



Indicators of Holocene high-stage flood events and tributary confluence migration in the lower Narmada Basin, western India

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In this study, sedimentary deposits around the confluence of the Narmada River and its tributary, Orsang River, western India, were studied to understand the confluence dynamics. The results indicate that the sediment sequences exposed at three sites represent the contribution from the Narmada River, the Orsang River and the Heran River at various stages. During the Late Pleistocene, the sedimentation occurred as channel beds and bars in the wider than present and bedload dominant Narmada River. The channel aggradation, shifting and realignment, guided the Orsang River to change its course to flow through the lower course of the Heran River and join the Narmada in response to the early Holocene tectonic activity. High flood flows deposited fine sediments in the channel widening due to tributary confluence and within backflooded Orsang (tributary) valley during mid-late Holocene. The lateral migration of Narmada due to successive high flows during the mid-late Holocene probably led to the downstream movement of the Narmada–Orsang confluence.

Keywords. High-stage flood deposits; tributary junction migration; Holocene; Narmada River; Western India.

1. Introduction

River channel confluences are the geomorphological nodes that control the water and sediment movement downstream (Dixon *et al.* 2018). The junction angle and discharge of confluent streams control the sediment deposition and geomorphic processes at confluences (Mosley 1976; Best 1986). Shifting of channels and also confluences, to an extent, are common phenomena in alluvial plains; however, the rate and pattern vary regionally. With a change in the hydrogeological conditions in the region, these confluences migrate upstream or

downstream leaving behind sediment bars (Hackney and Carling 2011).

Mouth bar deposition at the confluence is facilitated by a decrease of junction angle which creates a zone of separation downstream of the junction and suspension fall out of sediments (Best and Reid 1984; Roy and Sinha 2007). Tributary confluences also provide suitable sites for the accumulation and preservation of palaeoflood deposits that result from large-scale flood events in the main-stem river (Ely and Baker 1985). The slackwater flood deposits along with the morphologic, stratigraphic and sedimentological characteristics of

the palaeobars deposited at tributary confluences provide clues to the past high-stage flood discharges. Although important, studies on confluence morphodynamics in the rivers of India are few and on shorter timescale. Studies on the confluence dynamics in the Ganga plains over a hundred years have related the shifting of river channels and confluences to local gradient adjustment and hydrological fluctuations including the flood magnitude and frequency (Jain and Sinha 2003; Roy and Sinha 2005, 2007; Singh *et al.* 2019, 2020). The confluence dynamics of the Sone River with the Ganga River in response to the tilt-induced avulsion and channel migration during Holocene in the South Ganga Plains has been studied by Sahu *et al.* (2015). The palaeoflood sediments at a tributary junction in lower Narmada Valley archiving the Little Ice Age (LIA) have been studied to determine the sources for the mainstem and the tributary sediments (Sridhar *et al.* 2016). Recent studies in rivers of the eastern Himalayan foothills such as the Rangmati, Jaldhaka and Lower Chel rivers have suggested the movement of confluence points upstream as well as downstream at variable rates over a temporal scale of seven decades in response to channel avulsion and stream capture (Shit and Maity 2013; Chakraborty and Mukhopadhyay 2014; Lama 2020). The inferences from these studies on a short timescale may have implications on the significant movement of the confluence points on a longer time scale induced by climatic and/or tectonic changes during the Late Quaternary.

The rivers in the alluvial plains of western India are not prone to channel shifting and avulsions on a decadal timescale owing to the highly incised river banks. However, instances of stream capture and realignment of courses in the alluvial plains in response to early Holocene tectonic upheaval and climate change have been noted (Maurya *et al.* 2000; Raj 2004; Juyal *et al.* 2006; Sridhar 2007a). The process of avulsion, river capture and aggradation result in river confluence migrations which generate interfingering deposits from the mainstream and tributary channels. This study is based on the sedimentary deposits around the confluence of the rivers Narmada and Orsang in the alluvial plains of Gujarat, and aims to understand the confluence dynamics in terms of mainstream high-stage flooding and tributary junction migration.

2. Study area

The Narmada River (figure 1a) is the largest west-flowing peninsular river in India having major tributaries such as the Burhner, Banjar, Hiran, Tawa, Chota-Tawa, Kundi, Orsang and Karjan. The river flows along the ENE–WSW-trending Narmada–Son Fault (NSF) (Biswas 1987) and debouches into the Gulf of Cambay (figure 1b). The lithology of the Narmada Basin comprises of the Proterozoic metasediments of the Vindhyan Supergroup, Precambrian granite-gneisses, the Deccan Basalt and Cenozoic marine sedimentary formations (figure 1b). The river has a narrow course in the upper bedrock reach exhibiting waterfalls, rapids, scablands and gorges (Rajaguru *et al.* 1995) and a wide expansive course with entrenched meanders in the Gujarat Alluvial Plains (Chamyal *et al.* 2002). Located in the sub-humid climatic zone and the heart of the Indian monsoon region, the Narmada basin receives monsoonal rain; mean annual rainfall varies between 550 and 850 mm (figure 1a). The modern, historical and palaeoflood data suggests that the Narmada River is prone to large magnitude flooding during summer and that extraordinary floods occurred in the last few decades with peak discharge close to $60,000 \text{ m}^3 \text{ s}^{-1}$ (Kale *et al.* 1994, 1996; Ely *et al.* 1996).

The study area is located near the confluence of the Narmada River and its tributary, i.e., the Orsang, in the lower reach of the Narmada Basin (figure 2). The Orsang River emerges from the fringe of the Aravalli ranges comprising dominantly granites and quartzites and flows through the alluvial plain before meeting the Narmada (figure 2). The slope deviator course of the Orsang River is influenced by E–W and NE–SW trending subsurface lineaments (Maurya *et al.* 2000). The area has been tectonically active during the late Quaternary due to reactivation of the major East Cambay Basin Margin Fault (ECBMF), the Narmada–Son Fault (NSF) and the Orsang Fault (OF) (figure 2) along with other minor lineaments (Maurya *et al.* 2000; Juyal *et al.* 2004; Raj 2004).

The major geomorphic features developed in the study are the ravines, terraces and entrenched meanders (figure 3a). A cross-section of the area (figure 3b) between the Narmada and its tributary, the Orsang River shows uplifted terraces on the northern bank and deeply incised ravine surfaces. Chamyal *et al.* (2002) have attributed the presence of incising rivers evidenced by 40–50-m high

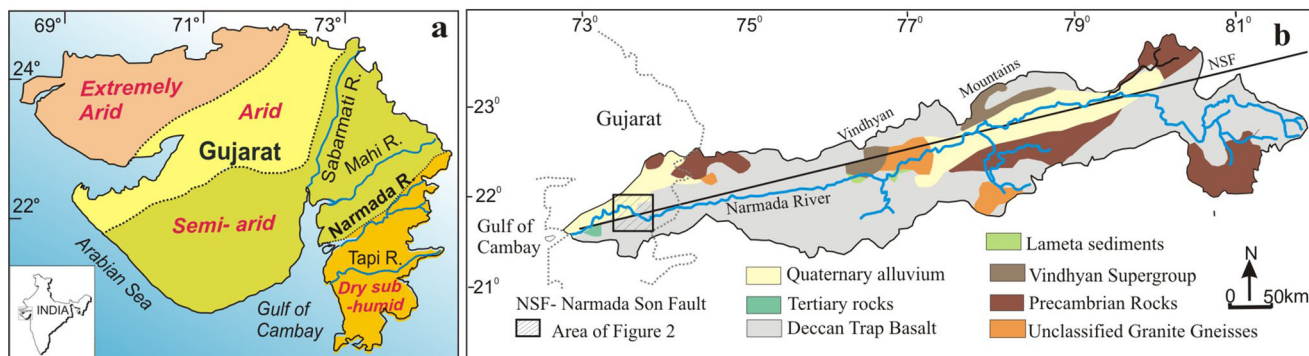


Figure 1. (a) Location of Narmada River and other west-flowing rivers in Gujarat along with the climatic zones. Inset is the map of India showing the location of Gujarat. (b) Major geological formations in the Narmada Basin (after Gupta *et al.* 2011). The square box marks the area of figure 2.

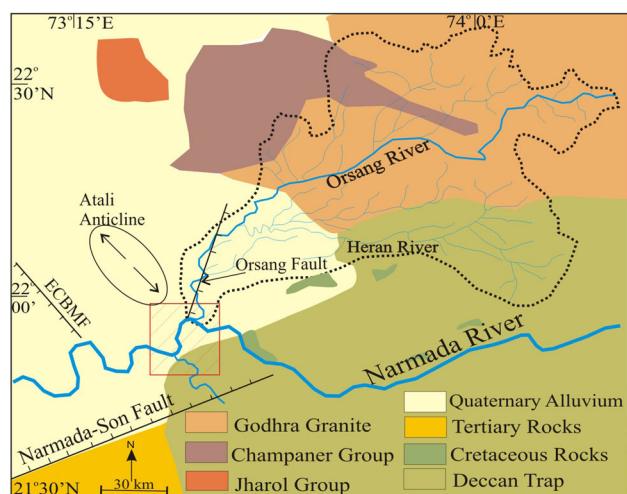


Figure 2. Geological formations and major structures in the catchment of the Orsang and Heran drainage basins, the two tributaries of the Narmada in the study area (after GSI 1978; Raj 2004).

alluvial cliffs and deeply entrenched meanders, deep gullies, uplifted Holocene terraces, and palaeobanks away from the present channel to reactivation of the faults and lineaments during the early Holocene. Several traces of palaeochannels trending E–W direction in the form of cut-off meanders, meander scar, ox-bows are observed to the west of the Orsang River (Raj 2004). The change in the course of the Orsang River and capture of its tributary, the Heran River occurred due to tectonic uplift along major faults in the region (Maurya *et al.* 2000; Raj 2004).

3. Methods

Three sites were studied: (i) Chanod, at confluence, on the northern bank of Narmada, (ii) Sanor, ~1.5 km upstream from the confluence along Orsang

and (iii) Karnali, at confluence, on the southern bank of Orsang (figure 3a). The preliminary interpretation and site selection was based on the satellite data (Google Earth images) and the topographical sheets on 1:50000 scale (46 F/8, G/5 and G/9) followed by field survey for the identification of flood indicators. A recent excavation for roadway construction exposed the sediment sequences at Karnali (Site 3) providing an opportunity to assess the sediment character. The stratigraphical and sedimentological attributes of the exposed sediment sections were described using sedimentary facies code and architectural elements as summarised in table 1 (Miall 1996). Flood units were demarcated and various depositional environments such as channel widening, channel expansions, back-flooded tributary mouths and valleys were described (table 2) according to Ely and Baker (1985) and Benito *et al.* (2003). The sedimentary units of high-stage flood deposits are considered to have been deposited by successive flood events over periods of centuries to millennia, building up a sedimentary sequence and the breaks and contacts are indicative of individual flood events. To demarcate individual flood units, the criteria suggested by Baker and Kochel (1988), Benito *et al.* (2003) and Shukla and Singh (2004) were used. This includes (a) a distinct clay layer at the top of a flood unit, representing the waning stage of a flood, (b) deposition of inter-bedded coarse tributary alluvium (couplets) or colluvial sediments, (c) change in the physical characteristics of the flood units, such as sediment colour or particle size, and (d) presence of palaeosols or mud cracks indicating soil surface exposure.

Optically stimulated luminescence (OSL) chronology on one sample from Karnali (Site 3) was obtained from the Institute of Seismological

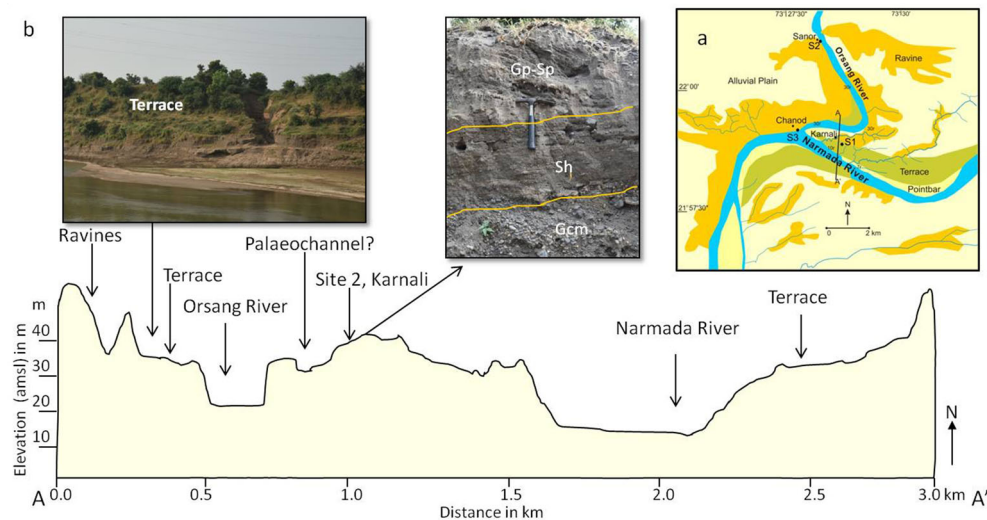


Figure 3. (a) Geomorphic features around the Narmada–Orsang confluence. A–A' is the line of cross section. S1, S2 and S3 are the sites where exposed sediment sequences were studied. (b) A profile showing various topographical features along the line A–A'. Also given are the pictures of the terrace adjacent to the Orsang River on the right bank and the sediment sequence exposed at Karnali (Site 3).

Research (ISR), Gandhinagar. The analysis was carried out following standard protocol (Prizomwala *et al.* 2018) and the measurement details are given in table 3.

4. Results

4.1 Site at Chanod

The section at Chanod is about 20 m above the river level and has a total thickness of 2.5 m (figure 4a). Based on the texture, sedimentary structure, colour and composition, the sequence has been divided into six units. The basal unit-1 of the section is about a meter thick and comprises matrix-supported gravel (Gm) with faint laminations. The matrix comprises of poorly sorted coarse to medium sand. The clasts vary in size with intermediate axes between 2 and 5 cm and are largely composed of basalt. The overlying unit-2 is 30 cm thick comprising pale-coloured massive silt and medium to fine sand (Sm). The matrix-supported gravel (Gm) unit-3 is 20 cm in thickness with predominantly basaltic clasts ranging in size from 2 to 5 cm. The overlying unit-4 is 40 cm thick comprising pedogenized silt (P) above which lies the 20-cm thick massive sand (Sm) unit-5. The top of the section is 20-cm thick unit-6, comprising pedogenized silt (P) showing very faint laminations.

The matrix-supported gravel facies suggest their formation by process of cohesive clast-rich high-

strength non-channelised sediment flows (Blair and McPherson 1994; Miall 1996). The massive fine sand facies with occasional faint laminations suggests rapid deposition from suspension and the silt facies with weak laminations indicates accumulation from suspension deposits and settling in overbank areas during flood stage (Miall 1996). The presence of pedogenic features such as blocky nature, mottling and organic matter suggests break in deposition and sub-aerial exposure.

4.2 Site at Sanor

The total thickness of the section exposed at Sanor, along the Orsang River, is about 2.2 m (figure 4a, b). The bottom-most unit 1 (50 cm) comprises of gravel composed of basaltic clasts (Gc) and is overlain by 30-cm thick silty sand (Sh) horizon, which shows weak horizontal laminations (Unit 2). The sequence repeats in the overlying units with 10 cm gravel and 15 cm silty sand (Unit 3 and 4). The overlying unit comprises 15-cm thick black silty sand (Sm) horizon and is overlain by 10-cm thick weakly laminated silt (Sh) (Unit 5 and 6). This is overlain by 5-cm thick fine sand horizon followed by 40-cm thick laminated silt (Unit 7 and 8) overlying which is 55-cm thick pedogenized silt (P) (Unit 9).

The horizontally stratified silty sand facies suggest transportation as bedload by persistent flows in channels and deposition in upper flow regime conditions (Collinson and Thompson 1982). The faintly laminated fine silt indicates rapid

Table 1. *Summary of facies associations and architectural elements observed at study sites (after Miall 1996).*

Architectural element	Litho facies	Characteristics	Inferred process	Palaeoenvironment
Channels (CH)	Gp–Sp, Gm–Sm	Cross-bedded gravel and sand. Comprising clasts of basalt, including channel fill geometries, maximum clast size ~7 cm	Channel fills	Accretionary deposit, cutoff channel
Sandy bedforms (SB)	Sp, Sh, Sl	Planar cross-bedded fine to coarse sand, also pebbly. Few horizontally laminated units. Show light and dark colour laminations	Channel fills and minor bars, aggradational	Meandering channel, episodic flood deposition and fluctuating precipitation
Lateral-accretion macro form (LA)	Sp, Sh, Sl	Planar cross-bedded fine sand, horizontal laminations and low-angle cross-bedding	Accretionary	Point-bars, middle channel bars
Laminated sand sheet (LS)	Sh, Sl, Sp	Horizontal laminations and low-angle cross-bedding	Sheet or blanket of sand by flash flood deposition under upper flow-regime conditions	Stacked sequences along channel banks

Table 2. *Facies sequences observed in various flood environments at the study sites (after Benito et al. 2003).*

Site	Flood environment	Facies observed
Chanod	Channel widening	Massive silt-clay (pedogenised) (P) Fine sand with cross-beds and occasional current ripples (Sp–Sr) Coarse sand massive (Sm) Fine sand with parallel laminations (Sh) Crudely stratified gravels (Gm)
	Tributary mouth	Medium to fine sand and silt with parallel lamination
Sanor	Tributary back flooding	Alternating silt-sand and silt-clay
Karnali	Channel widening	Fine sand with cross-beds and occasional current ripples (Sp–Sr) Coarse sand massive (Sm) Crudely stratified gravels (Gm)
	Slack water bench	Massive silt-clay (pedogenised) (P) Fine to very-fine sand parallel lamination Fine sand with occasional pebbles

deposition by suspension in overbank channel conditions during high flood stage (Miall 1996). The fine gravel with faint laminations suggests persistent stream flows in gravels transported as bed load and deposited under waning flow. The intercalation of light and dark-coloured silt and sand horizons suggests contribution of sediments from the Orsang and the Narmada rivers.

4.3 Site at Karnali

At Karnali, six lithostratigraphic units have been demarcated in the 3.75 m section (figure 4c). A 75-cm thick unit (Unit 1) of gravel (Gm)

comprising basaltic clasts is exposed at the base and is overlain by a meter thick dark-coloured silty sand (Sh), horizontally stratified (Unit 2). It is overlain by about 30-cm thick unit of matrix supported, low angle planar cross-stratified gravel (Gp) and is, in turn, overlain by 50-cm thick horizontally stratified black sand deposits (Sh) (Unit 3 and 4). A 30-cm thick planar cross-stratified sand (Sp) unit with basaltic gravels (~2 cm size) is seen above (Unit 5). Overlying this unit is the 50-cm thick gravely sand (Unit 6). It is characterised by dominant amount of fine to medium black coloured gravels. On top of the vertical sequence, 30 cm brown-coloured pedogenized silty clay (P) is seen (Unit 7).

Table 3. Details of radioactivity, palaeodose, dose rate and ages obtained using the single aliquot regeneration (SAR). The final ages are computed using central age model (CAM) and minimum age model (MAM). Cosmic ray dose rate: 150 ± 30 ($\mu\text{Gy/a}$), water content used: 10 ± 2 (%).

Lab code	Sample no.	Depth (m)	U (ppm)	Th (ppm)	K (%)	CAM De (Gy)	MAM De (Gy)	OD%	Dose rate (Gy/ka)	CAM age (ka)	MAM age (ka)
ISR 468	NK	1.3	1 ± 0.05	10.9 ± 0.54	1.18 ± 0.02	25 ± 0.8	22.2 ± 1.13	27	2.1 ± 0.09	11.6 ± 0.7	11 ± 1

The horizontally stratified silty sand (Sh) facies suggests transportation as bedload by persistent flows in channels and deposition in upper flow regime conditions (Collinson and Thompson 1982; Miall 1996). The matrix-supported cross-bedded gravel and planar cross-stratified sand, however may have been deposited as channel/transverse bar under sustained flows (Miall 1996; Bridge 2003). The sandy gravel facies suggests vertical accretion of progressively smaller clasts during the waning flow with high sediment-discharge ratio in shallow aggrading channels. However, viewing in combination, the sequence comprises clast to matrix-supported gravel units interstratified in alternations with 10–35-cm thick, fine- to coarse-grained, sometimes pebbly, generally laminated sand. The horizontally laminated gravel-sand couplets are understood to be the products of alternating phases of transportation and deposition of gravel and sand in sheet floods (Blair and McPherson 1994). However, the presence of occasional cross-bedded gravel and coarse sand horizons within dominantly sandy facies and interbedding of horizons showing contrast in grain size provides evidence for recurring floods of variable energy (Shukla and Singh 2004). The pedogenized horizon on top implies a stable surface where slow or no deposition has occurred over a long period of time.

5. Discussion

5.1 Indicators of high-stage flooding

The most common criterion for demarcating distinct flood events in the main stem river is the presence of intermittent tributary load sediments within the flood sediment sequence. The sediment sequences at the Narmada–Orsang confluence studied at Chanod, Karnali and Sanor provide clues to palaeoflood events in the Narmada basin. The catchment lithology for the Narmada and the Orsang River are quite distinct. A major part of the Narmada River catchment comprises the Deccan Basalt and minor outcrops of Proterozoic metasediments, granites, and tertiary marine sedimentary formations (Subramanian *et al.* 1985), whereas the Orsang River emerges from the fringe of the Aravalli ranges and flows through the granite-gneisses but for the Heran River, its tributary which has a Deccan Trap catchment (figure 2). Therefore, the characteristics of the

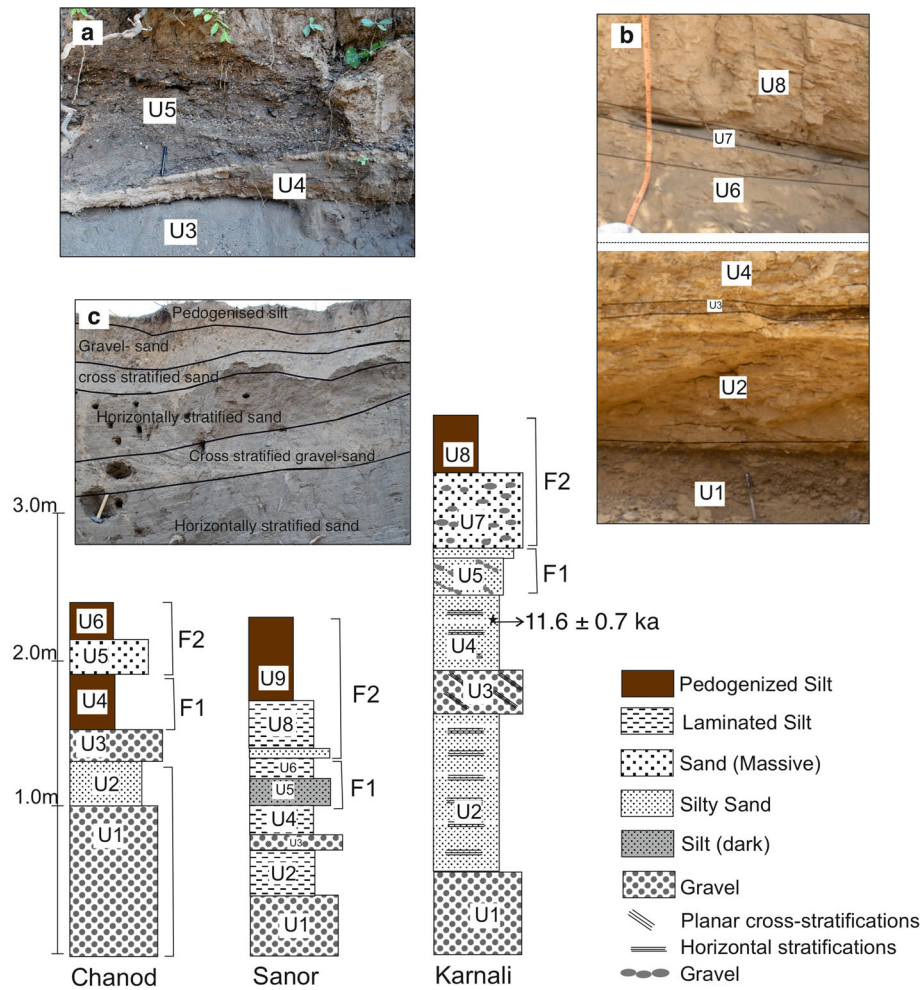


Figure 4. Lithologs of the sediment sequences exposed at Chanod, Sanor and Karnali. (a) View of the dark-coloured coarse sand and gravel units separated by pedogenized silt layer at Chanod. (b) The exposed section at Sanor shows alternate layers of dark-coloured coarse sand/gravel and fine silt. (c) View of the horizontally stratified and cross-stratified coarse sand and silt units exposed at Karnali.

sediments contributed by both the basins are also very distinct.

The results of the present study indicate that the sediment sequences exposed at three sites represent the two depositional phases of the Narmada and Orsang rivers. The gravel and sand (Units 1, 2, 3 and 4) exposed at the base comprise the lithofacies assemblages Gmm, Sm under LA and LS architectural elements (table 1). The gravel comprises of dominantly basalt clasts and is overlain by laminated silt. The OSL chronology on the laminated silt (Unit 4) at Karnali (Site 3) has provided an age of 11.6 ± 0.7 ka (figure 4). A distinct change in the sediment size and character is seen in the upper part of the sections, especially at Chanod and Sanor (figure 3). The sand and pedogenized silt units at Chanod represent the high flood deposits in the widened Narmada channel (table 2) at the

Orsang confluence. The slackwater sedimentation due to back flooding in the tributary, i.e., Orsang is observed at Sanor. The two dark silt units (figure 4b) possibly indicate the deposition during the high magnitude flood in the Narmada creating back flooding in the Orsang. These units are separated by light coloured laminated silt deposited as overbank sediments during high flows in the Orsang. Since these slackwater deposits overly the coarse gravel and sand units dated to 11.6 ± 0.7 ka, we attribute these to palaeofloods in the Narmada during mid-late Holocene.

At Karnali, the upper units in the section deposited after the early Holocene (~ 11 ka) gravels comprise reworked gravel and sand. These units with planar cross and horizontal stratifications suggest deposition as bars. At confluences, the common morphological features include sediment

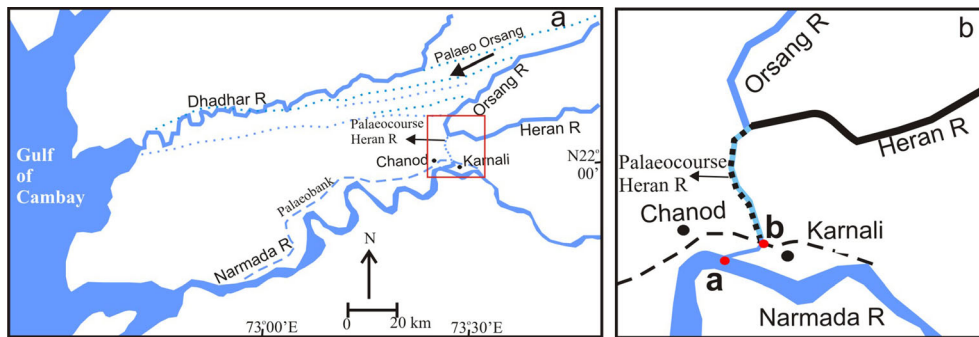


Figure 5. (a) The palaeocourses of the Narmada, Orsang and Heran rivers prior to early Holocene and related tributary junction migration (modified from Raj 2004). Red box marks the area of (b). (b) The black broken line represents the palaeocourse of the Heran River through which the present-day Orsang River (light blue line) flows and joins the Narmada. Point 'a' is the tributary junction point of Narmada and Orsang at present. Point 'b' is the probable junction point of Heran/Orsang and the Narmada Rivers prior to early Holocene.

deposition within the stagnation zone and formation of bars within possible flow separation zones or mid-stream in down-stream channel (Szupiany *et al.* 2009). Sheets of laminated sand (element LS of Miall 1996) with minor cross-stratified sand have been interpreted as the product of flash floods depositing sand under fluctuating flood levels (Miall 1977; Tunbridge 1984; Shukla and Singh 2004), whereas the horizontally laminated silt facies indicate waning flow conditions at the end of a flood event. Sand sheets gradationally capped by Sp, St or Sr indicate waning flow at the end of the flood (table 2).

Flood deposits located within tributary mouths contain typical sequences of reworked floodplain deposits (Benito *et al.* 2003). We, therefore, interpret that the lower units comprising gravel and sand, the top of which is dated to 11.6 ± 0.7 ka, as channel bed and channel bar deposits in the mainstem Narmada River (when Narmada had a wider channel or a bifurcated channel). The upper units comprising sand with reworked gravel and pedogenized silt were deposited during mid-late Holocene high flood flows at the tributary confluence. The coarse load is the contribution from the tributary and the fine silt units are slackwater sediments deposited at channel expansion (as at Karnali) and back flooded tributary (as at Sanor) (table 2). In the absence of chronology, it is difficult to infer the time period for these high-stage floods in the Narmada River. However, these may be correlated with the multiple large magnitude flood events recorded in the lower reaches of the Narmada River (Sridhar *et al.* 2015, 2016) and other rivers of semi-arid western India (Sridhar 2007b; Sridhar *et al.* 2014, 2020) during the mid-late Holocene.

5.2 Migration of tributary confluence

The occurrence of gravel composed of basalt at all the three study sites (upstream of confluence, on the northern and southern bank) is intriguing as the catchment of Orsang River is predominantly granite-gneissic rocks. The source of the basalt clasts can only be from the Narmada itself or the Heran River, a tributary of Orsang just upstream of the Narmada–Orsang confluence. This provides clues for the possible migration of the channel and the tributary junction of the Orsang with the Narmada River. The migration of the tributary junction is a common phenomenon in alluvial reaches of river systems and the confluence mobility is often related to the lithological and hydrological characteristics of the drainage basins that determine sediment yield (Dixon *et al.* 2018). The occurrence of sediment deposits now exposed near the confluence of the Orsang with the Narmada River, indicates a change in the planform morphology of either or both rivers. The sediment facies from these deposits near the confluence at Karnali (Site 3) suggests that the sediments were deposited under sand-bar environment. The confluence later migrated downstream at its present position with a probable decrease in the junction angle between the Narmada and the Orsang (figures 3a, 5). The deposition of bars at or near the confluence commonly occurs as tributary mouth bars and mid-channel bars in post-confluence channel. The episodic bank erosion and changes in bar formation at confluences can be in response to large flood events (Ettrema 2008). The tributary mouth bars may also migrate in response to variation in discharge between the confluent channels (Best and Roy 1991). The change in the confluence

location and morphology may well be simply caused by the tributaries that transport huge sediment loads into the main channel (Zhang *et al.* 2015). The tributary junction angle also plays a significant role in the migration of the confluence point upstream or downstream (Roy and Sinha 2007; Hackney and Carling 2011). The migration of the tributary junction may be caused by lateral channel migration, deflection due to sand-bar downstream and tectonic activity (Hackney and Carling 2011).

Earlier studies based on the geomorphic parameters and stratigraphic attributes in the Orsang and the adjacent Dhadhar River basins have suggested that the course of Orsang formed an independent river until Pleistocene (figure 5a) and was subsequently changed to become a tributary of the Narmada River (Juyal *et al.* 2004; Raj 2004). The Orsang probably occupied the lower course of the Heran River to join the Narmada River. The evidence of this can be observed in the predominance of basaltic gravel deposited as bedload along the present-day lower Orsang River, which was earlier the course of the Heran River. The Heran River is now a tributary of the Orsang River (figure 5b). It is interesting to note that the sedimentary sections exposed along the middle and upper reaches of the Orsang show gravel horizons at the base comprising predominantly of quartzites, granites and calcrites (Raj 2004) which is contrary to the basalt-dominated clasts in the lower reaches. This provides further evidence for the role of Heran River in the tributary confluence dynamics and related Late Pleistocene lithostratigraphy of the lower Orsang Basin. The disruption of the Orsang River has been attributed to the reactivation along the East Cambay Basin Margin Fault, Orsang Fault and the Narmada–Son Fault during the early Holocene (Maurya *et al.* 2000; Raj 2004).

The palaeo-bar deposits at Karnali suggest that the avulsion of the mainstem Narmada channel in response to Late Pleistocene–early Holocene aggradation also played a significant role in the confluence migration. Large magnitude floods are recognised to be triggers for avulsions of river channels causing movement of the confluence points (Roy and Sinha 2007). A wider than present channel of the Narmada River has been proposed by the earlier workers based on the geomorphic analysis, sediment characteristics and discharge estimates (Chamyal *et al.* 2002; Raj 2004; Bhandari *et al.* 2005; Sridhar and Chamyal 2010). The gravel deposits at the base of the sediment sequence at

Karnali, may then be understood as the contribution from the wider mainstem Narmada River as channel bar deposits (figure 5a). The bifurcated channel on the northern side was later on abandoned in response to the tributary confluence changes during the early Holocene. The formation of a mid-channel bar in the post-confluence channel (Mosley 1976; Best 1988) can occur through convergence of sediment transport pathways (Best 1988; Best and Rhoads 2008) and declining flow velocities and turbulence intensities downstream of the zone of maximum flow acceleration (Best 1988; Rhoads and Sukhodolov 2004). Such bar formation can promote bank erosion and channel widening (Mosley 1976), potentially driving changes in confluence morphology over time.

The migration of the confluence between the Narmada and Orsang can be therefore attributed to the avulsion of main stream and capture of the Heran River (tributary) by the Orsang River, which has moved the confluence point downstream. Since the chronological constraint on the sedimentation events is very limited at present, we do not emphasis here on the timing of these events.

6. Conclusions

Based on the present study on the fluvial sequences around the tributary confluence in the Narmada River, the following conclusions can be made:

- (1) Two phases of sediment deposition at the Narmada–Orsang confluence in the lower Narmada Basin during the Late Pleistocene and Holocene.
- (2) The first phase of deposition is related to the bedload dominant Narmada channel as well as the Heran River channel. Sediments were deposited as channel bars by flows with higher sediment-to-discharge ratio during the Late Pleistocene, which ceased around 11 ka.
- (3) The early Holocene tectonic activity and enhanced monsoon resulted into channel aggradation, shifting and realignment, whereby the Orsang River changed its course to flow through the lower course of the Heran River and join Narmada.
- (4) The Narmada–Orsang confluence migrated downstream due to avulsion of main stream and river capture by the tributary during the early Holocene.
- (5) The upper sedimentary sequences represent the slackwater deposits in the back-flooded

Orsang River and at channel widening at the Narmada–Orsang confluence resulting from the more prevalent large magnitude flood events in the Narmada during the mid to late Holocene.

- (6) The study suggests that in tectonically active and monsoon-dominated regions such as the Narmada Basin, understanding confluence dynamics on a longer time scale may provide insight into the river behaviour and drainage realignment.

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Author statement

AS: Conceptualisation of work, field survey and documentation, data synthesis and interpretation, writing original manuscript. DMM: Data synthesis and interpretation, review and editing of manuscript. LSC: Field survey, interpretation of results, editing of manuscript.

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