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Late Pleistocene–Holocene uplift driven terrace formation and climate-tectonic interplay from a seismically active intraplate setting: An example from Kachchh, Western India

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ABSTRACT

Fluvial terrace formation is often regulated by external forcings like climate, tectonic and eustatic changes. These terraces, particularly in a dryland environment, preserves the discrete signatures of these external forcings, thus enabling us to reconstruct the fluvial response to the late Quaternary palaeoenvironmental changes and factors governing them. The present study focuses on reconstructing the aggradation/incision phases in the Lotia River which is located in the eastern segment of the Northern Hill Range (NHR) of the Kachchh Peninsula. The Lotia river drains through Mesozoic rocks before cutting across the Kachchh Mainland Fault (KMF) and finally debouch in the Banni Plains. Reconstruction based on tectonic geomorphology, sedimentology, sediment geochemistry, mineral magnetic, and OSL chronology suggests the fluvial response to monsoon variability archived during the last 15 ka. The time frame was also marked by incision enhanced by uplift along the KMF, which led to strath terrace formation. The accommodation space thus created was filled by an aggradational event between 14.8 ka and 10.6 ka. Sedimentological and geochemical parameters have also suggested that the time period between 12.5 ka and 11.5 ka showed a decline in the monsoon strength, which coincides with 'Younger Dryas'. It has been observed that the sediments spanning between 10.6 ka and 7.8 ka are absent from the archive, which is most likely the manifestation of the early Holocene optimum that led to severe erosional processes. The period between 7.8 ka and 3.3 ka is marked as another aggradational phase with fluctuating climatic conditions. At 3.3 ka, the region has experienced an incision of 4 m, which led to the formation of Holocene terrace T_1, most likely due to tectonic uplift. During the last 3.3 ka, another pulsative uplift has occurred, which led to the formation of unpaired Holocene terrace T_2, along with tilting of the Lotia basin. Based on the OSL chronology of bedrock strath terrace, we reported a minimum uplift rate of 1.04 mm/a for the eastern KMF during the Late Pleistocene–Holocene period, hinting seismically active nature of the KMF during this period. The terrace formation in the eastern Northern Hill Range is mostly regulated by tectonic uplifts along the KMF.

1. Introduction

In tectonically active regions, the landscape evolution is modulated by tectonic processes which lead to formation of the characteristic geomorphic signatures and sedimentary succession. In dryland environments, the fluvial response to climatic/tectonic processes is more peculiar leading to the formation of discrete landforms and sedimentary successions (Tooth, 2000). River terrace is one such landform, which is found in all environments and is formed by initial aggradation followed by vertical incision into bedrock or underlying sediments on account of base level lowering by climatic, sea level and tectonic forcing (Schumm et al., 2000; Stokes et al., 2012). River terraces have been widely and successfully used to reconstruct past climatic changes and tectonic perturbations, globally (Lave and Avouac, 2001;Maddy et al., 2001; Starkel, 2003; Bridgland and Westaway, 2008; Gibbard and Lewin, 2009; Steffen et al., 2010; Stokes et al., 2012; Bekaddour

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et al., 2014) as well as on the Indian subcontinental scale (Srivastava et al., 2001; Mathew et al., 2006; Srivastava et al., 2008, 2009; Juyal et al., 2010; Bhattacharya et al., 2013b, 2014). However the causal mechanism which controls the formation of river terraces is still debated (Blum and Tornqvist, 2000; Maddy et al., 2001; Hancock and Anderson, 2002; Starkel, 2003; Bridgland and Westaway, 2008; Gibbard and Lewin, 2009; Vandenberghe et al., 2011). In intraplate settings with dryland environment, it is even more difficult to decouple the climatic and/or tectonic signatures responsible for the terrace formation. Owing to the dryland climatic conditions, associated fluvial systems are more often sediment deficient and lack vegetation; which makes them more sensitive to subtle climatic/tectonic perturbations. The study of river terraces in such environments supported by absolute chronology provides important clues on the extent and intensity of tectonic deformation along the active faults (Cunha et al., 2008). Simultaneously, topography and drainage development can also provide vital information about the tectonic control on landform evolution (Keller and Pinter, 2002; Azor et al., 2002; Kale et al., 2014).

The Kachchh region is considered to be one of the most seismically active intraplate regions in the world; recent studies have suggested that the seismic activity is mainly concentrated in the eastern segment of Kachchh mainland (Mathew et al., 2006; Rastogi et al., 2012, 2014). Owing to its intraplate setting and seismicity, the Kachchh region is often considered as analog counterpart of eastern North America's New Mexico region (Boudin et al., 2001; Tuttle et al., 2001). The landscape of Kachchh peninsula provides an ideal setting for reconstructing climatic and tectonic interplay in an arid environment from its deeply incised fluvial successions (Maurya et al., 2003). There have been very limited studies to reconstruct climate-tectonic interplay from the terrace sequences in Kachchh region of Gujarat (Mathew et al., 2006; Patidar et al., 2007; Bhattacharya et al., 2014). These studies have shown that the dryland fluvial systems of Kachchh have responded and archived the Late Pleistocene–Holocene climatic fluctuations in a discrete manner. Several studies have shown how fluvial systems of Kachchh have responded to tectonic perturbations during the Late Quaternary Period (Mathew et al., 2006; Chowksey et al., 2011; Bhattacharya et al., 2014). Bhattacharya et al. (2014) have suggested that the monsoon initiated in Kachchh at around 17 ka which was followed by a period of overall stronger monsoon between 12 ka and 8 ka which is synchronous with other archives spanning the entire western India (Overpeck et al., 1996; Gupta et al., 2003; Enzel and Prasad, 2006; Raj et al., 2015). This was followed by a steady decline in the monsoonal activity during the Middle Holocene Period i.e. from 8 ka to 3 ka (Gupta et al., 2003; Enzel and Prasad, 2006; Tyagi et al., 2012; Bhattacharya et al., 2014; Raj et al., 2015). During the Late Holocene Period, there was a short period of aggradation associated with stronger conditions of monsoon at around 1 ka which was followed by a period of aridity till date (Ngangom et al., 2012; Bhattacharya et al., 2014). However, there are few studies which have documented fluvial response to the climate change in dryland environment (Tooth, 2000). Similarly, due to the lack of chronological support, detailed sedimentological analysis and multiproxy data, most of these studies from the Kachchh region have remain largely qualitative and provided hardly any quantitative estimates of uplift/incision rates or timings of aggradation/incision events (Mathew et al., 2006; Bhattacharya et al., 2014).

The aim of the present study is to (1) evaluate the external controls on the terrace formation in a seismically active dryland setting, (2) estimate the uplift/incision rate of the eastern segment of the seismically active Kachchh Mainland Fault (KMF), and (3) reconstruct the fluvial response of dryland fluvial systems to the Late Quaternary climatic variability.

2. Geology and geomorphology of the study area

The Kachchh peninsula is situated in the western most part of India (Fig. 1a). It forms a crucial geodynamic part of the western continental margin of India and marks an intra-cratonic basin, which has been important site of Mesozoic and Cenozoic tectonism and sedimentation (Biswas, 1993, 2005). The Kachchh mainland is divided into northern and southern segments by the Katrol Hill Range at the center (Fig. 1b). The Northern part of the Kachchh Mainland consists of Northern Hill Range (NHR) which encompasses the hills and domes of Mesozoic sandstones and shale (Biswas, 1993). The uplifts are marked by domes and asymmetrical anticlines which are confined to the south of the major faults. The Northern fringe of the rocky mainland, where the Northern Hill Range abuts against the Great Rann-Banni plains, is marked by the Kachchh Mainland Fault (KMF) (Biswas, 1993, 2005). The north flowing streams originate from the Katrol Hill Range in the south and traverse through Mesozoic sandstone, shale and limestone lithologies before debouching into the Banni plains/Great Rann of Kachchh (Biswas, 1993). The Kachchh Mainland Fault (KMF) is a south dipping reverse fault (Chung and Gao, 1995), which is geomorphically expressed as E–W oriented steep north dipping scarp in the Northern Hill Range (NHR) (Maurya et al., 2003). The NHR comprises a chain of domes comprises of Jurassic and Cretaceous rocks, which is flanked to the north by E–W trending KMF abutting against the Banni plain. From east to west, it is marked by a series of structural domes and anticlines. Kas Hill forms a prominent anticline and with its escarpment facing the north. It occupies the entire length of the eastern half of the main flexure.

Lotia River is situated in the eastern part the Kas hill range of NHR (Fig. 1c). It originates from the rocky uplands of the Kas Hill and traverses through the pediment zone in the middle and alluvial plains in the lower reaches. Similar to the north flowing rivers, Lotia River also forms an alluvial fan, when it terminates into the Banni Plain (Fig. 2). The Lotia River shows thin Quaternary apron, upstream with the development of an 11 m thick bedrock strath terrace. As it crosses the scarp, the bedrock is no longer exposed, however two unpaired terraces are formed (Fig. 2a). The incision in fluvial sequence in Lotia-1 (i.e. bedrock strath sequence; Fig. 2a) is about 15 m whereas in Lotia-2 (i.e. Holocene terraces; Fig. 2a) is about 6 m.

Lotia River emerges from an altitude of 300 m south of Kas Hill and flows in an ENE–WSW trend along the southern fringe of the Kas Hill before deflecting abruptly towards northward along a transverse fault across Kas Hill Anticline. After cutting the Kas hill the river is trunked towards west as it enters in KMF zone and forms gorges, knick points and incised valley in friable calcareous Late Jurassic sandstone. The trunk channel is fed by several first and second order dendretic streams originating from the southern fringe of the Kas hill anticline.

3. Climate

The Kachchh region is geographically located in a semi-arid to extremely arid climatic zone and hence exhibits dryland fluvial characteristics. The precipitation is predominantly controlled by the Indian Summer Monsoon (ISM) during July to September months. The monthly average rainfall for the period 1901–2000 is shown in Fig. 2b. The present studied drainage basin of the Lotia River covers an area of approximately 25 km^2 and with its principle