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The Rivers of Indian Peninsula: Their Salient Geomorphic Characteristics and Ancestry

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Abstract: *The Indian Peninsula dominantly displays an erosional landscape. Bedrock landforms and bedrock rivers are more common. The diversity in topography, drainage and landforms visible today has developed during the nearly 9000 km long northward journey of the Indian Plate since the breakup of the Gondwanaland. Some of the distinctive topographic and drainage network characteristics of this ancient landmass are described in this paper. An attempt has also been made to tentatively reconstruct the ancestry of the main-stem rivers on the basis of available geological and geomorphic data.Multiple lines of evidence suggest that many of the river systems of the Peninsula consist of segments of different ages, and the complete integration of the older and younger drainage has taken place during the Cenozoic. Recently acquired geochronological data strongly suggest that climate rather than tectonics is primarily responsible for the modern-day relief of this ancient landmass.*

Introduction

With an area of about 2.1 M km^2, the Indian Peninsula is the largest and the oldest geomorphic province and morpho-tectonic unit of India. Underlain by rocks of Archean to Cretaceous-Eocene age and bordered by passive margins to the east and west, the fluvially sculpted landscape of the triangular-shaped Peninsula bears the legacy of its long denudational history that dates back to the late Mesozoic times (Kale and Vaidyanadhan, 2014). The spatial diversity in topography, drainage and landforms displayed by this ancient landmass is the product of the rifting and drifting of the Indian Plate and Deccan volcanism as well as significant changes in the regional climate and erosional base level (sea level) since the breakup of the Gondwana land in the late Jurassic.

Rainfed rivers are the backbone of the Peninsular landscape. Since its separation from the Gondwanaland and onset of the northward drift, the Indian landmass has been chiefly fashioned by fluvial erosion, apart from weathering and mass wasting processes. In spite of their modest catchment size (0.2 to 3.2 × 10^5 km^2), the major Peninsular rivers, such as Godavari, Krishna, Mahanadi, Narmada, Tapi, Kaveri, Pennar, Son, Mahi, Sabarmati, Subarnarekha, and others (Fig. 1), have played a crucial role in the evolution of the present prominent topographic features, such as the valleys, ridges, plateaus and escarpments.

In the last two to three decades, the availability of high resolution remote sensing data, DEM derived morphometric data and geochronological data of rocks, bedrock landforms and Quaternary deposits have enabled earth scientists to make better observations and interpretations

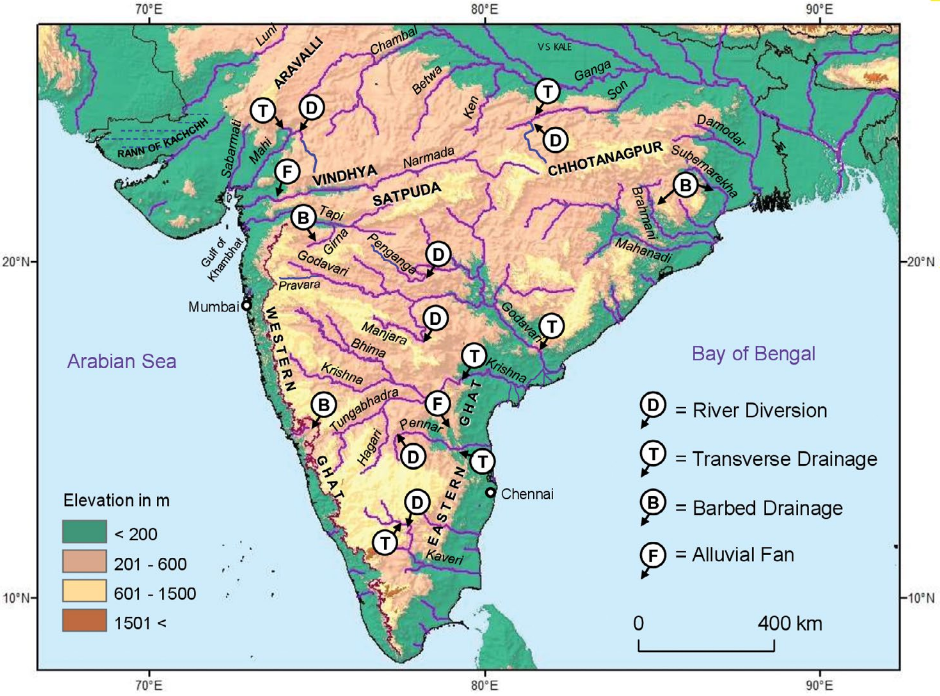

Figure 1. Map of the Indian Peninsula showing the major relief features and rivers. The map also shows the location of noteworthy geomorphic features mentioned in the text.

about regional denudation rates, landscape evolution and denudation chronology on different spatio-temporal scales that were not possible previously. Some of the noteworthy findings about the Indian Peninsula and its rivers that have emerged from recent as well as some previous studies are briefly summarised here.The two main objectives of this review are: (a) to outline the salient features of the Peninsular rivers, and (b) to tentatively reconstruct the ancestry of the Peninsular rivers on the basis of available geological, geomorphic and geochronological data.

In order to appreciate the distinctive geomorphic characteristics of the Peninsular rivers, it is imperative to have a general idea about the litho-structural setup of the Peninsula as well as the geological and climatic history spanning the last approximately 200 million years (~200 Ma in the standard notation). In the following section the geological setup and the geological history are briefly described.

Geology and geological history of the Indian Peninsula

The Indian landmass attained its present outline between 130 and 65 Ma ago (Chatterjee and Bajpai, 2016), but the basement rocks and major geological structures are much older (Valdiya, 2016). Even though the Indian Peninsula formed a part of the Gondwana super-continent from Cambrian until its breakup in Mesozoic times, it constituted part of three older super-continental configurations, namely the Ur, the Columbia andthe Rodinia (Meert *et al.*, 2010).Geologically, the Indian Peninsula, described as the Indian Shield, is composed of several Archean cratonic blocks bordered by rifts and Proterozoic orogenic (fold) belts.

The Bundelkhand-Aravalli, Singhbhum, Bastar, and Dharwad cratons (Fig. 2) contain some of the oldest granitic rocks ranging in age from 3 to 4 billion years (Valdiya, 2016). The cratons include intra-cratonic basins

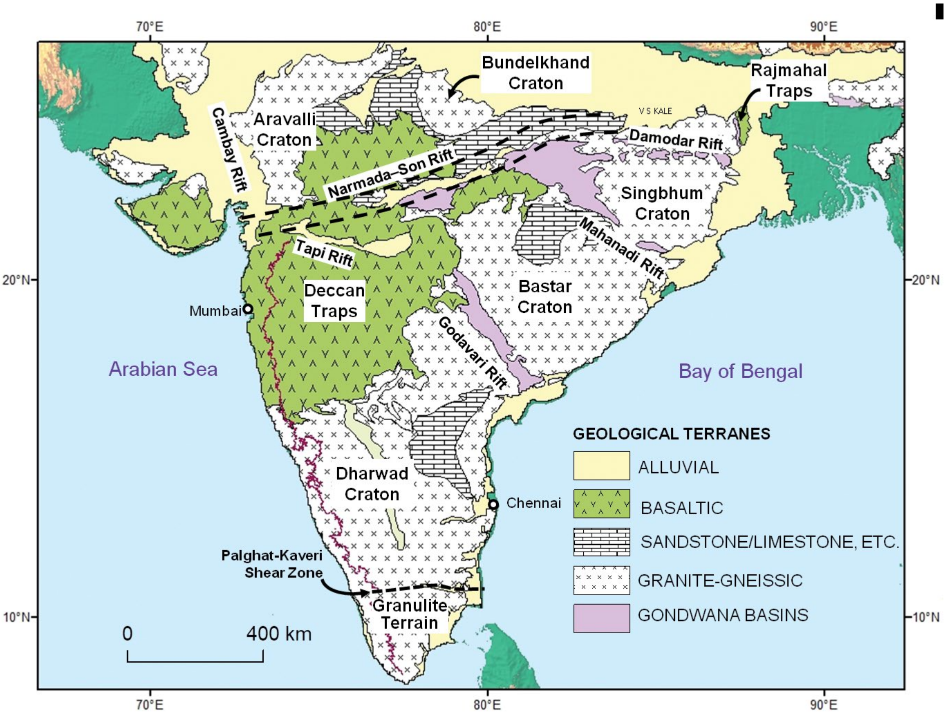

Figure 2. The main geological terranes of the Indian Peninsula. The map is based on the Geological Map of India published by the Geological Survey of India (GSI)

filled with Proterozoic sediments (areas of sandstones/limestones, etc. in Fig. 2). The cratons are separated by rifts or grabens, such as the Son-Narmada-Tapi (SONATA) rift zone, the Mahanadi graben, and the Godavari rift (Fig. 2) and in some cases the cratons are flanked by Proterozoic fold (orogenic) belts, such as the Aravalli, the Satpuda, and the Eastern Ghat (Fig. 1). The Palghat-Kaveri Shear Zone forms the boundary between the Dharwad Craton and the Southern Granulite Terrain (Fig. 2). While the SONATA and the Palghat-Kaveri Shear Zone are much older (Precambrian), the roughly W–E and NW–SE oriented grabens of Damodar, Mahanadi and Godavari attained their final form during the rifting of the Gondwana landmass in the early Permian (Valdiya, 2016). In comparison, the formation of the Cambay rift is considered to be coeval with the split between India and Seychelles, during terminal Cretaceous-Palaeogene (Biswas, 1999).

Until the end of the Jurassic Period (~145 Ma), Precambrian rocks formed the land surface over much of the Peninsula. Only Gondwana basins (Fig. 2) contained Mesozoic sediments. However, this scenario changed during the Cretaceous following voluminous outpouring of lava around 113–118 Ma in eastern India (Rajmahal Traps) and around 65 Ma in western and central India represented by the Deccan Traps (Valdiya, 2016).The Deccan lava flows flooded and buried the ancient rocks and the Gondwana landscape over an area of ~1.5M km^2. The split between India and Seychelles immediately after the end of Deccan volcanism created the present western margin of India. The Western Ghat Escarpment is the product of the erosion and inland retreat of this 65 Ma old continental edge (Kale, 2010).

During the terminal Cretaceous-Paleogene, when the Indian Plate was drifting northward as a huge island, partially covered by Deccan

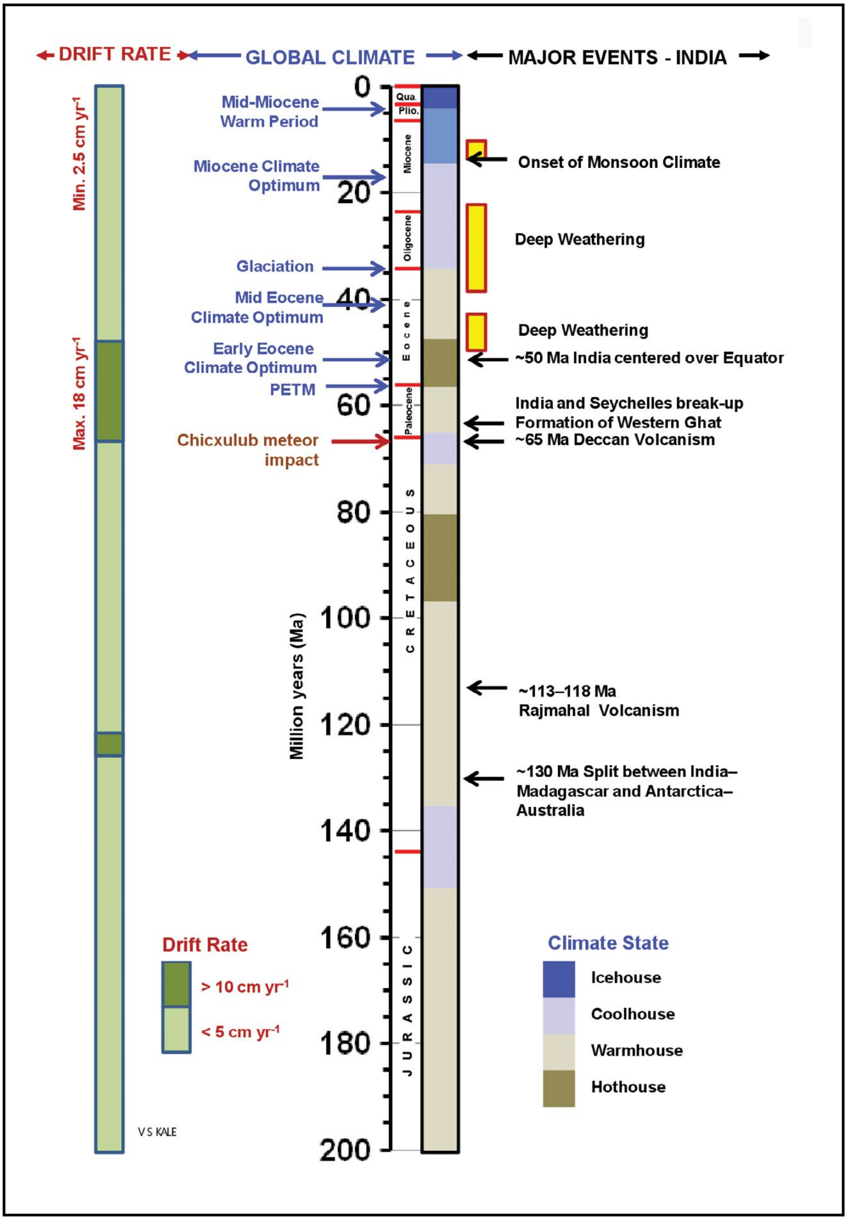

Figure 3. Major geological, geomorphic and climatic events during the last 200 Ma. Global climatic events are mainly based on Huber *et al.* (2018), Westerhold *et al.* (2020) and other sources. PETM = Paleocene-Eocene Thermal Maximum. The temporal changes in the rate of drift of the Indian Plate from 200 Ma to the present estimated by Yoshida and Santosh (2018). Major weathering events (yellow boxes) after Jean *et al*. (2020).

Traps, and at unusually high velocities of ~18 cm yr^{-1} (Yoshida and Santosh, 2018), the Earth's climate was extremely warm (Fig. 3) and the eustatic sea level was higher by several tens of meters (Zachos *et al*., 2001; Gasson *et al.*, 2012). Recent analyses of high-fidelity palaeoclimatic records reveal that warmhouse and hothouse states have prevailed during Palaeocene and Eocene (~66 to 34 Ma), and hothouse conditions (temperatures > 10°C warmer than present) were experienced during early Eocene between 56 to 47 Ma (Westerhold *et al.*, 2020). The analyses further indicate that the present coolhouse state began in the early Oligocene and lasted until the terminal Pliocene (~34 to 3.3 Ma). The Quaternary period (the last 2.6 Ma) has been dominated by icehouse conditions (Fig. 3) with alternating glacial-interglacial periods driven by cyclic changes in the Earth's orbital parameters or the Milankovitch cycles. The hydro-climatic characteristics of the Peninsular rivers were affected by these global changes in the climate as well as the latitudinal position of the Indian Plate during the drift.

Salient features of the Peninsular rivers

The Indian Peninsula displays an erosional landscape dominated by bedrock landforms and partially to deeply weathered rocks (Kale, 2014). Bedrock landforms and bedrock rivers are more common than the depositional features and alluvial rivers. Many of the landscape features of the Peninsula have developed their present characters during the nearly 9000 km long northward journey of the Indian Plate since the break-up of the Gondwana land. Some of the distinctive topographic and drainage network characteristics are described below.

Asymmetric drainage

The drainage network of the Peninsula is strikingly asymmetric. The large rivers all flow to the east (Fig. 1). Due to the eastward slope of the Deccan Plateau and roughly W–E and NW–SE orientation of the grabens, rivers originating in the Western Ghat, the Maikala range, and the Chhotanagpur Plateau flow eastward and drain into the Bay of Bengal. In comparison, the small-sized west- or south-west flowing rivers such as the Narmada, Tapi, Mahi, and Sabarmati occupy structural depressions (rift valleys) and the short and swift flowing west coast rivers drain into the Arabian Sea.

Structurally controlled drainage

Rifts or grabens are structural forms that act as major drainage corridors on geological time scales. The intra-cratonic grabens, filled with sediments of the Gondwana period, exist as linear belts and it is along these elongated depressions that the present river valleys of Pranhita-Godavari, Damodar, and Mahanadi occur. Similarly, the Narmada, Tapi, Mahi, and Sabarmati occupy ancient structural depressions represented by the Cambay graben and the SONATA rift zone. These rivers have the thickest (1–5 km) Palaeogene to Quaternary deposits in the Indian Peninsula. Furthermore, the control of Neoproterozoic Palghat-Kaveri Shear Zone on the lower course of Kaveri is also evident.

Transverse drainage

Several Peninsular rivers, such as the Son, Godavari, Krishna, Pennar, and Kaveri flow across hill ranges in their middle or lower domains. Some of the most spectacular gorges are observed in these stretches, such as the Gandikota gorge on Pennar (Plate 1A), the Srisalium gorge on Krishna, the Papikonda gorge on Godavari, and the Mekedatu gorge on Kaveri (Fig. 1). River Som, the highest order right-bank tributary of the Mahi river, cuts across the Aravalli ranges. Four mechanisms have been suggested in the geomorphic literature to explain the transverse drainage- antecedence, superimposition, stream piracy and overflow (Larson *et al.*, 2017). The first two mechanisms provide likely explanation for some of the rivers mentioned above. The Godavari, Krishna and Pennar rivers are cutting across the Eastern Ghat, and the Kaveri flows through the Biligirirangan Hill ranges, and appear to be antecedent in nature. The Som river flowing across the Aravalli ranges also displays all the characteristics of antecedent rivers. However, geological evidence indicating that the rivers predate the Eastern Ghat or Biligirirangan Hill ranges or Aravalli Hills is lacking. While the ages of the rocks forming these hill ranges are broadly known, the exact geological ages of the hill ranges (topographic form) *per se* are not known. If stream piracy or river capture via head ward erosion was responsible for the transverse river courses, presently there is very little sedimentological or morphological evidence in support of this hypothesis about river capture. Therefore, proving antecedence or superimposition unambiguously remains a difficult proposition. Only in the case of the Papikonda gorge, there is a satisfactory geological explanation. The lower Godavari occupies the early Permian rift, and this graben cuts across the Eastern Ghat.

Plate 1A. The Gandikota gorge on Pennar river. The almost horizontally bedded rocks exposed on the gorge walls are quartzites of Meso-proterozoic age. (Photo: V.S. Kale)

Plate 1B. Narmada river bank section showing the coarse-grained alluvial fan deposits near Tilkwada, downstream of the Dhadgaon gorge. The horizontally bedded units, containing well-rounded pebbles and cobbles, were dated by OSL to about 90 ka (Chamyal and Juyal, 2008). (Photo: V.S. Kale).

Misfit rivers

The Narmada, Tapi, Son and Sabarmati as well as lower Mahi, Mahanadi and Godavari do not flow through self-formed valleys, but occupy geologically formed rift valleys or grabens and thus are misfit. The Narmada drainage through the SONATA is particularly atypical. This largest west-flowing river has highly elongated basin shape and has no matching tributary. Except Tawa, all other tributaries of Narmada are very small in size, length and stream order. Son is another river that occupies the SONATA zone, but flows in the SW-NE direction to join the Ganga. The upper Son valley displays the characteristics of a beheaded or head-truncated valley. Furthermore, the Deccan Traps rivers, such as the Godavari, Krishna, Bhima and most of their major tributaries originating in the Western Ghat, display all the features of under-fit streams and beheaded or head-truncated valleys. These rivers occupy unusually large valleys right from their source (Kale and Shejwalkar, 2008). These rivers have acquired their under-fit characteristics after the loss in the headwater area due to beheading. The eastward retreat of the Western Ghat Escarpment was responsible for the beheading of the Maharashtra Plateau rivers (Kale and Rajaguru, 1988).

River diversions and barbed tributaries

Drainage network modifications are represented by drainage anomalies, such as river diversion and barbed drainage. There are many examples of sharp changes in the river direction and anomalous drainage networks in the Peninsula. Rivers such Kaveri, Pennar, Mahi, Manjara, Penganga and Son are marked by prominent sharp bends or elbows (Fig. 1). Many southern tributaries of the Tapi, such as Girna, Bori, and Panzara also follow anomalous trends. They all flow in the opposite direction for considerable distances and then abruptly turn northward and join the main river. Similarly, the drainage networks of the Subarnarekha and Brahmani-Baitarani rivers are characterised by barbed tributaries and/or discordant junctions. Different mechanisms of river diversion and barbed drainage have been suggested in the geomorphic literature, such as river capture, structural control, tectonic tilting, etc. (Bishop, 1995). The barbed drainage patterns displayed by some of the west coast rivers cutting across the spine of the Western Ghat, such as the Kali, Gangavali, Aghnashini, Mandvi, Ulhas, etc. are without doubt related to river capture and subsequent drainage diversion. The Jog falls on Sharavati river, the highest waterfall in India, is also related to river capture and river diversion. However, in all other cases, there is inadequate geomorphic, geological and geochronological data to confidently infer the exact process or processes involved and the probable temporal sequence of the events.

Bedrock-dominated rivers

Although many Peninsular rivers have alluvial reaches, there are long segments where bedrock is exposed along the channel perimeter. The channel gradient of bedrock rivers is a semi-independent variable and is not directly determined by the hydraulic regime (Howard, 1980) but by the sub-strata characteristics. There are significant differences in the channel morphology on account of differences in the underlying rocks. Although sandstones, quartzites and limestones are present in the catchments of some of the rivers (Fig. 2), the two dominant types of geological terranes in the Peninsula are — the granite-gneissic (including charnockites and khondalites) terrane and the basaltic (Deccan Traps) terrane (Kale and Vaidyanadhan, 2014). Apart from channel morphology, the control of lithology is also reflected in the textural characteristics of the bed sediments. Fluvial sediments in the granite-gneissic terrane are sand-dominated, and the fluvial sediments in the Deccan Traps region generally show preponderance of finer fractions (silt and clay) and gravels. Sand-bed rivers, therefore, are more common in the granite-gneissic terrane, and elsewhere the bed is generally covered by coarse gravel.

The rock-dominated river segments are often characterised by irregular channel beds, breaks in channel profiles (rapids and waterfalls), inner channels, straths and bedrock gorges. Although single channel pattern is the most common channel planform in bedrock rivers, multiple channel reaches are also present. The Narmada river near Punasa provides the best example of a multi-channel pattern in bedrock (Kale *et al.*, 1996). Whereas some of the sudden changes of gradients or breaks in the river profiles (knick points) have formed in response to more resistant lithology, others are manifestations of disequilibrium conditions induced by changes in erosional base level (due to rock uplift or fall in sea level). However, since all the knick points migrate upstream, it is often difficult to pinpoint the exact reason(s) for their initiation (Kale and Shejwalkar, 2008). The presence of incised bedrock channels or gorges downstream of the knick is the common evidence of the headward migration of the knick points. For example, the Marble Rocks canyon downstream of the Dhuandhar Falls (15 m) on Narmada is about 3 km long, the Kaveri gorge downstream of Shivasamudram Falls (101 m) is almost 100 km long, and the Pravara gorge downstream of Randha Fall (50 m) on the Pravara river (a tributary of Godavari) is nearly 20 km long. In addition, there are several examples of gorges and retreating waterfalls at the gorge-head along the northern edge of the Rewa Plateau in Madhya Pradesh (Kale and Vaidyanadhan, 2014).

Low-gradient rivers

The wide and shallow valleys of the east-flowing rivers are occupied by low-gradient rivers and contrast very strikingly with the steep and swift-flowing west coast rivers. Even the longitudinal valley-floor gradients of the large Peninsular rivers are remarkably low. River gradients provide a good idea about the degree of disequilibrium conditions in the drainage systems. The Hack's (1973) stream-gradient (SL) index has been widely used to characterise a stretch of the river or the entire longitudinal river profile. The average SL index computed from source to mouth can be used to compare rivers of different sizes and length (Brookfield, 1998). In general, the average SL index should decrease with an increase in the catchment area. The plot given in Fig. 4 indicates that the average SL index for the Peninsular rivers is less than 120. In comparison, the average SL index values for the Himalayan rivers (Indus, Ganga, Brahmaputra and all their major tributaries) are several times higher and range between 600 and 700 (Brookfield, 1998). As the stream-gradient index is considered as a proxy for stream power, it is reasonable to infer that the rivers of this ancient landmass are modest in terms of power and competence. Fig. 4 shows that for the given drainage basin area, the average SL values for Narmada and Kaveri are much higher (>100) than expected due to higher elevation in the source areas (Amarkantak and Talkaveri, respectively). Further, while the Narmada occupies the SONATA rift zone, in case of Kaveri the upper course (over the Mysore Plateau) and the middle course (through Biligirirangan-Mahadeswaramalai hill ranges) are anomalous (Kale *et al.*, 2014).

Incised rivers

Most of the large rivers and their tributaries are partially or deeply incised in bedrock or late Quaternary alluvium and are therefore, devoid of significant flood plains. The incision and excavation in the alluvial reaches was induced by stronger monsoon and higher river discharges in the early Holocene (Kale *et al.*, 2003 and references therein). However, incision in bedrock is the result of slow and steady lowering of the river channels in response to long-term fall in the base level. Although direct geological evidence is lacking, it is reasonable to infer that with the onset of coolhouse conditions about 34 Ma (Fig. 3), the eustatic sea level has been steadily declining, and all the rivers draining into the adjoining seas have adjusted to this decline in the erosional base level since Oligocene times in general, and during rapid changes associated with Quaternary glacial cycles in particular.

Seasonal hydrologic regime

Monsoon is the defining characteristic of the tropical climate over the Indian Peninsula, at least during the last 8–10 Ma (Kale and Vaidyanadhan, 2014). The Indian monsoon precipitation regime is dominated by high to extreme rainfall seasonality (Nandargi *et al*., 2017). All the rivers of the Indian Peninsula are monsoon-fed and, therefore, the discharge regimes are characterised by sharp peaks and seasonality. The seasonality index (R), which is the ratio between maximum and minimum average monthly discharges (Thomas and Kale, 2011), is significantly higher for the Peninsular rivers than the Himalayan rivers (Fig. 5). The seasonality index is particularly elevated for Peninsular rivers with smaller drainage basin areas and lower mean monthly

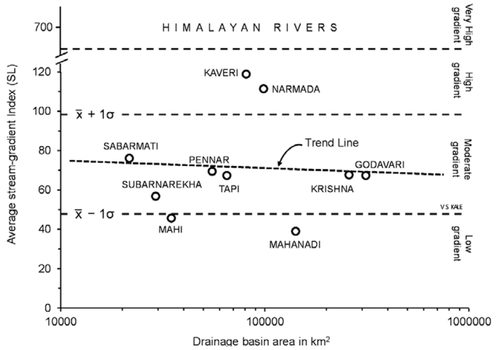

Figure 4. Plot of average stream gradient Index versus the drainage basin area for major Peninsular rivers. The trend line shows that the SL index decreases with an increase in the catchment area.

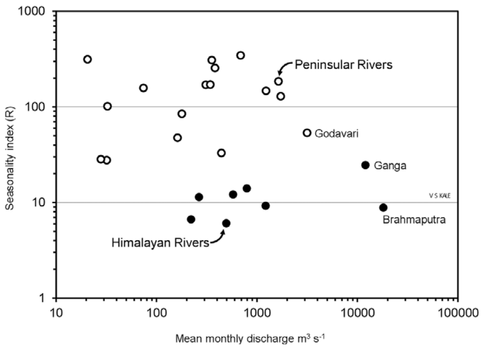

Figure 5. Plot of seasonality index (R) against the mean monthly discharge for the major Peninsular (hollow circles) and Himalayan rivers (filled circles). Basic data from Central Water Commission (CWC) and other sources.

discharges (Fig. 5). This in other words means that the rivers are morphologically active only for a short duration during the water year. Most of the geomorphic work of erosion and transportation is performed during large-magnitude floods that occur from time to time (Kale, 2003).

Subdued regional denudation rates

It is evident from the analyses of the sediment load data available for a number of gauging sites, that the Peninsula is subjected to very slow denudation (Fig. 6). Although the Godavari river transports the highest sediment load in the Peninsula, its annual sediment load is several times less than the annual sediment load of the conjoined Ganga-Brahmaputra (> 500 x 10^6 tons yr^{-1}; Rahman *et al.*, 2018). Rivers draining the Dharwad craton, namely the Kaveri and the Pennar have some of the lowest erosion rates (Gupta *et al.*, 2012). In recent years, the regional erosion rates on the longer geological time scales have been estimated on the basis of apatite fission-track, apatite (U-Th) / He thermochronology, ^{10}Be cosmogenic radionuclide measurements and ^{40}Ar/^{39}Ar dating (Gunnell *et al.*, 2007; Sahu *et al.*, 2013; Mandal *et al.*, 2015a; Mandal *et al.*, 2015b; Jean *et al.*, 2020). These studies indicate that, by and large, the southern Peninsula has been subjected to very slow denudation since the Mesozoic times. Even in the high rainfall zone of the Western Ghat, the erosion rates since the Neogene have been exceptionally low, below 8 m Ma^{-1} (Jean *et al.*, 2020). The results further indicate that the Nilgiri plateau (~2600 m ASL), the highest plateau in the Peninsula, has remained largely unaffected by erosion during the last 200 Ma (Mandal *et al.*, 2015b). Studies from other parts of the world have shown that denudation rates are remarkably high in the tectonically active terrains (Himalaya and Andes, for example) and over the stable shields and cratonic domains, the rates are generally modest (Thomas and Kale, 2011). The main implication of these recent studies is that most of the major topographic features of the landscape observed today have been inherited from the geological past and have not been significantly modified during the recent geological epochs.

Quaternary alluvial formations

Quaternary deposits in the valleys of the Peninsular rivers are noticeably limited in areal extent and thickness. The only exceptions are the structurally-controlled river reaches of the Narmada, Tapi-Purna, Mahi, Sabarmati and Son,and the deltaic plains on the east coast. There are indications that even the bedrock gorges of Narmada may have been completely filled and buried by the Pleistocene deposits (Gupta *et al.*, 2007). In the Deccan Traps terrane, thick alluvial-fill deposits are exposed in the upper reaches of the Godavari and Krishna in general and downstream of the bedrock gorges in particular. Elsewhere the riverine deposits are shallow or absent. From the existing radiometric ages (^{14}C, OSL, U/Th) as well as fossil fauna, stone age tools (Acheulian to Mesolithic) and the ~75,000 years old Toba volcanic ash (tephra) bed occurring within these deposits, it appears that alluvial sediments were deposited mainly during weaker monsoon phases (glacial periods) and incision was induced by stronger monsoon (inter-glacial periods) during the mid to late Quaternary Period (Kale and Rajaguru, 1987; Rajaguru *et al.*, 1993; Williams *et al.*, 2006; Chamyal and Juyal, 2008 and references therein).

Anthropogenic impact

Human presence in the India Peninsula encompasses a span of at least 1.5 million years. The Peninsula is rich in prehistoric (Stone Age, Chalcolithic and Iron Age) and historic sites (Mishra, 2001). Radiometric dates of an early stone age or Palaeolithic (Acheulian) site from Tamil Nadu indicates that the hominins had occupied the southern part of the Peninsula during the early Pleistocene, roughly between 1.7 and 1.1 Ma (Pappu *et al.*, 2011) and the Middle Palaeolithic culture occurred between 0.38 and 0.17 Ma (Kumar *et al.*, 2018). Archaeological evidence further suggests that while the early to mid-Holocene was dominated by Mesolithic culture, the agriculture based Deccan Chalcolithic cultures in central and western India and the Deccan Neolithic culture in southern India flourished approximately between 4500 and 2800 years before present (Mishra, 2001; Ponton *et al.*, 2012; supplementary material). The transition from Iron Age to the early Historic period occurred around 2600 years before present (Mishra, 2001).

Numerous types of human interventions have affected the Peninsular river systems since the introduction of agriculture during the Chalcolithic period. The increase in soil erosion during the late Holocene (Meghalayan Stage) has been attributed to increased agricultural activity in Deccan (Giosan *et al.*, 2017). In the last few decades, the natural functioning of almost all the streams and rivers in the sub-continent has been seriously affected by human activities, such as changes in the land use/ land cover within the catchments, land surface modifications, construction of dams and weirs, flow diversion, sand mining, ground water extraction, etc. Studies based on satellite data and historical archives reveal a significant loss of forests and conversion of forested land into cropland area during 1880–2010 in the Indian sub-continent (Tian *et al.*, 2014). Some of the key consequences of human impact include flow modifications, decline in the sediment fluxes, bank erosion, siltation, pollution and coastal erosion. River gauge data indicate an increase in the inter- and intra-seasonal variability in the river discharges of most of the large Peninsular rivers due to river flow regulation and water diversion. Due to decline in the groundwater level and base flow, many streams and rivers are drier now for a longer duration during the non-monsoon season. Many middle and lower order seasonal streams have acquired the regime characteristics of ephemeral streams. The sediment fluxes also reveal a remarkable decline in the last few decades in general and the current period in particular (Gupta *et al.*, 2012). Analyses of the annual sediment load data show consistently lower sediment quantities downstream of the large dams (Nageswara Rao *et al.*, 2010). The results

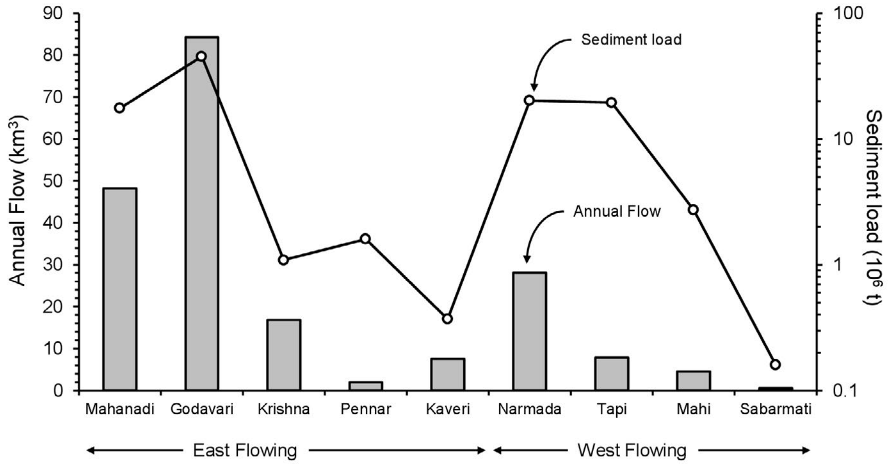

Figure 6. The long-term average annual flow and the annual sediment load of the major Peninsular rivers. Basic data from Gupta et al. (2012)

further show pronounced coastal erosion in the past four decades, particularly along the deltas on the east coast, due to trapping of sediments by large dams (Nageswara Rao *et al.*, 2010).

Role of tectonics and climate in the evolution of the Peninsular landscape

The role of tectonic activity is commonly invoked by geoscientists to explain high relief topography and drainage network anomalies, even in the case of stable, ancient shields bordered by passive continental margins, such as the Indian Shield (Roy, 2006; Valdiya, 2016 and references therein). Richard *et al.* (2016), primarily based on the analysis of river profiles extracted from DEM and geophysical data, concluded that Neogene rock uplift is responsible for the modern-day relief of the Peninsula. As the highest elevations in the Peninsula are observed in the Nilgiri-Anaimalai-Palniarea (> 2600 m ASL), they concluded that the Neogene (23.03 to 2.58 Ma) uplift initiated in the south and propagated northward along the western margin (Richard *et al.*, 2016).

However, millennial-scale erosion rates determined from cosmogenic ^{10}Be indicate that the Peninsular landscape is remarkably stable and tectonically inactive (Mandal *et al.*, 2015a). In addition, old apatite (U-Th-Sm) / He ages of the rocks exposed on the divides, high plateaus (Nilgiri Hills) and valleys in southern India suggest remarkably low exhumation rates during the last 200 Ma (Mandal *et al.*, 2015b). As expected, the erosion rates are comparatively higher along the Western Ghat Escarpment and along active river channels (Mandal et al., 2015a and b). The ^{40}Ar/^{39}Ar geochronology of laterites, occurring over the Mysore Plateau and the coastal lowland (Karwar/Goa), lends a strong support to the hypothesis of tectonic stability of the Peninsular landscape during the Cenozoic (Jean *et al.*, 2020). The ages of the laterites indicate very low denudation rates over the Mysore Plateau and the coastal lowland, and unexpected locational stability of the Western Ghat Escarpment since the mid-Eocene (~47 Ma) times (Beauvais *et al.*, 2016; Jean *et al.*, 2020).

Here it is pertinent to mention that, in spite of the evidence of regional tectonic stability of the landscape, there are indications that some areas within the Peninsula may have experienced domal uplift or block tectonics during the post-Gondwana-breakup (Roy, 2006). Some known evidence are presented below:

The Pachmadhi sandstone beds, consisting of fluvial sediments deposited by an ancient river system in the Gondwana rift basin in the Triassic, are today occurring >1 km ASL over the Pachmadhi plateau (1352 m ASL at Dhupgarh). The Pachmadhi plateau is the highest plateau in the Satpuda range. It is a very well established fact that a river channel, without exception, occurs at the lowest elevation in all types of topographic settings (mountains, plateaus, plains). Therefore, the occurrence of river deposited sediments at the highest elevation indicates uplift and the role of tectonics. The present elevation of the fluvial beds has been attributed to significant post-Deccan Traps uplift in the area (Sheth, 2007).

Lignite beds of Mio-Pliocene age, known as Ratnagiri Beds, occur up to 8–10 km inland and up to 150 m above the present sea level in south Konkan and Goa. These clay beds, often overlain by thick laterites, contain plant fossils and indicate deposits of nearshore to estuarine environments (Badve *et al.*, 2002). Only two mechanisms can explain the present elevation of these marine/estuarine deposits — higher sea level or tectonic uplift along the coast. Although tectonic uplift is likely, other types of supporting evidence is yet to be identified and presented.

U/Th and ^{14}C dates of marine terraces, beach rocks, marine shells and corals provide indications of higher sea levels or possible tectonic uplift along the southern tip of India (Kanyakumari to Rameswaram) and along the Saurashtra coast during the late Quaternary (Banerjee, 2000; Sharma *et al.*, 2017).

Thick river deposits occur immediately downstream of some long bedrock gorges, for example, downstream of the Dhadgaon gorge on Narmada. These coarse gravel deposits of Narmada (Plate 1B) form a large fan (axial length ~20 km) at the exit point of the Dhadgaon gorge. The unusually thick exposed deposits (>20 m), characterised by rounded to sub-rounded pebbles and cobbles, were dated to about 90ka (Chamyal and Juyal, 2008, and references therein). The clast size decreases away from the fan apex. The nature of deposits clearly suggests intense bedrock erosion in the Dhadgaon bedrock gorge, most likely induced by rock uplift related to the movements along the Son-Narmada or Tapi Faults (Copley *et al.*, 2014). Similarly, downstream of the Pravara gorge in the upper Godavari basin, and in the lower reaches of the Par river in north Konkan, thick alluvial deposits are present. These unusually thick Quaternary fluvial deposits indicate an episode of intense valley erosion and incision in bedrock, most likely induced by tectonic uplift. Only a fall in the base level of erosion rather than climate change can account for such intense erosion of the bedrock. The presence of incised bedrock meanders and prominent knickpoints upstream as well as in the adjoining basins (Mandvi, Dhamanganga, etc.) lends a strong support to the hypothesis of block or domal uplift in this part of the Deccan Traps region (Kale and Shejwalkar, 2008).

Typical alluvial fans at the mountain front, although common along the Himalayan foothill zone, are rare features in the Indian shield, perhaps because of the tectonic stability of the landscape. However, a ~10 km wide and ~7 km long, symmetric alluvial fan has been developed by a lower order tributary of the Sagileru river in the Pennar basin (Kale, 2009). In a rocky terrain and an erosional landscape, such large depositional features are anomalous. Therefore, this and other smaller fans developed along the east-facing front of the Nallamalai hills (coinciding with the Cuddapah Boundary Thrust) as well as the deep incision of the Krishna river within the Nallamalai hills further north (Fig. 1), possibly indicate the control of tectonics in this part of the Cuddapah basin. Needless to state, the role of lithology (erodibility of the rocks) and structure cannot be ruled out completely.

Alluvial fans of modest size are also present along the southern slopes of the Satpuda ranges in the Tapi-Purna basin. Vertical offset in the fan surfaces indicates movement along the Tapi Fault during the Holocene (Copley *et al.*, 2014). This evidence plus the historical records of seismicity (Allah Bund-1819, Coimbatore-1900, Satpuda-1938, Anjar-1956, Koyna-1967, Broach-1970, Killari-1993, Jabalpur-1997, Bhuj-2001, etc.) along or close to the major lineaments/fractures suggest deformation and reactivation of pre-existing structural features in the Indian Shield (Roy, 2006).

Another factor that has played an important role in the evolution of Peninsular landscape during the Cenozoic is the climate. Reconstruction of the Cenozoic global climate by scientists indicates warm to hothouse conditions during Palaeocene and Eocene (~66 to 34 Ma), and hothouse conditions during early Eocene (56 to 47 Ma) (Westerhold *et al.*, 2020). Lignite and other types of deposits of this period occurring in some parts of India also indicate hot and humid climatic conditions over the Peninsula. This was also the time of intense weathering and lateritisation/bauxitisation over the Indian Peninsula (Jean *et al.*, 2020). Most of the laterites occurring over different lithologies formed during this hot and humid phase (Kale, 2014). It is important to note here that this was roughly the time when the Indian Plate was centred over the equator during the northward drift. As a result, the climatic conditions were highly favourable for deep weathering over the divides and concentrated fluvial erosion along the active channels (Kale, 2014). It is most likely that the present dimensions and forms of the Peninsula valleys were largely acquired during this very warm and moist phase.

A second phase of intense weathering and lateritisation/bauxitisation over the Indian Peninsula has been identified by Jean *et al.* (2020) during the Miocene (Fig. 3). This phase closely follows the globally identified warmer period from ~17 to 14 Ma, known as the Miocene Climatic Optimum (Westerhold *et al.*, 2020). It is likely that the laterites overlying the Ratnagiri lignite beds in Konkan and Goa, formed during this warmer phase or during the Mid-Pliocene Warm Period (~3.29–2.97 Ma). Multiple lines of evidence suggest that the present monsoon climate was firmly established over the Indian sub-continent during the Miocene, about 8–10 Ma ago (Kale, 2014). The onset of monsoon climate might have further enhanced the rates of weathering and fluvial erosion, especially in the Western Ghat zone (Jean *et al.*, 2020). By the end of Neogene, the Peninsular landscape had, more or less, acquired its present surface configuration.

During the Quaternary, the river systems underwent repeated adjustments in response to glacial-interglacial cycles and associated sea-level changes (Kale, 2014). On the basis of radiometric dates and sedimentological data of the last glacial and the present inter-glacial periods, it appears that, in general, fluvial aggradation in the valleys was associated with cooler and drier periods, and degradation was the dominant fluvial activity during the warmer inter-glacial periods (Kale *et al.*, 2003).

Ancestry and antiquity of the Peninsular rivers

Generally, the palaeo flow-paths of rivers are inferred from, either deposits relatable to the existing rivers or from palaeogeographic maps. The fluvially sculpted landscape of the Indian Peninsula shows poor preservation of fluvial archives. The Cretaceous to Neogene fluvial deposits are conspicuously absent on land. The Quaternary fluvial deposits, although present, are mostly confined to a narrow belt in certain stretches of the present river valleys, and record only the late Quaternary fluvial history. In the absence of continental fluvial records of the earlier period, inferring and reconstructing the ancestry of the main drainage courses unambiguously remains a difficult proposition. However, considering some of the well-known facts about the geological history and palaeogeography of India it is possible to tentatively reconstruct the geomorphic history of the main-stem rivers. Some of the well-established facts are listed below:

The general slope of the Deccan Plateau is towards the east over the Precambrian terrain as well as over the Deccan Traps terrain, particularly to the south of the SONATA zone. The rivers draining the Precambrian terrain, such as the Kaveri and Pennar as well as the Tungabhadra, do not provide any indications of drainage reversal. This in other words means that the easterly drainage has been in existence throughout the Cenozoic, and even before the Deccan Volcanism (late Mesozoic).

The Deccan Traps presently cover an area of over 500,000 km^2. Estimates indicate that immediately after the end of Deccan Volcanism (~65 Ma ago) it covered about 2–3 times more area. The drainage network over the Traps has without doubt evolved after the end of the Deccan volcanism. Therefore, the rivers draining the Deccan Traps terrain are young and thus Cenozoic in age.

The Mahi and Sabarmati rivers are associated with the Cambay graben, which formed during the rifting and separation of India and Seychelles. This implies that the modern water courses of these rivers are not older than 65 Ma.

The present courses of the Pranhita-Godavari, Damodar, and Mahanadi occupy the intra-cratonic grabens (rift valleys), filled with sediments of the Gondwana period. As the palaeocurrent trends from various Gondwana basins suggest drainage alignment towards the NW or NE direction (Valdiya 2016), it is logical to infer that the present roughly eastward courses of these rivers were established (or re-aligned) sometimes after the Gondwana period (post-Jurassic).

The palynological assemblages and fossils occurring within the sediments underlying the Deccan Traps (the Bagh and Lameta beds) in the lower and upper Narmada Valley, the planktonic foraminifera in the Deccan intertrappean beds in the Chhindwara district, and pollen data of infratrappeans from the Yavatmal area in Maharashtra suggest that an arm of the sea from west coast extended through the Narmada Valley, and another arm of shallow sea from the east coast extended through the Godavari-Pranhita valley during the late Cretaceous (Keller *et al.*, 2009; Prasad *et al.*, 2018). These palaeogeomorphic reconstructions imply that the existing courses of the Narmada-Tapi and lower Pranhita-Godavari were established after the retreat of sea at the end of Cretaceous Period or beginning of Palaeocene. Similarly, the thick Ariyalur marine formations in Tamil Nadu suggest major marine transgression in the lower Kaveri and adjoining basins during Cretaceous (Nagendra and Reddy, 2017), which coincided with the time of hothouse conditions and higher eustatic sea levels.

Considering all the above facts, it is reasonable to infer that the foundations of the existing drainage systems of the Peninsula were laid sometimes during the post-Jurassic period over the non-Deccan Traps areas, and the drainage network over the Deccan Traps was established after the end of Deccan Volcanism (Palaeocene-Eocene). This in turn implies that many of the river systems of the Peninsula consist of segments of different ages, and the complete integration has taken place, perhaps during the early or mid Cenozoic (Kale, 2014). Kaveri is one of the major exceptions, because it neither occupies the Gondwana basins, nor it was flooded and buried by Deccan Traps lava flows, nor affected by continental collision, marine transgression (except in the delta region) or glaciation. Further, none of the earlier studies has suggested that the Kaveri drainage was disrupted during the Gondwana breakup in the Mesozoic. It is therefore likely that the Kaveri drainage has retained characteristics of the ancestral drainage to a considerable extent. In the absence of sedimentological records, it is not possible to independently verify this hypothesis. However, the sharp bends and its course across the Biligirirangan Hill ranges (a horst) in the middle domain suggest that the river has undergone some changes and drainage re-arrangement during the Cenozoic. Further, in other parts of the Indian Peninsula, the presence of sharp bends in the river courses, barbed tributaries, and head-truncated valleys similarly implies that most of the rivers have undergone drainage re-organisation to a variable extend due to river capture, diversion and beheading. Although there is ample evidence now to suggest that the Peninsula has remained tectonically stable during the Cenozoic, there is geological and geomorphic evidence of block tectonics in some parts. These and other geomorphic evidence thus suggest that the drainage re-arrangement or re-organisation in the major drainage basins was induced by stream piracy, structural control, block tectonics and changes in the erosional base level at different time periods. The net effect is the present surface configuration and drainage network of the Peninsula.

Concluding remarks

It is apparent from the above discussion that in spite of the availability of better geochronological data and powerful analytical tools in the last few years, there are large gaps in our understanding of the geomorphic processes and geomorphic history of the Peninsular rivers. Several issues have emerged from the present review that remain less understood or completely unanswered. One of the main reasons for this is the decline in the number of purely field-based studies in recent years. Geomorphology is an empirical science as well as a field science and hence intensive and rigorous fieldwork and field-based measurements / monitoring are some of the fundamental requirements for successful research. In the last few years, the focus of the geomorphic studies in India has gradually shifted away from field-based studies towards remote sensing and GIS based studies. The DEMs, satellite images and GIS are only reconnaissance tools. Without adequate field knowledge and field data, the interpretations largely based on the processing of satellite images and DEM-derived morphometric data are not likely to contribute significantly to the existing knowledge on the geomorphic processes, feedback mechanisms and long-term legacies of human impact on landscapes. Improved understanding of the geomorphic processes and feedback mechanisms under different landscape settings can lead to better understanding of the range and extent of human impacts and can help in anticipating and mitigating future impacts of anthropogenically-driven earth system processes in general and the fluvial processes in particular.

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