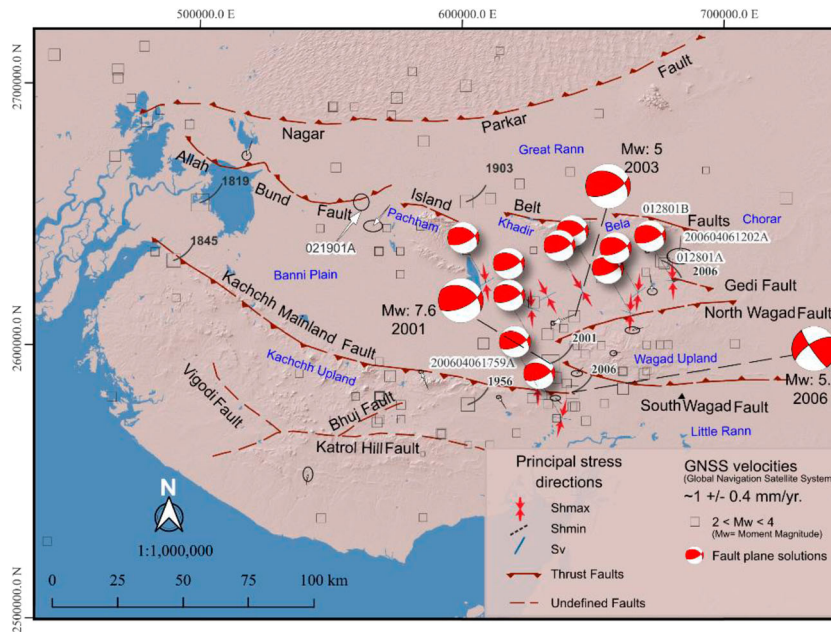


Figure 1. Seismic events $M_w > 5$ from 1819 to 2006 with principal stress directions in the Kachchh basin.

position, elevation, and age of paleo-shorelines, for the last few thousand years (Gaur and Vora, 1999; Flemming, 2004). The Harappan civilization prospered on the edge of the rocky hills and the salt pans of the Rann of Kachchh from 2800–1800 BCE through extensive maritime activity, suggesting that the upland area was navigable (Gaur & Vora, 1999; Gaur et al., 2013; Giosan et al., 2012; Figure 2). The book ‘Periplus of the Erythraean Sea’ (first century CE), describing this area as a shallow marine gulf during Alexander the Great times and reporting sea-ports along the northern coast of KU till 37 km northwest of the city of Bhuj, now located 50 km from the present coastline, support such indication (Burnes, 1834).

Sivewright (1907), based on field observations, proposed that (a) the evolution of the region was controlled by seismic events, such as the 1819 earthquake, which induced a coseismic uplift of about 6 to 9 m in the northern part of Allah Bund and 6m of subsidence to the south, (b) the sea that encircled Kachchh must have entered either from the Kori creek or through the Gulf of Kachchh, (c) the area have been navigable for many hundred years even after the Arab conquest of the area in 712 CE, (d) the former sea gulf was by siltation and progradation of the deltas located eastern of the present day Indus River and by small streams deltas from the KU (Figure 2).

Harappan sites, located 30–50 km from the present shoreline, host dockyards and stone anchors highlighting the trading activities of these sites (Gaur and Vora, 1999; Figure 2). This is also supported by the area’s high flooding probability, which makes this region unattractive for an agrarian

society like the Harappan (Gaur et al., 2013). The seismic events datable 2200 BCE, the climate shore-line shifting, and the fluvial siltation of the region led Harappan to leave the Kachchh region (Gaur and Vora, 1999).

Archaeoseismological information, such as the seismic events around 2900, 2700, and 2100 BCE, suggest intense tectonic activity during the Harappan times (Bisht, 2011). The 2100 BCE event is regarded as the causing factor for the abandonment of early settlements near the KMF that have also experienced damage from events ranging in age from 325 BCE to 2001 CE (Satuluri et al., 2020).

5. Holocene sea-level fluctuations in the study area

The SL curve derived along the coast of W-India describes that around 14,500 years BP, the SL located at -100 m below present-day, followed by a sudden sea level SL rise, at a rate of 10 m/thousand years, up to -80 m around 12,000 yr BP. A still stand with minor fluctuations characterized the period between 12,000 to 10,000 yr BP, followed by an extremely fast rise from -80 m to the present SL from 10,000 to 7,000 yr BP at a rate of 18 mm/year (Kale and Rajguru, 1985; Hashimi et al., 1995; Figure 3).

During the Early to Late Holocene, the Kachchh was regarded as a navigable gulf from around 6000 to 2000yr BP, followed by a shallowing to its present level (Gaur and Vora, 1999; Malik et al., 1999a; Gaur et al., 2013; Makwana et al., 2019; Figure 3). The Saurashtra region, south of the Gulf of Kachchh, recorded the highest SL, ranging from 2 to 3 m between 6,500 and 4,500 yr BP (Kale and Rajguru, 1985).

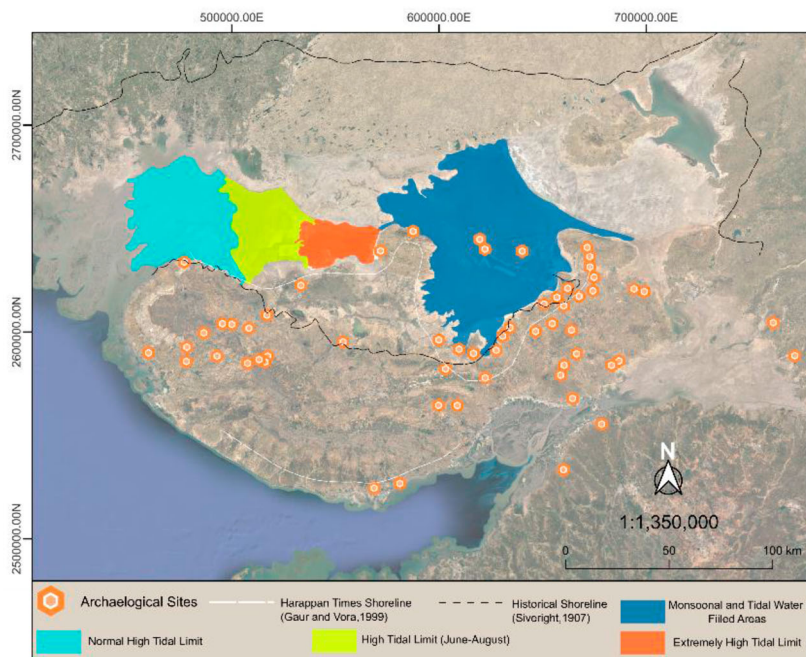


Figure 2. Harrapan archaeological sites and paleo-shoreline in the Holocene period. The dotted black line represents the shoreline proposed by Siveright (1907). The white dotted line represents the Gaur and Vora (1999) shoreline deciphered from the positioning of the Harrapan sites during the Middle to Late Holocene. Present-day tidal incursion limits in Kachchh have been derived from the MNDWI indices from LANDSAT-8 data (<https://earthexplorer.usgs.gov/>).

Geomorphic markers and ^{14}C ages in the same region indicate a SL high up to 4 m in the mid-Holocene, followed by a falling trend (Mathur et al., 2004). Mid-Holocene notches at 4–5 m above present SL in the Saurashtra Coast recorded a rapid fall at around 3000 yr BP, contemporary to the flourishing of the Harappan centers from ca. 2800–1800 BCE (Tyagi et al., 2012; Das et al., 2017; Makwana et al., 2019) testified by sea notches and wave-cut platforms describing a tectonic uplift of the area up to 2 m of vertical upthrow (Bhatt and Bhonde, 2006; Pant and Juyal, 1993, please see the Figure 3 to locate the Saurashtra coast).

The mangrove patches north of the central part of KMF in the Banni Plain, proxies for a shallow mar-

ine/coastal environment in the area (Tripathi et al., 2013), suggest the onset of the late Holocene SL fall started after 3000 BP. At around 1000yr BP SL was estimated at 0.53 ± 0.43 m (Sharma et al., 2020).

6. Methods

The main map was produced through a remotely sensed geomorphic interpretation of landforms and faults from CARTOSAT-I and Corona satellite products stereo pair with a geometrical resolution of 2.5 and 3 m, respectively. From the forward and afterwards CARTOSAT-I imagery (Indian government web portal, <https://bhuvan.nrsc.gov.in/home/index.php>), we generated a 3D anaglyphs mosaic following the methodology

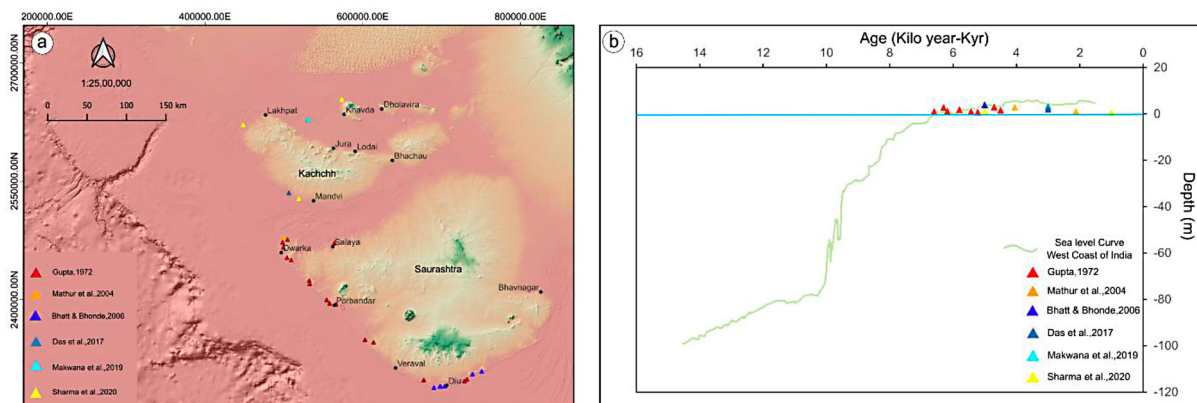


Figure 3. (a) Locations of the literature study area around the Kachchh basin. (b) Sea level curve of the W-India. Colour-coded triangles show age constraints collected from the literature.

proposed by Evans et al. (2008) and Gianinetto & Fassi (2008). We depicted the topography along NHR using CORONA stereo images (Mission No. 1028-2; Camera No. KH-4A; Date of acquisitions 31-Dec-65) following the methodology proposed by Sahoo & Malik (2017), Arora et al. (2019). In five years, from 2018-2022, we carried out multiple field surveys to validate the achieved outcome regarding lithological contacts, structures, and landforms.

The location of the Harappan settlements and paleo shorelines were digitized from literature and plotted into a georeferenced environment (Sivewright, 1907; Gaur and Vora, 1999; Gaur et al., 2013; Figure 2). Through a literature review, we digitized the Quaternary-Holocene Sea levels along with plotting the collected data locations into a georeferenced environment (Gupta, 1972; Mathur et al., 2004; Bhatt and Bhonde, 2006; Das et al., 2017; Makwana et al., 2019, please see the main map).

To explore the KU relief distribution through swath profiles, we generated a DEM with a geometrical resolution of roughly 15 m, following the methodology proposed by Braun (2021, <http://step.esa.int/docs/tutorials/S1TBX%20DEM%20generation%20with%20Sentinel-1%20IW%20Tutorial.pdf>). We extracted four swaths: (1) a 10 km width and 156 km long, running parallel to the NHR, and (2) three 5 km width and 25 km long, running across the NHR to the Banni plain. Following the baseline of the first profile, we created a 40 km width swath section sampling instrumental and historical seismic events. The structural pattern was inferred from a literature review and from remotely sensed dataset interpretation, while the stress orientation, fault plane solution, and GNSS data result from catalogues review (Ekström et al., 2012; Gahalaut et al., 2019; Heidbach et al., 2019; Shaikh et al., 2020, 2022). To constrain lithological, structural, and geomorpho-

logical features, we consulted the published Geological Survey of India Maps at 1:500,000 and the CORONA satellite dataset (Dashora et al., 2007).

7. Results

The main features displayed in the here presented main map are:

- Lithological contacts deposited since the rifting and formation of the Kachchh basin up to the present ('Lithological Map of Kachchh' in the main map).
- The main active tectonic faults, striking NW-SE, E-W and NE-SW, are highlighted by fault scarp displacing the Quaternary deposits at the fringe of the KU. Active anticlines along the KMF are the Jhura, Habo, Kaswali and Khirsara.
- Landforms (Figure 4), such as (i) V-shaped valleys formed by the downcutting of the rivers in the Mesozoic rocks along their upper reaches across the anticlines and in the Cenozoic deposits near the fold limbs; (ii) series of anticlines and cuesta successions striking NW-SE to E-W forming the NHR; (iii) different generations of alluvial-deltaic fan surfaces, located at the boundary of the Uplands and the Banni plain-the Great Rann; (iv) several orders of river terraces, incised within the alluvial-deltaic fans; (v) syncline depressions cut in the Mesozoic formations outcropping near the limbs of the anticlinal domes in the western and eastern extremity of NHR, identified using the anaglyphs; (vi) identified/inferred fault traces from high-res satellites datasets and field visit outcropping in the Quaternary-Holocene deposits (please refer the main map).

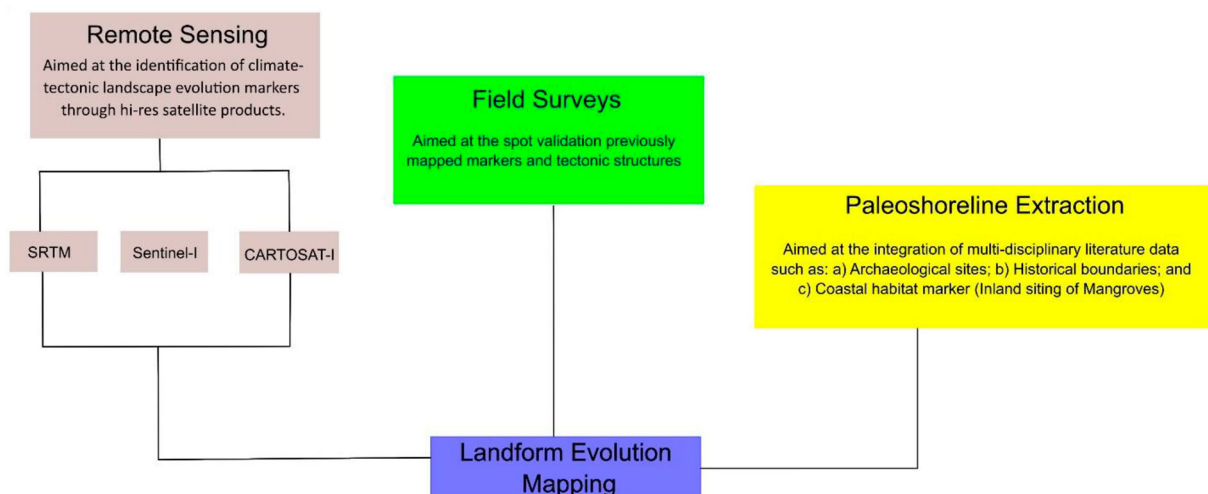


Figure 4. The methodology was organized as follows: high-resolution satellite mapping, digitization of historical maps and archaeological sites, validation through field surveys, and identification of markers for the evolution of landforms.

We mapped the coastlines ranging from the Harappan settlements periods to the Arab conquest in 712 CE, compiling a georeferenced dataset from bibliographic sources.

The swath profile parallel to the NHR shows four main isolated reliefs, labelled Guneri, Jura, Kas and Khirsara anticlines, respectively, that alternate with low relief areas hosting northward flowing major rivers (profile X-X' in Figure 5). The maximum sampled altitudes vary from 200 to 350 m a.s.l., and the highest relief values characterize the central-eastern portion. Among the NHR perpendicular profiles, the central and eastern profiles show that the escarpments characterized by the most significant relief are also the current cliff. In contrast, the western profile (c) shows incisions north of the prominent escarpment that testifies to a recent uplift of the area after the escarpment

formation (Figure 5(a-c)). The eastern and western profiles show that in the northern ridge, the average elevation (thick black line) approaches the maximum altitudes suggesting recent tectonic activity of these anticlines and a possible control on the local coastal evolution (e.g. Corradino et al., 2021). The western and central profiles show the presence of two external reliefs, characterized by a single frontal relief (Figure 5 (a,b)).

The seismicity catalogues allow the detection of almost absent seismicity in the Kachchh western portion and hypocenters of Mw 4–5 events clustering at about 30 km of depth in the central portion. Hypocenters between 15 and 25 km depth characterize the eastern portion where occurred the most significant event of Mw 6–7 (Figure 6, Choudhury et al., 2016). (figure 7)



Figure 5. Landforms in the KU. (a) panoramic view of Kaswali river, (b) Knickpoint in the Lothia river, (c) degraded fault scarp near Lodai, (d) syncline depression between the younger anticline domes in the eastern extremity of NHR, (e) multiple terrace levels of Kaila river, (f) hanging pediment near Khari river, (g) depleted mangroves near the toe of the Lodai fan, and (h) small canyon in the Habo dome carved by a seasonal river.

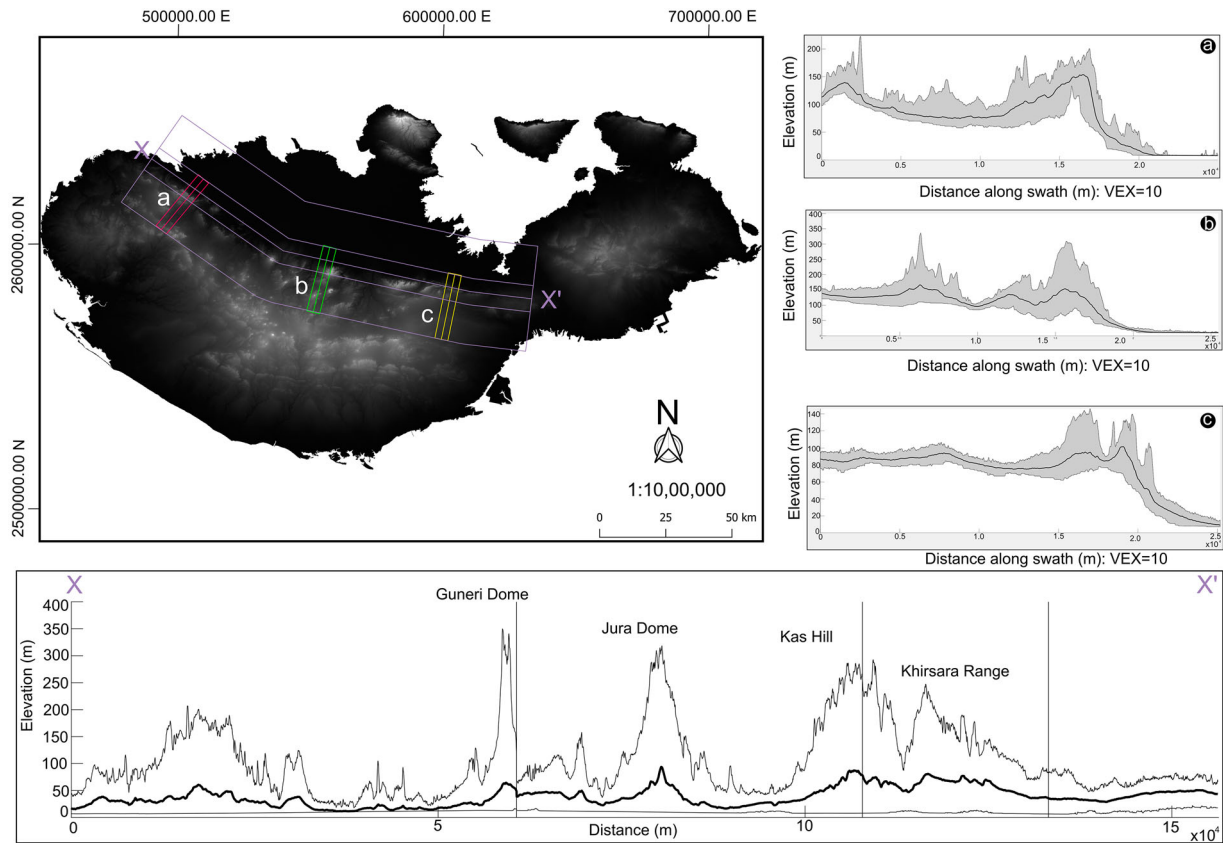


Figure 6. The transverse and longitudinal swath profiles depicting the topographic relief distribution along and across the NHR.



Figure 7. Swath-section, along the X-X' swath profile shown in Fig. 5, depicting the hypocenters from the revised literature. Circles represent the hypocenters of seismic events in the Kachchh Basin collected in a 40 km width swath and plotted along the cross-section. The colour code represents the distance from the swath baseline, and the circle's size represents the event's magnitude.

8. Discussion and conclusion

The geomorphologic map presented in this work provides, for the first time at the scale of the whole Kachchh basin, information that could improve the knowledge about the reconstruction of its coastal landscape evolution. This basin has witnessed coupled climate and tectonics processes that have forced shore-line migration since the Holocene.

The Banni Plain supports the long-term tectonic forcing on the landscape evolution of the Kachchh region. The different levels of deltaic-alluvial fans, their associated incised Quaternary-Holocene river terraces, the valleys that fed the sediments, and the identified/inferred faults in quaternary alluvial sediments (in the Main map and Figure 4(a)) are such landforms that testifies to the persistence of low

gradients since the Late Quaternary, which made the Banni Plain prone to tectonics and climatic events. The long list of seismic events and SL fluctuations since the Holocene, along with the previous deltaic environment, must have played a significant role in the drastic changes in the coastal landscape from being once the arm of the Arabian sea to the present raised fluvio-intertidal environment (Sohoni & Malik, 1998; Morino et al., 2008; Malik et al., 1999b, 2000). The SL fluctuations describe a high-water stand ranging between 2 to 4 m till 6000 BP and a sea level falling trend since then (Mathur et al., 2004; Bhatt and Bhonde, 2006; Tyagi et al., 2012; Das et al., 2017; Makwana et al., 2019).

Climate and tectonic perturbations on the coastal landscape evolution significantly influenced the Harappan civilization, making the maritime Harappan

settlements an interesting SL proxy as this area has been known as non-cultivable land since prehistoric times. The Harappans were an agrarian society; that is why the question arises regarding the reasons for settlement (Gaur and Vora, 1999; Giosan et al., 2012; Gaur et al., 2013; Figure 2). The dockyards and stone anchors proved them as maritime trading centers. The other archaeological sites located in the Rann, if compared with the present major towns such as Gandhidham, Mandvi and Bhuj, are far away from the Gulf of Kachchh.

We believe that the review and map made in this paper of geomorphological, paleoseismological, tectonic, and archaeological studies may serve as starting documentation for future research in the field of active tectonics and paleoseismology, geochemical and sedimentological studies and modulation of overall possible landscape evolution models of Kachchh basin.

Software

The DEM and anaglyph from CARTOSAT-I were produced by ENVI, while the DEM data from the Sentinel-1 dataset was extracted through SNAP. Morphometric analyses, general processing, and the extraction of swath profiles were performed using QGIS 3.24-Tisler, MATLAB, and TopoToolbox (Schwanghart & Scherler, 2014), respectively. The vector-based creation of the Map was done using Inkscape.

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ORCID

Eshaan Srivastava  <http://orcid.org/0000-0001-8074-2247>
 Javed N. Malik  <http://orcid.org/0000-0002-7600-8514>
 Nicolò Parrino  <http://orcid.org/0000-0003-1814-622X>
 Pierfrancesco Burrato  <http://orcid.org/0000-0001-6588-7560>
 Attilio Sulli  <http://orcid.org/0000-0002-7705-3632>
 Cipriano Di Maggio  <http://orcid.org/0000-0002-2813-8242>
 Maurizio Gasparo Morticelli  <http://orcid.org/0000-0002-9966-6800>

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