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Tectonic controls on the paleogeography of mountain exits of the Western and Central Himalayan Rivers☆

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ABSTRACT

The rivers exiting from the Himalayan mountains are a lifeline for millions of people residing in the Indo-Ganga-Brahmaputra plains. In this study, we examine the characteristics and evolution of the major Himalayan river exits in a segment of the Western and Central Himalaya between the Sutlej and the Tista Rivers. We investigated their morphology, tectonic setting, and their relation to the tear faults, and pre-existing structures of the basement.

The structural grain of the Himalayan front on a broader scale is sinuous and can be divided into areas of salient, recess, their transition, and straight mountain front (lacking salient and recess); the river exits can be classified depending upon where they exit with respect to the structural grain. The development of river exits is closely linked to tectonic processes. At geological timescales, the river exits are governed by the interaction between lateral fault propagation and structural curvature, leading to varying degrees of geographic changes in the drainage that include avulsion and deflection.

We distinguished four types of rivers exits: (a) exits along transition zone of salient and recess, with the least river deflection (e.g., Ganga), (b) exits guided by the tear faults at segment boundaries (e.g., Kosi), (c) exits, developed around lateral fold growth tips (e.g., Ghaghara), and (d) a combination of lateral fold growth and tear faults (e.g., Sutlej).

Chronological analysis indicates that the frontal folds corresponding to river exits were developed between ~112 to 1008 ka, with most concentrated at ~300 ka.

1. Introduction

The long-term drainage basin evolution in active convergent mountain belts is established through complex interactions between surface processes, tectonic uplift, and geometry of the underlying detachment (Wobus et al., 2006; Whittaker et al., 2008; Kirby and Whipple, 2012; Willett, 1999; Zhang et al., 2022; Whipple et al., 2023; Chen et al., 2023; Habousha et al., 2023). Surface processes through erosion driven by fluvial incision, hillslope diffusion and landslides determine the shape and size of the drainage basins and sediment supply to the foreland. Tectonic uplift on the other hand is manifested by progressive growth and propagation of faults and folds which cause the re-organization of the drainages in response to the growing structures. The geometry of the detachment, pre-existing structures or discontinuities in the basement control the segmentation of the mountain fronts and the spacing of the drainage basins. The evolution of the drainage systems in actively uplifting and eroding mountain belts has major implications on the complex history of structural deformation and geomorphic growth of the associated mountain belt (Elliott, 1976; Medwedeff, 1990; Gupta, 1997; Keller et al., 1998, 1999; Burbank et al., 1999; Friend et al., 1999; Van der Beek et al., 2002; Champel et al., 2002; Twidale, 2004; Keller and DeVecchio, 2013; Camafort et al., 2020; Trost et al., 2020; Seagren et al., 2022).

Particular emphasis has been laid on the antecedent transverse drainages that cut across the core of the growing mountains through deep gorges carved into the structural and topographic highs (Oberlander, 1985; Stokes and Mather, 2003; Montgomery and Stolar, 2006; Douglass and Schmeeckle, 2007; Douglass et al., 2009; Babault et al., 2012; Lang and Huntington, 2014; Pazzaglia and Fisher, 2022). A close linkage is established between anticlinal growth and drainage

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development which manifests itself as noticeable changes along the course of the antecedent rivers (e.g., Schumm et al., 2000; Snyder et al., 2003; Wobus et al., 2006; Amos and Burbank, 2007). Diversion of the antecedent drainages to an axial course, generation of wind or water gaps over the growing fold, exit of the drainages around the fold nose (plunge panel), and stream capture associated with fold growth are some of the common features that have been linked directly to the direction and rate of lateral propagation of the folds (Jackson et al., 1996; Delcaillau et al., 1998, 2023; Keller et al., 1999).

The structural and drainage co-evolution along the Himalayan front have resulted in the formation of several mountain exits of different Himalayan rivers originating in the glaciated Higher Himalaya and the monsoon-fed Lesser Himalaya. Several such studies have been conducted in the active fold-and-thrust belt of the frontal part of the Himalaya – the Himalayan frontal ranges (also known as the Frontal/ Outermost Siwalik Ranges) (Fig. 1a) to explore the link between drainage development and frontal fold evolution (e.g., Delcaillau et al., 2006; Singh and Tandon, 2008; Singh and Jain, 2009; Malik et al., 2010;

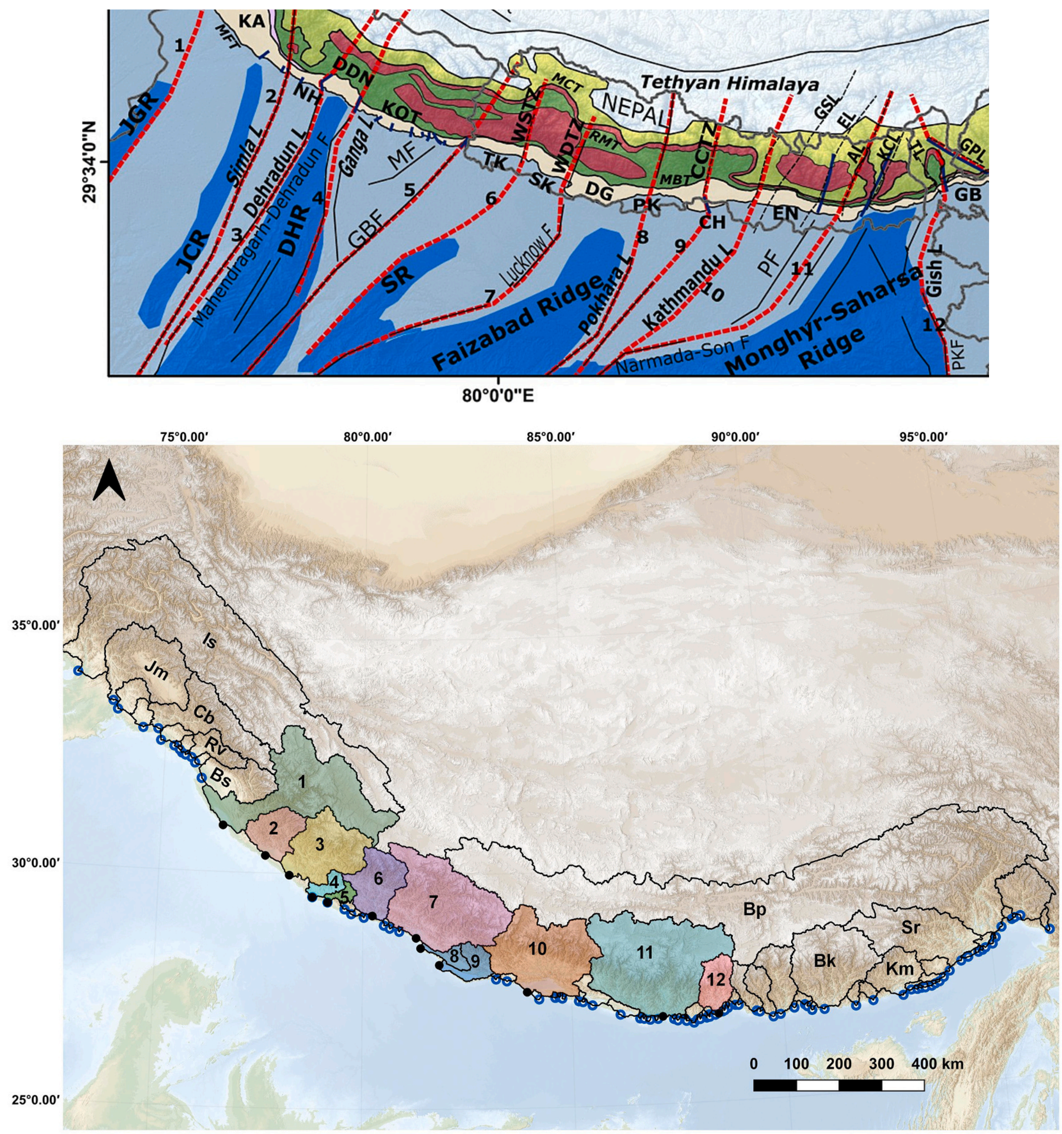

Fig. 1. (a) Figure showing the litho-tectonic divisons of the Himalaya and its orogenic segmentation along major transverse boundaries (marked as lineaments 1 to 11 – red dashed lines) that extend from the basement structures (black solid lines) of the Indo-Gangetic plains. Lineaments 2, 4, 5, 6, 7, 8, 10, coincide with gravity lineaments shown by Godin and Harris, 2014 and are accordingly extended northwards into the Himalaya. Other lineaments are interpreted by Divyadarshini and Tandon, 2022 based on the review of works by Mugnier et al., 1999; Ravi Kumar et al., 2013; Dal Zilio et al., 2021; Mukul et al., 2014. (KA – Kangra Recess, NH – Nahan Salient, DDN – Dehradun Recess, KOT – Kotdwara Salient, TK – Tanakpur Sector, SK – Surkhet Sector DG – Dang Recess, PK – Pokhara Salient, CH – Chitwan Recess, EN – Eastern Nepal Sector, DH- Dharan Salient, GB – Gorubathan Recess). WSTZ – West Surkhet Transfer fault, WDTZ – West Dang Transfer Zone, CCTZ – Central Chitwan Transfer Zone, GSL – Gourishankar Lineament, EL – Everest Lineament, AL – Arun Lineament, KCL – Kanchenjunga Lineament, GL – Gish Lineament, GPL – Goalpara Lineament, MF – Moradabad Fault, PF – Patna Fault, PKF – Pingla- Kishanganj Fault, DCF – Dhubri-Chungthang Fault, BF – Bomdilla Fault. **(b)** Map (overlain on SRTM-DEM) showing the basin shape, extent and drainage pattern of the transverse rivers investigated in this study (shaded in different colours) (1 – Sutlej, 2 – Yamuna, 3 – Ganga, 4 – Ramganga, 5 – West Kosi, 6 – Sharda, 7 – Ghaghara, 8 – Babai, 9 – Rapti, 10 – Gandak, 11 – Kosi, 12 - Tista) that cut across the Himalayan mountain with their exit location marked by bold black circle at the Main Frontal Thrust (MFT). Other river catchments that are not investigated in this study area also shown for reference and their mountain exits are marked with the open circle (Is-Indus; Jm-Jhelum; Rv-Ravi; Bs-Beas; Bk – Beki; Km – Kameng; Sr – Subansiri; Bp-Bramhaputra). Note: The use of the term “lineament” is intended to reflect the interpretive nature of the features, which may indicate subsurface structures but do not imply direct field validation unless explicitly stated in the cited literature. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Barnes et al., 2011; Divyadarshini and Singh, 2019; Sharma et al., 2019). Key insights on the timing and spatial extent of active deformation along the mountain front have been obtained from the paleogeographic development of these river outlets.

The frontal folds are formed along the Main Frontal Thrust (MFT) which is one of the most active structures in the Himalaya and accounts for nearly 50 % (10 to 20 mm/yr) of the convergence between the Indian and Eurasian plates (e.g., Lavé and Avouac, 2000; Mugnier et al., 2004; Kumar et al., 2006, 2010; Jayangondaperumal et al., 2017). The MFT mountain front is segmented and comprises of a series of thrust faults that extend from NW-SE along the strike of the Himalaya (e.g., Karunakaran and Ranga Rao, 1979; Nakata, 1989; Powers et al., 1998; Mugnier et al., 1999; Burgess et al., 2012; Srivastava et al., 2016, 2018). Major southward flowing transverse rivers viz., Sutlej, Yamuna, Ganga, Sharda, Gandak, Kosi and others (Fig. 1b), have undergone several diversions along their course before they debouch into the Indo-Gangetic foreland basin. These rivers collect other lower order transverse streams as they break through the Himalayan mountain front at specific locations called exits (Fig. 1b).

A key question that requires further examination is what controls the location of the drainage exits along the mountain front? Valdiya (1976) noted a close association between the major river exits and the tear faults at the Himalayan front (Fig. 1b); but most of these tear faults are yet to be confirmed by structural data and field evidences. In a later work by Gupta (1997), the location and number of the river exits have been attributed to the drainage reorganisation by the growth of structurally controlled topography which here is represented by the folded Frontal Siwalik Ranges formed along the MFT and by the Outer Lesser Himalayan mountains formed along the Main Boundary Thrust (MBT) (Fig. 1a).

The valleys of some major south flowing Himalayan rivers (viz., Indus, Sutlej, Kali-Gandaki, Karnali, Tista, Arun, Yarlung Tsangpo) are formed along the crest of anticlinal structures in the Higher and Lesser Himalaya named as the Himalayan River anticlines that are oriented transverse to the primary *E*-W structural grain of the Himalaya (Oberlander, 1985; Montgomery and Stolar, 2006). While crossing the Higher and the Lesser Himalayan Ranges, the transverse rivers flow parallel to and down the N-S trending axis of the river anticlines through steep gorges carved into the deeply exhumed structural highs (e.g., Wager, 1937; Meier and Hiltner, 1993; Zeitler et al., 2001).

The rivers cut across the MBT and after flowing for some distance in the Sub-Himalaya, they drain into the Indo-Gangetic foreland basin. In the Lesser and Sub-Himalayan reaches, the rivers display a distinctive gridiron or bi-forked geometry created either by focusing of deviated rivers between two linked structural segments, or by the merging of the deviated rivers with another river that has maintained its transverse course across the growing structures (Gupta, 1997).

In this study, we carry out an analysis of the characteristics and evolution of the major Himalayan River exits between the Sutlej and the Tista Rivers, and examine their link to the structural segmentation of the Himalayan Mountain front, associated tear faults, and basement topography and growth history of the frontal folds. We also present a review of previous works in the frontal Himalaya wherein the segmentation of the frontal Himalaya and associated drainage evolution, in addition to the role of transverse structures/tear faults has been investigated.

2. Approach of Study

We provide a detailed description on:

a) Morphology and tectonic setting of the river exits;
b) Tear faults and pre-existing structures of the basement, and their relationship with the river exits;
c) Segment boundaries in the frontal Himalaya with and without river exits, and their implication;
d) Classification of the exits
e) Structural and topographic evolution of the mountain exits.

We attempt to address the following questions: 1) what controls the focussing of a river at its present exit position, 2) what sets the spacing between the exits, 3) what sets the width of the exits, and associated geomorphic features, 4) what is the possible timing of the establishment of the major river exits at their present position and how does it relate to the age and growth history of the frontal Himalayan anticlines?

We have restricted our study to the principal river exits of the western and central Himalaya. However, certain rivers of the western Himalaya, such as Beas, Ravi, Chenab, Jhelum, and Indus, are excluded either because of their proximity to the western syntaxial bend or due to the limited understanding available of the geological structures at their mountain exits. The rivers of the eastern Himalaya were excluded from consideration since several of these rivers are situated near the eastern syntaxes of the Himalaya. Rivers with smaller catchments originating in the Sub-Himalaya are excluded; however, rivers like the Ramganga, Kosi, Rapti and Babai are included due to their distinct morphology and proximity to the major river exits. Our study is therefore focused on the mountain exits of the rivers Sutlej, Yamuna, Ganga, Sharda, Ghaghara, Rapti, Babai, Gandak, Kosi, and Tista (Fig. 1b).

3. Description of the River exits

3.1. Sutlej River exit

The exit of the Sutlej River is located near Ropar in the northwestern part of India at the boundary between the Janauri anticline and the Chandigarh anticline (Fig. 2). The location of the exit is marked along the Ropar Tear fault (e.g. Powers et al., 1998; Singh and Tandon, 2010) which forms part of a north-south extending major transverse boundary in the Himalaya known as the Manali-Ropar tear fault (Thakur et al., 2018). Before its exit from the Himalayan mountains, the Sutlej River flows in a southward course along the eastern edge of the Kangra recess. The course of the river is mainly focused around the Simla lineament (Fig. 1), also, called the Mandi Ramp, which is identified as an oblique ramp (Dubey, 1997; Yin, 2006) and marks the eastern edge of the Kangra recess and separates it from the adjoining Nahan Salient (Divyadarshini and Tandon, 2022). The southward continuation of the Simla lineament has been linked with the subsurface Jodhpur-Chandigarh ridge or basement faults branching from the western margin of the Delhi-Haridwar ridge (Ravi Kumar et al., 2013; Godin and Harris, 2014; Godin et al., 2019).

After crossing a series of structures within the Kangra valley progressively from north to south (Powers et al., 1998; Mukhopadhyay and Mishra, 1999), the Sutlej River enters into the Soan dun – an intermontane valley in the Kangra recess (Fig. 2). The Soan dun is developed between the Janauri anticline in the south and the bordering Siwalik Hills to its north (Powers et al., 1998). The Sutlej River is deflected to a south-eastward course to the north of the Janauri anticline, where it flows axially for a distance of ~40 km (Fig. 2). It is joined by the south-eastward flowing Soan River, which forms the major axial river of the Soan dun; together they collect all transverse streams arising from the bordering Siwalik mountains in the north and south, and this gives rise to a prominent bi-forked drainage pattern (Fig. 2). Prior to its exit from the Himalaya, the Sutlej River is joined by the westward flowing Sirsa River which is the major axial river of the Pinjaur dun formed by joining of streams arising from the Chandigarh anticline in the south, and the Tertiary Sub-Himalayan mountains in the north of the Pinjaur dun (Fig. 2). Together the two axial river systems form the baselevel for the streams originating from the northern sub-Himalayan mountains and giving rise to prominent fans thus controlling the development of the surfaces within the Sub-Himalaya (Suresh et al., 2007; Suresh and Kumar, 2009; Singh and Tandon, 2010). The Sutlej River turns around the southeastern edge of the Janauri anticline and takes two sharp

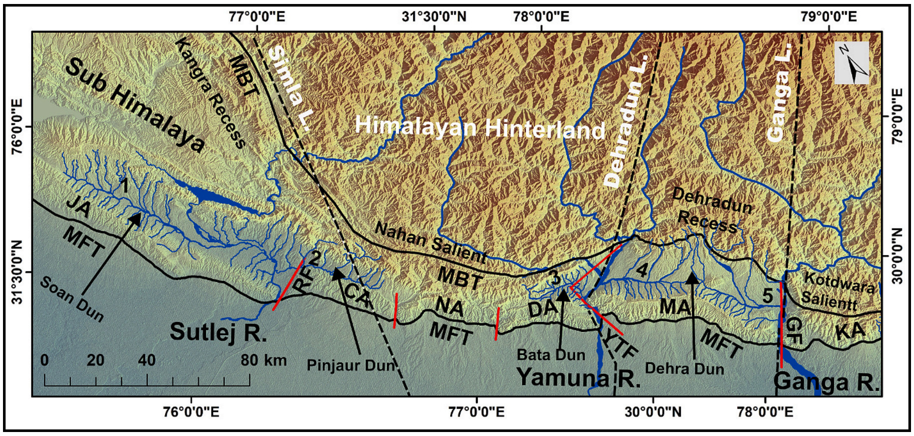

Fig. 2. SRTM-DEM of the northwest Himalaya showing the river exits of the Sutlej, Yamuna and Ganga rivers and its relation to tear faults (RF – Ropar Fault, YTF – Yamuna Tear Fault, Ganga Fault - red lines) and Frontal Siwalik Ranges (JA – Januari Anticline, CA – Chandigarh Anticline, NA – Nahan Anticline, DA – Dhanaura Anticline, MR – Mohand Range, KA – Kotdwara Anticline) at the MFT mountain front. The drainage pattern of these rivers and major tributaries (1 – Soan river, 2 – Sirsa river, 3 – Bata river, 4 – Asan river, and 5 – Song river) in the Sub-Himalayan region is also shown. The black dashed lines across the Himalaya show the lineaments from Fig. 1a that extend from the Indo-Gangetic Plains and divide the Himalayan arc into various sectors (after Divyadarshini and Tandon, 2022). The solid red lines mark the tear faults of the frontal Himalaya that displace the MFT. Structures and tear faults adopted from Powers et al. (1998); Sahoo et al. (2000); Singh and Tandon (2010). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

perpendicular bends near its exit from the Sub-Himalaya (Fig. 3a) (Singh and Tandon, 2010). The Siwalik Ranges on the eastern and western bank of the Sutlej River taper near the exit (Fig. 3a). The southeastern bank of the Sutlej River is marked by a NNE–SSW trending low elevation hill developed along the Ropar tear fault, joining the two segments of the MFT (Fig. 3a) (Singh and Tandon, 2010).

3.2. Yamuna River exit

The Yamuna River flows across the Sub-Himalaya in a southward course along the western edge of the Dehradun recess (Fig. 2). The course of the river, and its exit location across the MFT is marked along the Yamuna Tear fault (Raiverman et al., 1983; Nakata, 1972,) show sudden sharp bend from NNE- SSW in the Sub-Himalaya to NW-SE near the MFT (Sahoo et al., 2000; Srivastava et al., 2013) (Fig. 2). The Yamuna tear fault marks the transition between the Dehradun recess and the Nahan salient; it is shown to be associated with the northward extension of the Mahendragarh-Dehradun fault at the western margin of the Delhi-Haridwar basement ridge (Fig. 1a) (Godin and Harris, 2014) and together they are redefined as the Dehradun Lineament (Fig, 1a and 2) by Divyadarshini and Tandon, 2022. The river exit from the Himalayan mountains is located near Poanta Sahib at the boundary between the MFT segments separating the Dhanaura Range (e.g. Sharma et al., 2019) in the west and the Mohand Range in the east (Fig. 3b) (e.g., Srivastava et al., 2016); the tip of the Mohand Range associated MFT segment shows prominent offsets along the Yamuna tear fault, and the exit of the Yamuna River is focussed along the zone of displacement. (Fig. 3b).

Unlike the Sutlej River, the main channel of the Yamuna River is not marked by any axial stretch along its course through the Sub-Himalaya.

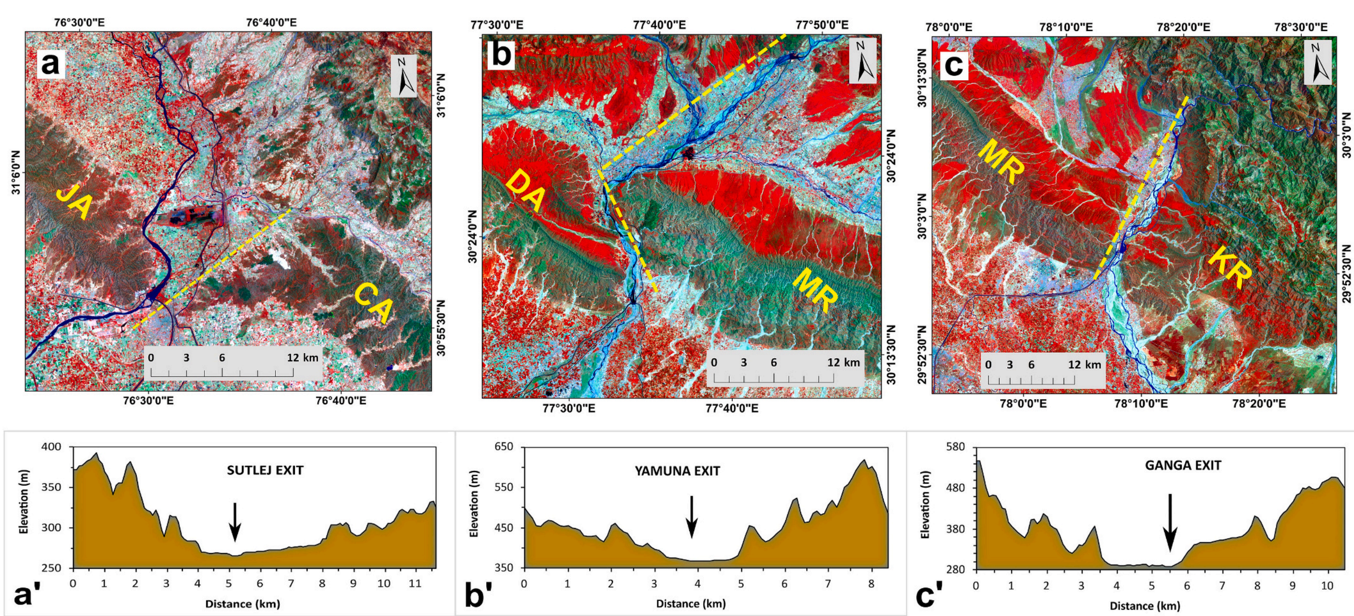

Fig. 3. False colour composites obtained from Landsat OLI images showing the river morphology and physiography of (a) Sutlej, (b) Yamuna, and (c) Ganga river exits. The cross-section profiles of the river exits are shown below the satellite image (JA – Januari Anticline, CA – Chandigarh Anticline, DA – Dhanaura Anticline, MR – Mohand Range, KR – Kotdwara Range).

After crossing the MBT, it drains into the Dehradun recess and divides the intermontane valley into the Bata dun in the west and Dehra dun in the east (Fig. 2) (Phillip et al., 2009). The major E-W trending structures of the Dehra dun and Bata dun truncate towards the northwest. Before its exit from the Himalaya, the Yamuna River is joined by two axial rivers i.e., the Bata River in the western bank, and the Asan River in the eastern bank (Fig. 2). The Asan River drains the western part of the Dehra dun and collects transverse drainages arising from the Mohand anticline lying to the south, and the Sub-Himalayan and Lesser Himalayan mountains lying to the north of Dehra dun (Fig. 2). Similarly, the Bata River forms the axial drainage of the Bata dun and collects transverse streams draining into the dun from the flanks of the Dhanaura anticline in the south and the Sub-Himalayan mountains in the north (Fig. 2). The Yamuna River within the Sub-Himalaya, is marked by well-developed terraces and floodplains (Thakur and Pandey, 2004; Sinha and Sinha, 2016; Densmore et al., 2016; Parida et al., 2017).

3.3. Ganga River exit

The exit of the Ganga River from the Himalaya is marked near Haridwar at the eastern tip of the Mohand Range (Fig. 2). The Ganga River flows in a southward course across the Sub-Himalaya along the eastern edge of the Dehradun recess (Fig. 2). Similar to the Yamuna River, the course of the Ganga River in the Sub-Himalaya, and its exit location across the MFT is marked along a tear fault i.e., the Ganga/Haridwar Tear fault (Nakata, 1972; Raiverman et al., 1983) (Fig. 2). The Ganga tear fault is a NNE-SSW trending structure extending between the MBT and the MFT (Fig. 2). It marks the transition between the Dehradun Recess and the Kotdwara Salient (Fig. 2). The MFT segments associated with the eastern tip of the Mohand anticline and the western tip of the Kotdwara anticline are truncated near the mountain exit of the Ganga River, and are displaced along the Ganga tear fault (Fig. 3c) (Sahoo et al., 2000). The Ganga tear fault is in alignment with basement faults extending from the Great Boundary Fault at the eastern margin of the Delhi-Haridwar ridge (Fig. 1) (Godin and Harris, 2014), named as the Ganga lineament (Divyadarshini and Tandon, 2022).

Here also, the main channel of the river does not flow along any axial stretch within the Dehradun recess. No major E-W trending structures are encountered along the path of the river which allows the river to flow straight across the Sub-Himalaya (Fig. 2). Close to its exit from the Sub-Himalaya, the Ganga River is joined by the axially flowing Song River that forms the major drainage network in the eastern part of Dehra dun (Fig. 2). The Ganga River is marked by four terrace levels along both its banks that extend from the MBT to its exit near the MFT. The higher T3 and T4 terraces are truncated abruptly near the MFT mountain exit, while the lower T1 and T2 terraces continue across the MFT (Sinha et al., 2010).

3.4. Sharda River exit

The exit location of some of the important Himalayan rivers viz., the Ramganga, West Kosi Gaula, and Sharda Rivers occur along the Himalayan mountain front in the Kotdwar-Haldwani region (Fig. 4). Here, the mountain front is cut across by many tear faults (viz., Baur fault, Nihal fault, Kathgodam fault, Haldwani fault and Chorgallia fault) (Goswami et al., 2009) that have displaced the adjoining MFT segments and mark the exit location of the Ramganga, West Kosi, Gaula, and Sharda Rivers (Fig. 4). The morphology is simple near the river exit as the rivers mostly flow straight across the Sub-Himalaya which is significantly narrow in the Kotdwara-Haldwani region (Fig. 4). A well-developed intermontane valley is lacking in this region but a similar setting can be observed near Kotabagh between Haldwani and Ramnagar. The course of the rivers is mostly unaffected by the lateral growth of the frontal ranges except some stretches which show local deflection near the offset thrust tips prior to their exit (Fig. 5). A prominent constriction of the rivers is observed in this region which forces the river to flow in narrow confined V-shaped valleys (Fig. 5). It was also noted that there is no recess or salient in this region.

The exit of the Sharda River from the Himalayan mountains is located near Tanakpur, in the west central part of the Himalaya (Fig. 4). The river exit is associated with two tear faults, i.e., the Kalunia Fault (in the western bank) and Tanakpur fault (in the eastern bank) – which have displaced the adjacent MFT segments and caused an embayment of the mountain front (Fig. 5d) (Goswami, 2012; Luirei et al., 2017). The exit is focused along a distinct lineament or transition zone that separates the Kotdwara sector from the Tanakpur sector (Divyadarshini and Tandon,

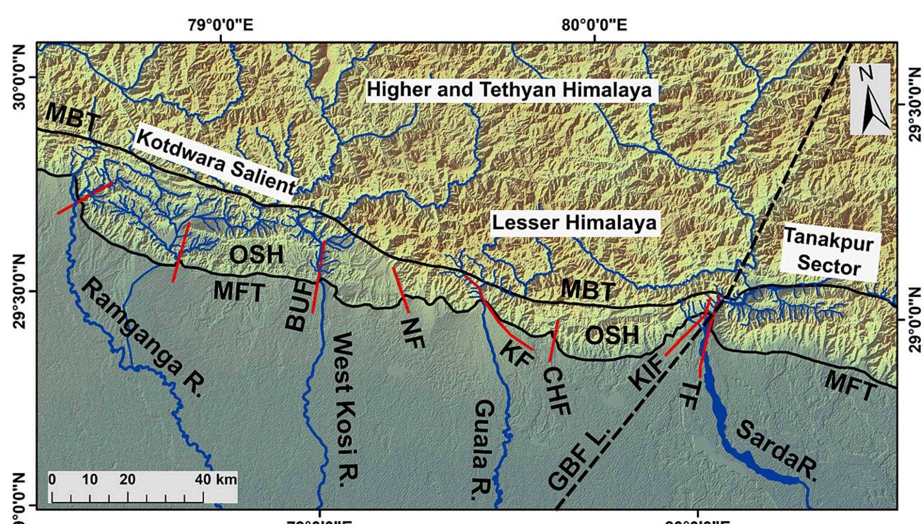

Fig. 4. SRTM-DEM of the west central Himalaya showing the river exits of the Ramganga, Gaula and Sharda rivers and its relation to tear faults (red lines) and Outer Siwalik Hills (OSH) at the MFT mountain front. BUF – Baur Fault, NF – Nihal Fault, KF – Kathgodam Fault, CHF – Chorgallia Fault, KIF – Kalunia Fault, TF – Tanakpur Fault, GBF L. – Great Boundary Fault Lineament. The drainage pattern of these rivers in the Sub-Himalayan region is also shown. The black dashed line across the Himalaya shows the lineament from Fig. 1a that extends from the Great Boundary Fault (GBF - basement fault of the Indo-Gangetic Plains) and marks the transition between the Kotdwara salient and Tanakpur sector (after Divyadarshini and Tandon, 2022). The solid red lines mark the tear faults of the frontal Himalaya that displace the MFT. Structures and tear faults adapted from Goswami et al., (2012), and Luirei et al. (2017). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

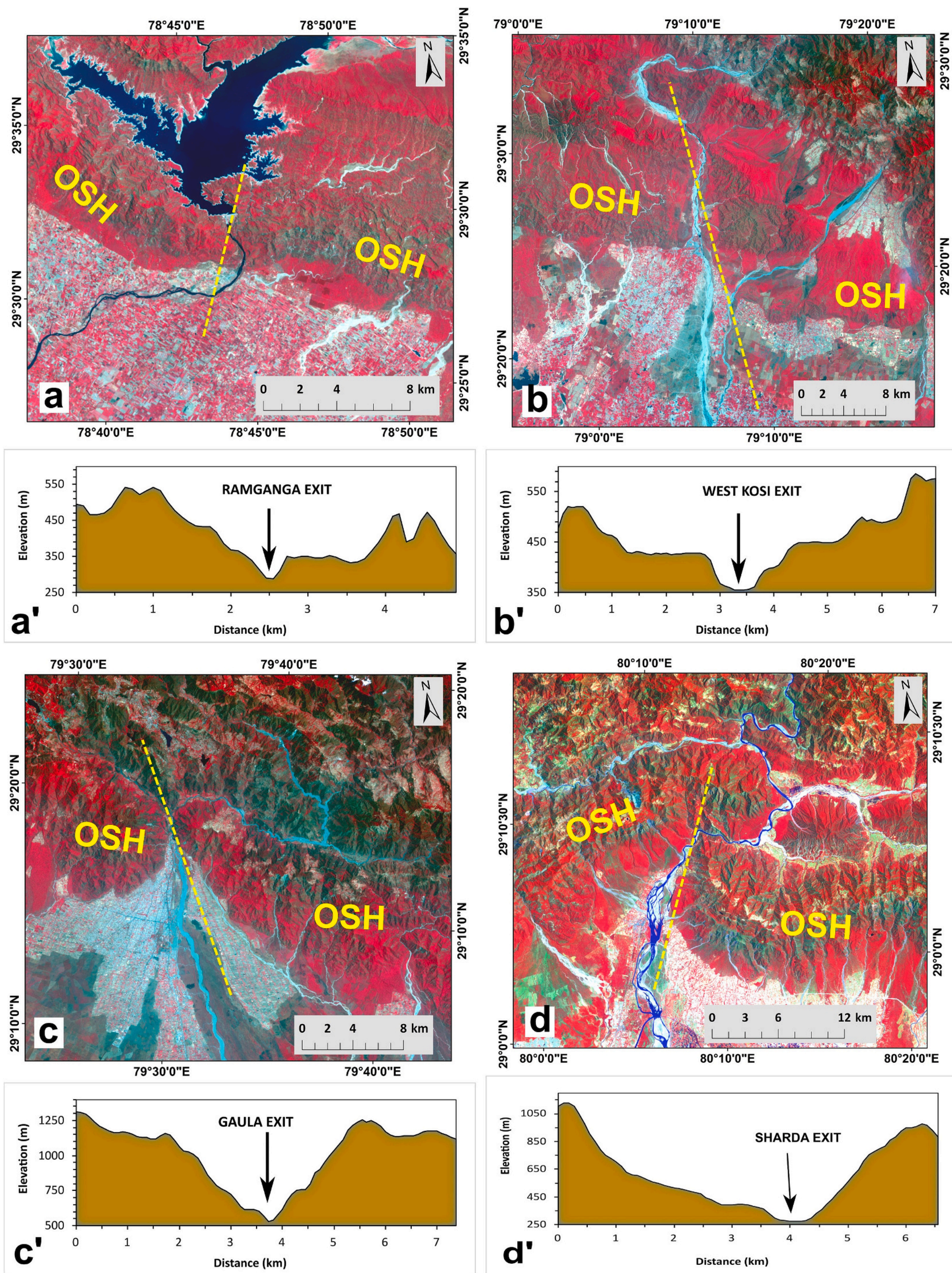

Fig. 5. False colour composites obtained from Landsat OLI images showing the river morphology and physiography of (a) Ramganga, (b) West Kosi, (c) Gaula and (d) Sharda river exits. The cross-section profile of the river exits are shown below the satellite image (OSH – Outer Siwalik Hills).

2022) (Fig. 1). This lineament has been related to the northward extension of the Great Boundary fault (basement fault of the Ganga basin) that intersects the frontal Himalaya along the Tanakpur tear fault (Dasgupta et al., 2000; Godin and Harris, 2014).

Unlike the rivers in NW Himalaya, the width of the Sharda River is extremely narrow near its mountain exit; the river appears to be constricted while crossing the frontal Siwalik hills (Fig. 5d). It is marked by a single, straight to sinuous channel lacking well-defined channel bars. Prior to its exit from the Himalaya, the southwest flowing river takes two sharp bends as it gets diverted locally for about 8–6 kms around the tips of the adjoining frontal ranges (Fig. 5d). The river width increases significantly after crossing the mountain front (Fig. 5d).

3.5. Ghaghara River exit

The Ghaghara River exit is located near Chisapani in western Nepal where the river flows between two segments of the MFT. (Fig. 6). Although there is no tear fault associated with the river exit, the exit location is focused near a proposed transfer zone/oblique ramp in the Sub-Himalaya, known as the West Surkhet Transfer Zone, (WSTZ) that separates the Tanakpur sector from the Surkhet sector (Fig. 1) (Mugnier et al., 1999). There is little evidence about the nature and N-S extension

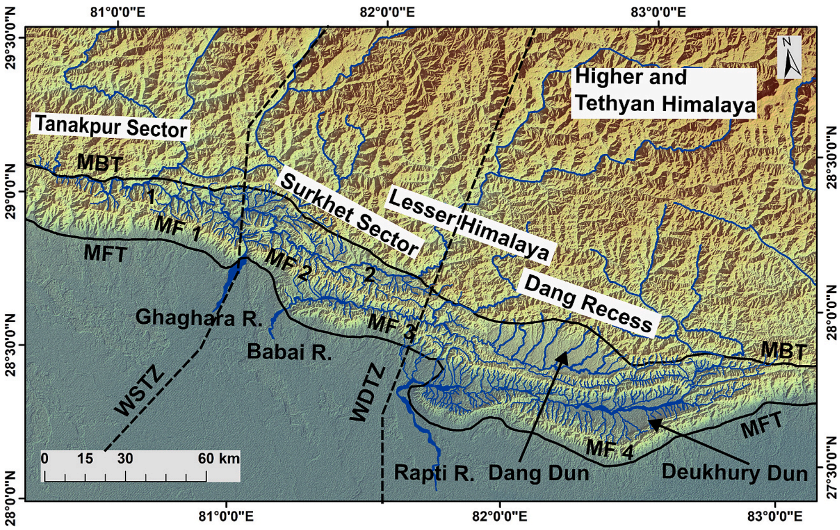

Fig. 6. SRTM-DEM of a part of the central Himalaya showing the river exits of the Ghagra, Babai and Rapti rivers and its relation to the Outer Siwalik Ranges (defined by the MF 1, 2, 3 and 4) at the MFT mountain front. The drainage pattern of these rivers in the Sub-Himalayan region is also shown. The black dashed lines show the transverse lineaments – WSTZ (West Surkhet Transfer Zone), WDTZ (West Dang Tranfer Zone) from Fig. 1a that extend from the Indo-Gangetic Plains and divide the Himalaya arc into the Tanakpur sector, Surkhet sector and Dang Recess (after Divyadarshini and Tandon, 2022). No tear faults have been identified in this region displacing the MFT. Structures adopted from Mugnier et al., 1999.

of this transverse zone, but a small embayment is noted along the MFT mountain front in this region Fig. 1). Earlier, we have shown that it could be related to a lineament (Divyadarshini and Tandon, 2022) that aligns with the sub-surface Sahjahanpur ridge of the Ganga plains (Ravi Kumar et al., 2013).

The Ghaghara River comprises of two major tributaries i.e., the Karnali River in the west and the Bheri River in the east that arise from the Higher and Tethyan Himalayan region (Fig. 6). After crossing the MBT, the Karnali and Bheri Rivers flow axially in narrow valleys within the Sub-Himalaya as they are deflected around the Frontal Siwalik Ranges (Fig. 6). The Sub-Himalaya is relatively narrow, devoid of intermontane valleys and marked by imbricate fold-and-thrust mountains in this region (Fig. 6). The Karnali and Bheri Rivers flow for ~50 kms towards east, and ~ 90 km towards west respectively in the Sub-Himalaya before they converge to form the Ghaghara River. The Ghaghara River is marked by a single, straight channel that appears to be squeezed or constricted in a narrow V-shaped valley along the river exit, and is devoid of channel bars (Fig. 7a). The river width increases drastically after crossing the mountain front (Fig. 7a).

3.6. Rapti and Babai River exits

The Rapti and Babai rivers form the major drainage networks of the Deukhury and Dang duns respectively in west central Nepal (Fig. 6). A prominent feature of the mountain front in this region is the overlapping of frontal thrust sheets for several kilometres in the E-W direction (e.g., Mugnier et al., 1999, 2005) (Fig. 6). The Deukhury and Dang duns are formed as narrow intermontane valleys between the overlapping frontal thrust sheets (Fig. 6). The Rapti River has a small catchment as it arises mainly from the Lesser Himalayan region (Fig. 1). After crossing the

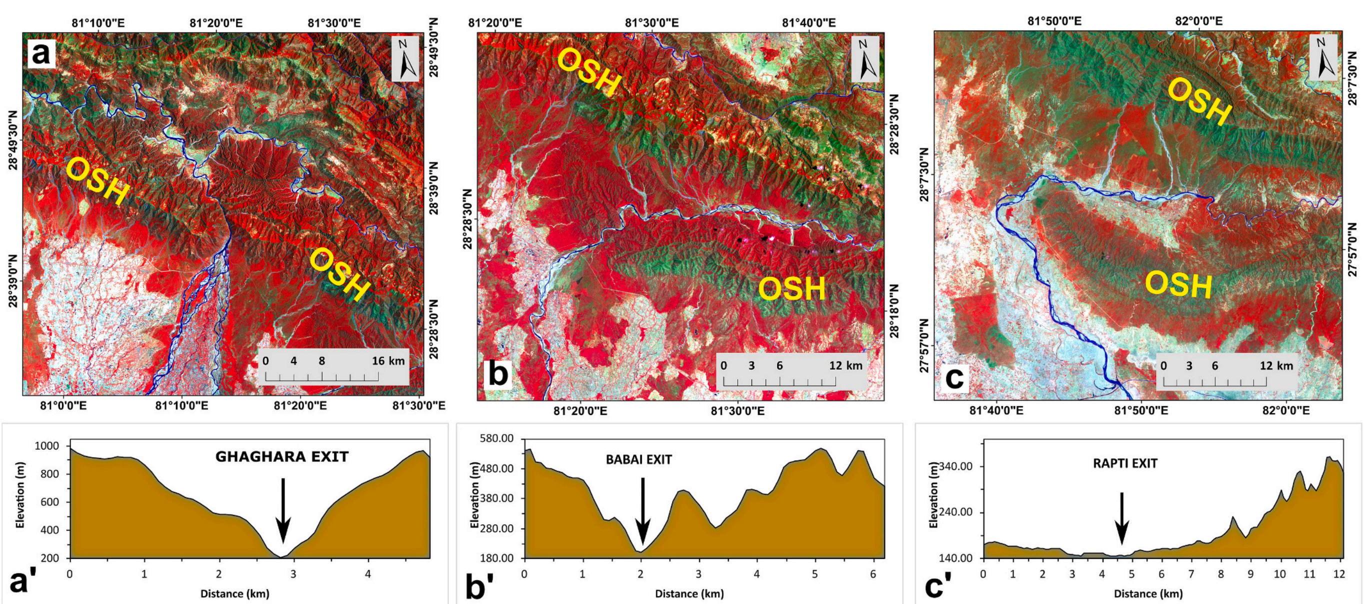

Fig. 7. False colour composites obtained from Landsat OLI images showing the river morphology and physiography of (a) Ghaghara, (b) Babai, and (c) Rapti river exits. The cross-section profile of the river exits are shown below the satellite image (OSH – Outer Siwalik Hills).

MBT, it flows axially for about 120 kms towards west before debouching into the foreland basin near Nepalgunj. The Babai River is formed by streams arising from the flanks of the Sub-Himalayan Ranges that surround the Dang Dun (Fig. 6). It flows for about 60 kms in westward direction along the southern margin of the Dang dun (Fig. 6). At the western end of the Dang dun, the river enters into a narrow valley between the overlapping segments of Frontal Siwalik Ranges, and continues with its westward course for another 90 kms (Fig. 6). The exit of the Babai River occurs near the Bardiya National Park region and is also focussed along the West Surkhet Transfer Zone (Fig. 1). Both the Babai and Rapti rivers are deflected for more than 100 kms by the frontal anticlines; their exit locations across the mountain front occur around the fold nose at the westernmost tips of the associated MFT segments (Fig. 7b and c). No tear faults are reported along the river exits. The exit of the Rapti River coincides with the West Dang Transfer Zone (WDTZ) (Mugnier et al., 1999) (Fig. 1) which marks the transition between the Surkhet sector and the Dang recess, and aligns southward with the Lucknow fault at the western margin of the subsurface Faizabad ridge (Fig. 1) (Divyadarshini and Tandon, 2022).

3.7. Gandak River exit

The exit of the Gandak River is marked near Tribeni in central Nepal (Fig. 8). The Gandak River is also called the Narayani River in Nepal and it is joined by a Sub-Himalayan fed East Rapti River in the Chitwan dun (Fig. 8). The Narayani River has a large catchment area extending up to the Higher Himalayas (Fig. 1). After crossing the MBT, the river enters into the Chitwan dun (Fig. 8) – the largest intermontane valley in the central Nepalese Himalaya (Divyadarshini et al., 2020). It is the major drainage in the western part of the Chitwan dun formed by joining of transverse streams arising from the Lesser and Sub-Himalayan mountains bordering the dun in the north (Fig. 8). It maintains a transverse course across the Chitwan dun and flows towards SW in the central part of the valley. The river takes a sharp westward turn at the southern margin of the valley and gets deflected around the Frontal Siwalik Range (Fig. 8). Here, the Narayani River assumes an axial course for about 25 kms.

The East Rapti River has a relatively small catchment that arises in the Lesser Himalaya. It is the major axial drainage in the eastern part of the Chitwan dun. Southward flowing tributaries of the river are deflected by the growth of the frontal Siwalik Range, and they join to form the East Rapti River that flows westward to meet the Narayani River (Fig. 8). The Narayani River takes a sharp southward bend around the western tip of the frontal anticline while entering the Indo-Gangetic plains (Fig. 8). After its exit from the Himalayan mountains, it is called the Gandak River in the Ganga plains. The mountain exit of the river is also often referred to as the Narayani River exit. Prior to its exit, the width of the river decreases considerably and appears to be squeezed as it flows between the tips of frontal thrust segments (Fig. 9). An abandoned meander scar is observed on the left bank of the Narayani River while crossing the frontal Siwalik Hills which forms a distinct paleo-valley in the frontal range, and points to the westward deflection of the river with progressive growth of the frontal anticline (Fig. 9).

There is no tear fault that is identified at the exit location of the Gandak River. The Gardi tear fault lies to the east of the Gandak River exit and displaces the associated frontal Siwalik Hills (Divyadarshini and Singh, 2019) (Fig. 8); it coincides with a major NE-SW trending transverse zone in the central part of the Chitwan recess mapped by Divyadarshini (2018) as the Central Chitwan Transverse Fault (CCTF) (Fig. 1) or the Judi Fault of Valdiya (1976). The exit of the Gandak River along the MFT is marked at the transition between the Pokhara salient and Chitwan recess which is bounded by the Pokhara lineament; it aligns with the eastern margin of the subsurface Faizabad ridge of the Ganga plains (Fig. 1) (Divyadarshini and Tandon, 2022).

3.8. Kosi River

The exit of the Kosi River is marked at the transition zone between the Eastern Nepal sector and the Dharan salient (Fig. 10a) (Divyadarshini and Tandon, 2022; Mukul et al., 2024). The exit location of the river is focused along the Kosi fault that aligns with the NE-SW trending Kanchenjunga lineament (Fig. 1) and ultimately connects with the western margin of the subsurface Monghyr-Saharsa ridge in the Ganga Plains (Mukul et al., 2018, 2024; Hubbard et al., 2021). The Arun River is the longest tributary which maintains a southward course along a deep narrow gorge across the Higher and Tethyan Himalaya. Other

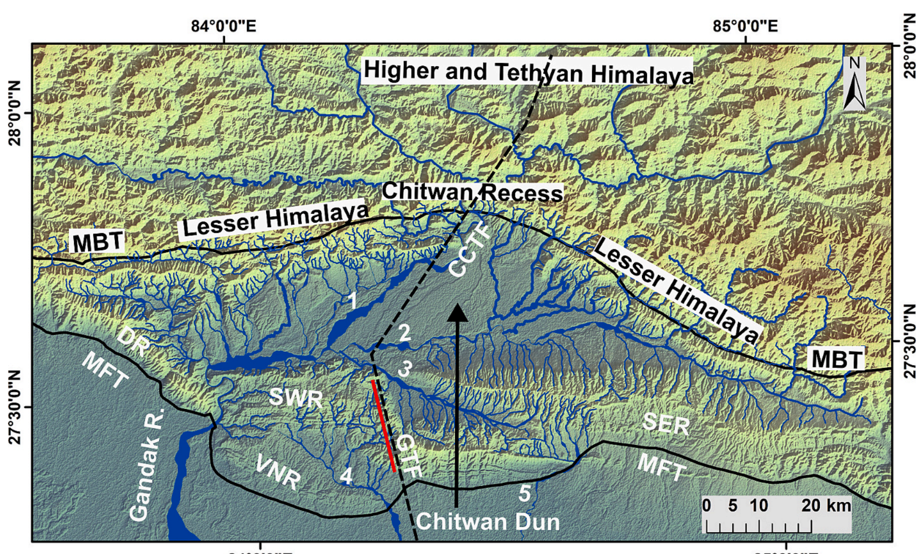

Fig. 8. SRTM-DEM of the central Himalaya showing the river exit of the Gandak River and its reorganisation around the overlapping Frontal Siwalik Ranges (DR – Dumri Range, SWR – South west Range, SER – South east Range, VNR – Valmiki Nagar Range) at the MFT mountain front. The drainage pattern of the river and major tributaries (1 – Narayani River, 2 – East Rapti River, 3 – Reu River) in the Sub-Himalaya is also shown. The black dashed line shows the transverse lineament – CCTF (Central Chitwan Transverse Fault) that extends across the Chitwan recess. The solid red line mark the Gardi Tear Fault (GTF) that displaces the MFT. Structures and tear faults adapted from Divyadarshini and Singh (2019). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

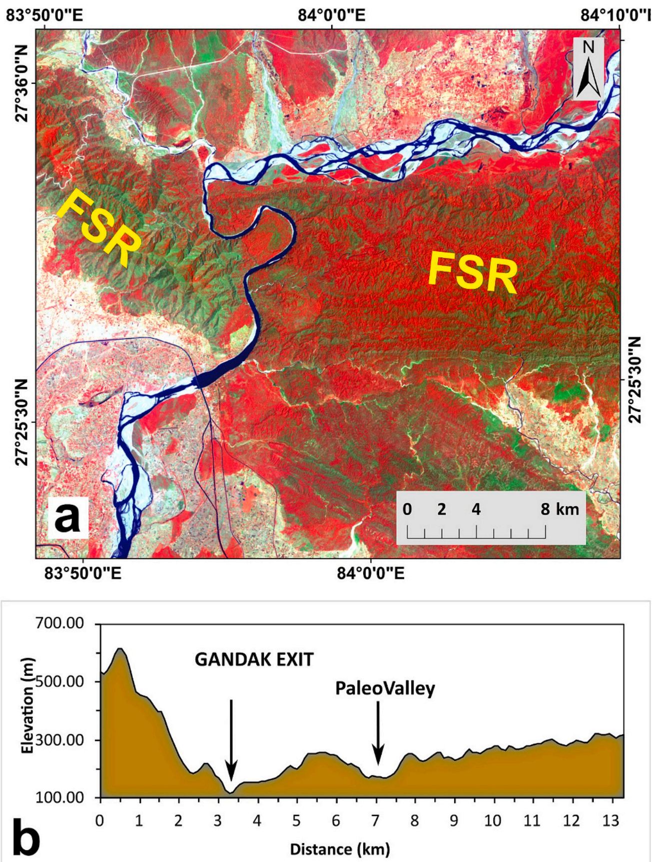

Fig. 9. (a) False colour composite of Landsat OLI image showing the river morphology and physiography of Gandak river exit. (b) The cross-section profile of the river exit is shown below.

major southward flowing tributaries that arise from the Higher Himalaya are diverted to an axial course along the southern margin of the Lesser Himalaya, and they converge with the Arun River near the MBT to form the Kosi River (Fig. 10a).

The Sub-Himalaya is extremely narrow (width is ~5 km), and the MBT and MFT are closely spaced at the mountain exit of the Kosi River (Fig. 10a). The river flows straight across a narrow-constricted V-shaped valley in the Sub-Himalaya (Fig. 10b and c). A small bend is observed along the river channel when it crosses the MBT indicating local diversion around the fault (Fig. 10b). The width of the river increases significantly after its exit across the MFT mountain front (Fig. 10b). The MFT is showing prominent overstepping in the western bank of the Kosi River; it is marked by the development of the Trijuga dun which is a very small and narrow intermontane valley formed between the over-stepped frontal thrust segments (Fig. 10a). The mountain front is embayed near the exit location and transitions into the Dharan salient on the eastern bank of the river (Fig. 10a).

3.9. Tista River

The Tista River exit is marked at the transition between the Dharan Salient and the Gorubathan Recess in the eastern Himalaya (Fig. 11a). There is no tear fault identified along the river exit but the boundary between the Dharan Salient and Gorubathan Recess marks a transverse zone in the Himalaya that aligns with the eastern margin of the subsurface Monghyr-Saharsa ridge in the Ganga plains (Divyadarshini and Tandon, 2022) (Fig. 1a). The Gish Transverse Fault (GTF) which forms a well-defined active strike-slip fault is identified to the east of the Tista River exit (Mukul, 2010; Mukul et al., 2014) (Fig. 11a) and also lies along the Salient-Recess transverse boundary. In the Ganga plains, the

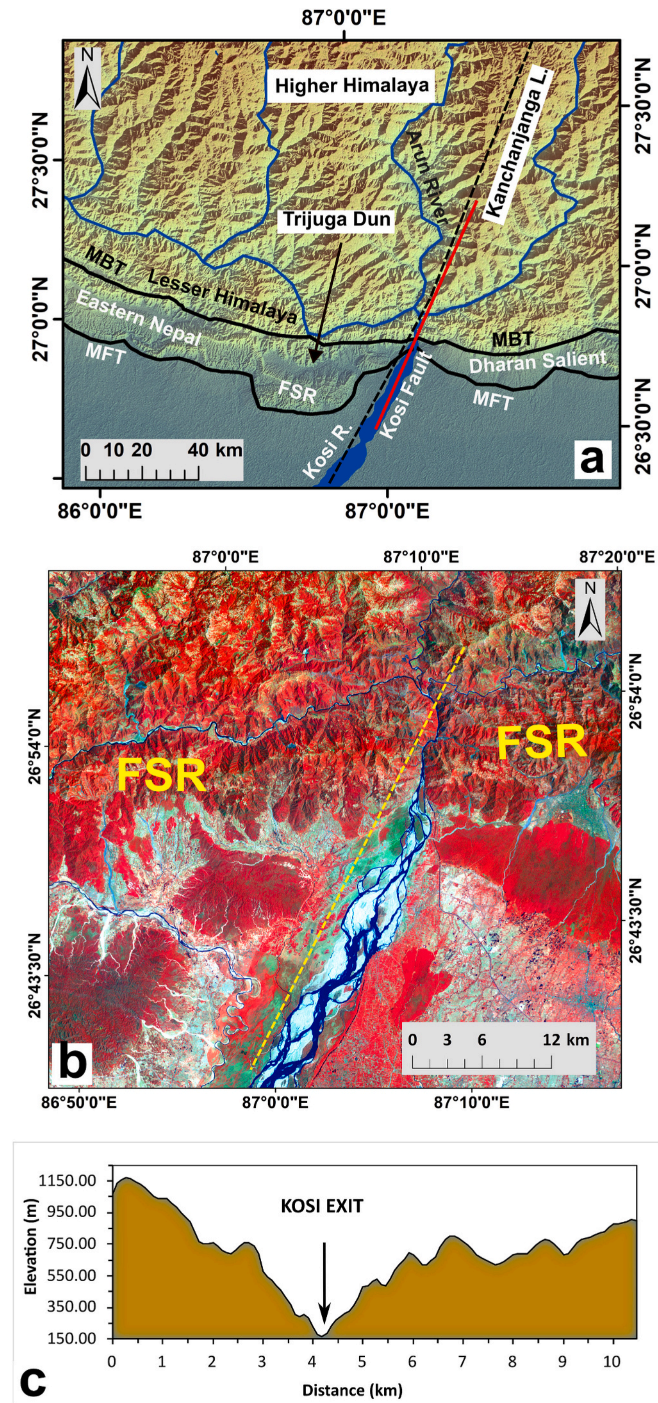

Fig. 10. (a) SRTM-DEM showing the river exit of the Kosi River and its relation to the Kosi tear fault that cuts across the MFT mountain front and extends further north. (b) False colour composite of Landsat OLI image showing the river morphology and physiography of the Kosi river exit. (c) The cross-section profile of the river exit is shown below. Structures and tear faults adopted from Mukul et al. (2018).

GTF is suggested to be connected with the Pingla-Kishanganj basement fault at the eastern margin of the Monghyr-Saharsa ridge (Godin and Harris, 2014) and together it has been redefined as the Gish lineament by Divyadarshini and Tandon, 2022 (Fig. 1a).

The Sub-Himalaya is narrow (width is ~5 km) in the Dharan Salient as the MBT and MFT are closely spaced and the MFT being marked by several imbricate thrusts (Fig, 11a). The Gorubathan recess on the other hand, remains open towards the foreland which is a distinctly peculiar

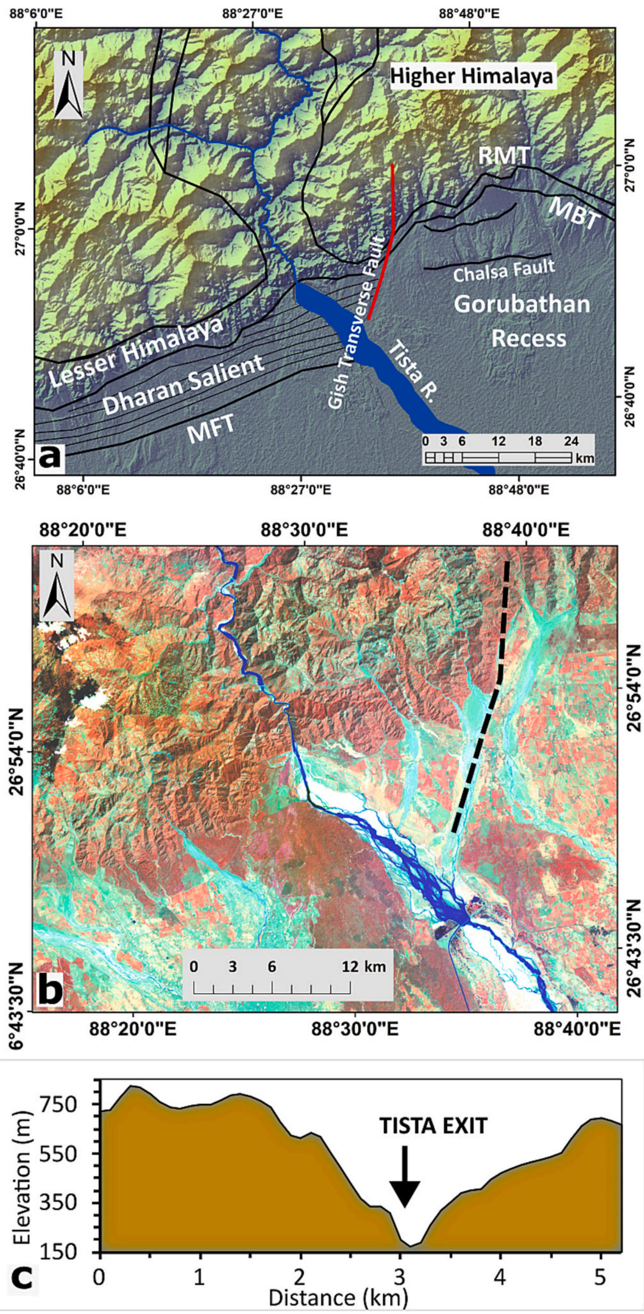

Fig. 11. (a) SRTM-DEM showing the river exit of the Tista River and its relation to the Gish Transverse Fault (GTF) that cuts across the MFT mountain front and extends further north. (b) False colour composite of Landsat OLI image showing the river morphology and physiography of the Tista river exit. (c) The cross-section profile of the river exit is shown below. Structures and tear faults adopted from Mukul et al., (2010).

setting of the Himalayan front in this region. The outer Siwalik hills are not well-developed and expression of the MBT and MFT is marked by uplifted Quaternary fans and surfaces; the frontal thrust here is defined by the Chalsa fault (Fig, 11a) (Srivastava et al., 2017). The mountain front along the Tista River exit is defined by the MBT and no major tributaries join the river before its exit location. To the east of the river exit, in the Gorubathan recess, the RMT (Ramgarh-Munsiari Thrust – a major structure south of the MCT that emplaces extensive Mesoproterozoic to early Cambrian crystalline thrust sheets over the Inner Lesser Himalaya; Robinson and Pearson, 2013) defines the mountain front. The Tista River flows southward in the Higher and Lesser Himalaya and gradually diverts eastwards after crossing the mountain exit (Fig. 11a). However, there are no sudden deflections observed along the course of the river near the mountain exit as the mountain front lacks distinct frontal topography (Fig. 11b). The Tista River flows in a single, straight channel constricted within a narrow V-shaped valley along the river exit, and is devoid of channel bars (Fig. 11c). The river width increases drastically after crossing the MBT and in the Ganga plains (Fig. 11b).

4. Segment Boundaries, Tear Faults and River Exits

In this section, we explore the relation of segment boundaries in the frontal Himalaya with exit locations of the major rivers discussed above. It is well known that the MFT is segmented and gives rise to a series of Siwalik hills that define the southern mountain front of the Himalaya.

The Janauri anticline is truncated at the western bank of the Sutlej River exit. Studies by Delcaillau et al. (2006) and Malik et al. (2010) suggest that the Janauri anticline is formed by the linkage of at least three MFT segments that have grown towards each other and merged to form a single linked chain of ~100 km. Malik et al. (2010) have shown that the Sutlej River used to flow between the growing folds along the two easternmost segments. However, lateral propagation and linkage of the two segments caused an eastward deflection of the river to its present exit position. Paleo-valley (wind gap/paleo-water gap) of the river is marked by a flat-uplifted surface in the central portion of the Janauri anticline formed by rapid uplift along the zone of linkage (Malik and Mohanty, 2007). The Chandigarh anticline on the eastern side of the Sutlej River exit is formed along a separate MFT segment (Delcaillau et al., 2006; Singh and Tandon, 2008). Growth of the Janauri and Chandigarh anticlines by lateral propagation of the associated segments have not only deflected the Sutlej River but also given rise to the axial drainages of the Soan and Pinjaur Duns: Soan and Sirsa River respectively that form the major Sub-Himalayan tributaries of the Sutlej River (Fig. 2). The Janauri anticline does not link up with the Chandigarh anticline; the boundary between them represents a segment boundary in the frontal Himalaya, possibly, due to the presence of a structural discontinuity in the sub-surface (Malik et al., 2010). The surface expression of this discontinuity is marked by the Ropar Tear Fault along which a NNE-SSW low relief topography has developed. Different terrace levels on the eastern bank of the Sutlej River have also developed due to activity on the tear fault (Singh and Tandon, 2008).

The exit of the Yamuna River occurs in the gap between the Dhanaura and Mohand Ranges. The Dhanaura Range is shown to comprise of at least three MFT segments that are linked into a single structure (Sharma et al., 2019) the eastern tip of which truncates along the Yamuna River exit (Fig. 3b). Similarly, the Mohand Range is also formed by linking of at least four MFT segments (Pandey, 2013) which is truncated in the west along the Yamuna River exit. The Dhanaura and Mohand segments have not been linked giving rise to a segment boundary at the Himalayan Mountain front which allows the focussing of the Yamuna River exit. The segmentation of the mountain front is caused by the Yamuna Tear fault which has produced a noticeable offset of the Mohand Range thrust tips (Fig. 3b). The deflection of the Yamuna River near the exit location is a result of the westward growth of the Mohand Range. The Ganga River flows out of the Himalaya along the segment boundary at the eastern tip of the Mohand Range (Fig. 3c). Here, the gap between the Mohand Range and the adjoining Kotdwara Range is influenced by the Ganga Tear fault (Sahoo et al., 2000). It is to be noted that the Yamuna and Ganga Tear faults are not just local structures at the mountain front, but they represent major transverse structures extending between the MFT and MBT (Sahoo et al., 2000; Srivastava et al., 2013) (Fig. 2). Both the Yamuna and the Ganga rivers do not show any axial stretches while flowing across the Sub-Himalaya; though Yamuna River appears to be deflected, no wind gap or paleo-water gap that has been reported in the Mohand Range around the Yamuna River exit. The axial tributaries joining the two rivers from the Bata and Dehra duns are influenced by the lateral growth of the frontal ranges (Fig. 2).

There are few studies that have explored the segmentation and linkage of the segments along the Himalayan mountain front in the Kotdwar-Haldwani region (e.g., Luirei et al., 2015, 2020). The exit location of the Ramganga, Kosi, Gaula, and Sharda Rivers occur along distinct tear fault guided segment boundaries along the MFT (Goswami et al., 2009; Luirei et al., 2017). However, except the Sharda River, other rivers do not suffer any significant deflection due to the propagation of the frontal thrust segments. This may be attributed to their position at the junction of two fault segments or around oblique ramps, where tear faults are present.

Further east, in the western Nepal region, the mountain front is formed by a succession of at least four laterally relayed thrust segments (marked as MF1, 2, 3 and 4) that die out laterally into propagating folds (Mugnier et al., 1999) or get branched (Fig. 6). Here, the Ghaghara River crosses the Himalayan Mountain front along the segment boundary between MF 1 and 2 (Fig. 6a). The course of the river is mainly influenced by the lateral growth of the frontal folds along MF 1 and 2; the major tributaries – the Karnali and Bheri Rivers – are deflected to an axial course for long distances by the associated folds. The exit of the Ghaghara River can thus be associated with deflection of the river around the propagating tips of the associated thrust segments followed by debouching of the river along the gap between the two segments. Although, there is no tear fault identified in this region, a prominent embayment is observed along the mountain front at the Ghaghara River exit indicating the possible influence of a subsurface discontinuity which is here represented by the West Surkhet Transfer zone. The mountain exit of the Rapti and Babai Rivers is controlled by the lateral growth of the MF 3 and 4 segments which cause the deflection of the two rivers for more than 100 km (Fig. 6a).

In the central Nepal region, south of the Chitwan dun, the mountain front consists of at least 7 segments that form the frontal topography (Fig. 8) (Divyadarshini and Singh, 2019). The frontal ranges display prominent overlapping (Fig. 8). Studies by Divyadarshini and Singh (2019) and Divyadarshini et al. (2020), suggests that the Narayani River once flowed straight across the Chitwan dun forming a large fan in the central part of the dun. It crossed the mountain front at the boundary between the SW and SE Siwalik Ranges. Paleo-valley of the river has been identified over the SW Range. Presently, the mountain front is closed between the SW and SE Siwalik Ranges which is a result of linking between the related sub-parallel thrust segments. Streams draining from the flanks of these thrust segments join to form the Reu River which flows northwestwards into the Chitwan dun and joins the Narayani River (Fig. 8). Together, increased uplift, sub-parallel growth, and linking of the SW and SE Siwalik Ranges have caused the deflection of the Narayani River to its present course. The lateral propagation of the SE Range and linkage of the associated segments also forced the East Rapti River to flow in an axial course. The present exit of the Narayani River is marked around the western tip of the SW Range. Here, the river flows in a narrow, V-shaped valley suggesting increased uplift and possible linking of the adjoining MFT segments to some extent.

Further east, around the Tista River exit, the segmentation of the mountain front is not well understood, firstly due to lack of studies exploring the development of the frontal Siwaliks, and secondly, as the expression of the MFT become gradually dispersed and lacks distinct Siwalik topography.

5. Spacing of River Exits

The spacing between outlets of river basins developed on faulted and folded mountains have been studied extensively. Previous works in varied tectonic terrains of the world (Hovius, 1996; Talling et al., 1997; Castelltort and Simpson, 2006; Purdie and Brook, 2006; Perron et al., 2009; Walker and Allen, 2012) reveal a regular spacing of the exit locations and this regularity is shown to be most pronounced for mountain belts with linear crests and constant half-width (measured perpendicularly from the mountain front to the ridge-crest). It has been suggested that the river basins display an organised geometry whereby, the spacing of the river exits is most likely established during the early stages of topographic development. A linear relationship is defined between the spacing of major drainage basins and the mountain half-width (Hovius, 1996; Castelltort and Simpson, 2006).

Hovius (1996) devised the spacing ratio which is expressed as the ratio of half-width of the mountain range (w) to the distance between adjacent exit location(s). The spacing ratios determined for most linear mountain belts of the world range between 1.91 and 2.23, suggesting that spacing between the major river exits is nearly half of the distance between the mountain front and the main drainage divide. The only exception is noticed for the Himalaya and especially in the Central Nepalese region where the spacing between the major river exits are unusually high and do not follow the general regularity as observed in other linear mountain belts of the world (Hovius, 1996). Spacing ratios of the major Himalayan river exits as calculated by Hovius (1996) are shown in Table 1. Except the Yamuna-Ganga exits (spacing ratio - 2.03), all the other rivers (Sutlej-Yamuna, Ganga-Sharda. Sharda-Ghaghara, Ghaghara-Gandak, Gandak-Kosi, Kosi-Tista) have significantly low values of spacing ratio (ranging between 0.41 and 1.22), indicating that the spacing between their exits is almost twice the expected range of values. One of the reasons given for this is the deflection of the river courses for several kilometres (up to 100–150 km) around growing anticlines in the frontal part of the Himalaya (Hovius, 1996). This is consistent with our observation that the focussing of the river exits (in the case of the Ghaghara, Rapti, Babai, and Gandak Rivers) in the central Himalaya is strongly controlled by the lateral growth of the frontal folds. In the case of the Sutlej, Sharda and Kosi Rivers it is guided by a combination of lateral fold growth (either in the Sub-Himalaya or in the Lesser Himalaya) and pre-existing tear faults. However, another plausible explanation is that except the Ganga and the Yamuna Rivers, other large rivers flow in separate recesses and it is the distance between the adjacent recesses that controls the spacing ratio. This indicates a major control of the dominant structural framework of the frontal Himalaya that guides the large rivers. The exit location of the Yamuna and Ganga Rivers are present within the Dehra Dun recess and thus, the spacing between them falls within the narrow range of most linear mountain belts.

6. Antiquity of the Mountain Exits

It is clear that the major Himalayan river exits are mainly focused along segment boundaries with or without tear faults, or around the tips of laterally propagating frontal folds. Here, we investigate the possible timing for the establishment of the river exits, whereby, two possible scenarios have been examined: 1) the existence of river exits prior to the adjoining frontal fold segments along pre-existing tear faults; 2) the position of the exits have changed progressively with evolution of the frontal topography. The current understanding mostly revolves around the relative initiation and propagation of the frontal thrust segments, and subsequent drainage reorganisation. As a limitation, there are not many studies that have explored the exact timing for the growth of the

Table 1
Table showing spacing ratio of the major Himalayan river exits (taken from Hovius, 1996).

Adjacent Rivers	Exit Spacing (s) km	Half-width (w) km	Spacing ratio (w/s)
Sutlej-Yamuna	160	190	1.19
Yamuna-Ganga	77.5	157.5	2.03
Ganga-Sharda	212.5	180	0.85
Sharda-Ghaghara	122.5	150	1.22
Ghaghara-Gandak	295	212.5	0.72
Gandak-Kosi	337	137.5	0.41
Kosi-Tista	135	140	1.04

frontal anticlines or movement on the related tear faults. In this section, we have reviewed the few previous works where age of the frontal anticlines has been determined, near the river exits.

In the Soan dun, the Sutlej takes a sharp bend after crossing a series of thrusts in the north and follows an axial course in the intermontane valley. A consistent cooling age (AFT and AHe) of ~2 Ma derived for the Siwalik rocks by some of the recent thermochronological studies in the NW Himalaya (Maitra et al., 2021; Lamont et al., 2023) indicates the commencement of thrusting along the MFT. Based on structural cross-sections and magnetostratigraphic ages of deformed Upper Siwalik rocks in the MFT hanging wall, the growth of the Chandigarh anticline is suggested to have begun at ~0.58 Ma (Rao, 1993; Powers et al., 1998; Barnes et al., 2011). In a first order estimate, Barnes et al. (2011) have applied the displacement-length scaling relationships of previous workers (e.g., Cowie and Scholz, 1992) to determine the age of the Chandigarh and Mohand Ranges. Here, the rate of the fault tip propagation is taken to be ~10 times higher than the slip rate on the fault, and most fold relief is assumed to be established over ~5 km length from its tip, with symmetrical lateral growth from the centre (Barnes et al., 2011). For slip rates of ~6–18 mm/yr (Kumar et al., 2006) in the northwest Himalaya, the fault tip propagation rate would be ~60–180 mm/yr which gives a rate of ~10 km in every 28–83 ka for fault tip propagation for the Chandigarh and Mohand Ranges. This gives an estimated age bracket of ~112–336 ka for the 40 km long Chandigarh anticline and ~ 224–664 ka for the 80 km long Mohand Range (Barnes et al., 2011). Assuming similar rates of fault tip propagation for the 120 km long Janauri anticline we determine an age of ~336–1008 ka which provides an approximation of time frame for the development of the Janauri anticline around which the Sutlej River exit has evolved.

We apply the above method of Barnes et al. (2011) to estimate the age of the folds in the central Himalayan region. For regional slip rates of ~20–18 mm/yr along the MFT (Lavé and Avouac, 2000), the rate of fault tip propagation will be ~200–180 mm/yr which gives a lateral growth rate of ~10 km in every ~25–28 ka for the MFT-related folds in the Central Himalaya. Based on this rate, we determine that the frontal folds defined by the frontal thrust segments – MF 1, MF 2, MF 3 and MF 4 having lengths of about 120 km, 100 km, 130 and 150 kms (Fig. 6) were established around ~336–300 ka, ~ 250–280 ka, ~ 375–420 ka and ~ 325–364 ka respectively. As the Karnali, Bheri, Babai and Rapti Rivers are deflected around these frontal anticlines, their exit locations are likely to have evolved during the above time frame. The Sharda River does not show much deflection suggesting that the its exit could have existed much before the development of the frontal anticlines and the river has maintained its course along a major tear fault-guided transverse boundary in the Himalaya.

It is to be noted that all the above estimates are based on the assumption that each of the frontal ranges represent a single large fault propagated fold; whereas, morphotectonic studies have shown that the frontal anticlines have grown over several linked up frontal thrust segments that have initiated separately, grown towards each other and merged to form composite linear chains (e.g., Delcaillau et al., 2006; Singh and Tandon, 2010; Divyadarshini and Singh, 2019; Sharma et al., 2019). Here, the length of the individual segments would be limited to few kilometres after which lengthening stops and fault growth is accommodated by increased vertical uplift along the fault tips (Cartwright et al., 1995; Trudgill and Cartwright, 1994; Wu and Bruhn, 1994; Anders and Schlische, 1994; Dawers and Anders, 1995; Scholz et al., 1993; Davis et al., 2005). In this case, the actual age of the frontal folds will be relatively younger than the above estimates. In addition, a recent study by Srivastava et al. (2018) has shown the structure of the Mohand to be a monocline, in which case, the displacement–length relationship may not be valid. Nevertheless, the above age brackets provide a first-order approximation for the maximum age of the frontal fold-thrust topography and its related river exits, and are broadly consistent with the ages determined from thermochronological studies.

7. Evolution Model for the Himalayan River Exits

On a broader scale, the river exits can be related to the structural grain of the Himalayan front and divided into four groups – (1) from within a recess (generally formed through combined fold growth and tear faulting), (2) from within a salient (often guided by the tear faults at segment boundaries), (3) along salient-recess transition (rivers usually having less deflection), and (4) across a straight or linear mountain front (generally developed around lateral fold growth tips) (Fig. 12).

Before discussing the evolution model of the exits, it is important to understand the salients and recesses. The salients and recesses are large scale curvatures of fold-thrust belt with salients being convex in the direction of tectonic transport and recesses being concave in the direction of tectonic transport (Marshak, 2004). The young topography developing towards the foreland is strongly influenced by the curvature of the fold-thrust belt and angle of convergence. Since salients protrude towards the foreland relative to recesses, over geological periods the structures in front of the recess grow laterally and attempt to adjust with the salient, and when they do, the mountain front becomes linear. We observe that the intermontane valleys are present in front of the recesses, where thrust spacing is large (probably to catchup with the front ahead of a salient), whereas, the thrusts in front of the salient are closely spaced (hence, lacking intermontane valleys). The spacing between the thrusts is also dependent on factors such as depth to detachment, rock strength, detachment strength and detachment slope (Marshak, 2004). The MBT shows remarkable sinuosity which defines the salients and recesses in the Himalaya (e.g., Singh and Tandon, 2008; Mukul et al., 2024). This sinuosity is either basin-controlled or obstacle-controlled (where fold-thrust belt interacts with the basement highs). However, origin of all the salients and recesses in the Himalaya is not known and it is beyond the scope of this study. Furthermore, the sinuosity in the thrust belts can be primary or secondary, and response of the river can vary in both the cases, but such detailed studies on the thrust belt curvatures are lacking in the Himalayas.

The major Himalayan rivers enter into the Sub-Himalaya either through a recess, a salient, at their transition, or in an area lacking any curvature. It flows through the Sub-Himalayan mountains, influenced by the growth of structures in this zone, before debouching on to the plains. While exiting, different scenarios are possible that are shown in Fig. 12. The first stage of evolution of river exit shows an example of a river leaving the Lesser Himalayan mountains either at recess, salient, at their transition zone, or straight mountain fronts (Fig. 12). In the second stage, the faults start growing in front of the salient and recess. While the frontal structures start developing parallel to the curvature in front of the salient, they are relatively straight in front of the recess and at the straight mountain front; however, it also depends on the direction of convergence (Fig. 12). This results in the deflection of rivers originating within a recess, whereas the rivers originating in the transition and salient zone show little or no deflection (Fig. 12). Also, the rivers exiting from the straight mountain fronts may or may not deflect depending upon where the fault initiates and whether or not there are any barriers obstructing the lateral growth of the frontal structures. The straight flow is due to the development of tear faults or transverse structures that result from the different rates of fault migration either during the development of salient and recess or faults developing in front of them (Fig. 12). These tear faults also act as barriers for the laterally growing faults, as a result two fault segments truncate around this region. In the third stage, the mountain front ahead of a recess catches up with the salient mountain front through lateral growth of the frontal fold-and-thrust topography. The rivers at this stage are competing with the growing topography at the mountain front; the rivers with lower rate of incision than the rate of uplift get deflected (Fig. 12). In the fourth stage, we observe that the river exits have got established at the junction of two fault segments; these are often marked by tear faults.

The Yamuna, Ganga, Sharda, Kosi and Tista Rivers exit through either recess-salient transition or salient zone. On the other hand, the

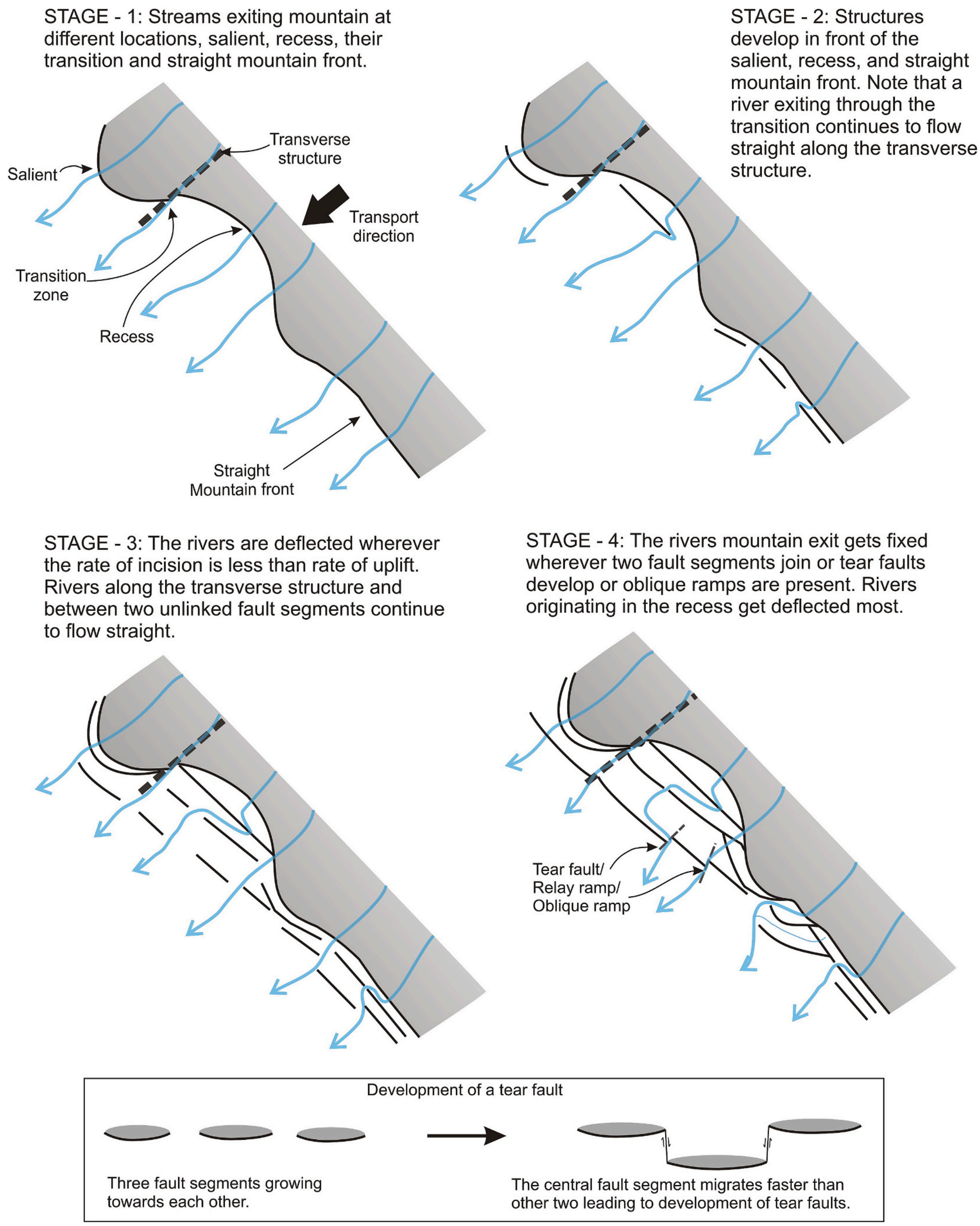

Fig. 12. Diagram showing an evolution model of different types of mountain river exits in the Himalaya. Process of development of tear fault is also shown in the box below.

Sutlej, Gandak, and Rapti Rivers enter into the Sub-Himalaya at the recesses (or closer to it) and flow through the intermontane valleys where they are deflected and flow through the junction of frontal fault segments. The Ramganga, West Kosi, Gaula Rivers, and several other small streams exit through the straight mountain fronts unrelated to salients and recesses.

8. Future directions

The mountain exits of rivers are one of the most important geographical features that influence the socioeconomic and ecological well-being of people living in the vast adjoining alluvial plains both in terms of water and food security. These are the locations that control the outlet of the river from the orogenic front; any activity (geomorphic, structural, or anthropogenic) at the mountain exit can significantly impact the entire course of the river downstream. Multiple avulsions of the Kosi River at the mountain exit resulting in over 100 km shifting in the downstream is an excellent example of this phenomenon. Yet the mountain exits have received little attention.

There are several important questions regarding the mountain exits and their evolution – What controls the location of the mountain exit of a river? How long does it take for a mountain exit to evolve? What controls the spacing of the mountain exit in an active mountain front? How do mountain exits influence sediment dynamics and river morphology? What is the relationship between the morphology of river exits and local tectonic structures? Do mountain exits preferentially align with specific structural discontinuities, such as tear faults or pre-existing basement structures? How does long-term tectonics influence the migration or abandonment of mountain exits? How have anthropogenic activities (e.g., dams, barrages etc.) affected the geomorphic and hydrological processes at mountain exits? How are mountain exits of tectonically active regions different from those of tectonically stable regions?

9. Conclusions

The localization of major river exits in the Himalaya is structurally controlled and related to three major factors: 1) their exit in the Sub-Himalaya with respect to the salient and recess, 2) Himalayan frontal folds/anticlines that cause the deflection of transverse rivers to mountain front parallel longitudinal course, 3) tear faults or junction of the fault segments at Himalayan mountain front that serve as pathways for the rivers. These factors give rise to four major styles of exit formation along the Himalaya as follows.

a. Exits along the transition zone of salient and recess often marked by transverse structure or the tear faults: here, the rivers do not show any major deflection. The river width along the exits is comparatively more than the other river exits and is marked by well-developed multithread channels and prominent channel bars. It is generally observed in the northwest Himalaya (e.g., the Yamuna and the Ganga Rivers exits). The basins are elongated and show narrowing of the basin width towards the mountain exit. The long axis of the basins is orthogonal to the strike of the Himalayan mountains pointing to the fact that no major drainage diversions have occurred.
b. Exits along tear fault guided segment boundaries where the adjoining MFT segments truncate: most of the river exits are tear fault guided but their genesis at the exit locations of the Ramganga, Gaula, West Kosi, Sharda and Kosi Rivers, is not linked to the process of salient and recess development. The rivers cut across the frontal ranges along V-shaped valleys and flow in relatively deep constricted channels devoid of prominent planform features. Such exits are generally seen at the mountain front of the west central Himalaya. Here as well, the basin shape is elongated and perpendicular to the linear mountain front.
c. Exits developed around laterally propagating tips of frontal thrust segments (such as the Ghaghara, Rapti, Babai, and Gandak Rivers): the rivers are deflected for several kilometres around the tips of the frontal thrust segments which provide the necessary gap for the river to drain out of the mountains. Tear faults are generally absent along the exits. The exit locations have evolved progressively with the growth of the frontal folds and the influence of the growing structures is strong. This type of river exit is characteristic of the Central Himalayan region. Here, the basins of the major rivers appear more circular and are marked by longitudinal reaches (long axis of the basins parallel to the E-W orientation of the Himalayan mountains) in the Lesser and Sub-Himalayan region. The lower order basins such as the Babai and Rapti have sickle-shaped basins which are also due to the development of longitudinal stretches prior to their river exits. The development of the longitudinal reaches attests to the diversion of the rivers around the growing structures of the frontal Himalaya.
d. Combination of lateral fold growth and a tear fault boundary such as the Sutlej River. The present exit location is guided by a major tear fault between unlinked segments of the MFT. However, the exit location has gradually shifted from a previous location by progressive growth of the frontal fold. This is a peculiar scenario where the influence of both the tear fault as well as the growing frontal fold is significant.
e. The basement structures are responsible for the orogenic segmentation of the Himalaya into various sectors such as the salient and recesses, localization of transverse and tear faults at the Himalayan front, and influence the lateral growth and linkage of the frontal folds, which ultimately forms the river exit.
f. The ages of the frontal folds are estimated to be bracketed between ~112 to 1008 ka, mostly centred around ~300 ka. This indicates that the river exits focused around the tips of the growing frontal folds have existed at least for the last ~300 ka. Whereas, the exits developed along the transverse faults could be much older and existed for over a million years where the frontal folds have grown around them.

CRediT authorship contribution statement

Ananya Divyadarshini: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Sampat K. Tandon:** Writing – review & editing, Visualization, Supervision, Methodology, Conceptualization. **Vimal Singh:** Writing – review & editing, Validation, Investigation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

Vimal Singh is serving as Editorial Board member. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors confirm that all data necessary for supporting the scientific findings of this paper have been provided.

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