Journal of Palaeosciences 70(2021): 289–303
0031–0174/2021

Mid to late Quaternary fluvial activity in allochthonous river systems of the Maharashtra Plateau, India: A review and new observations

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ABSTRACT

Kale VS 2021. Mid to late Quaternary fluvial activity in allochthonous river systems of the Maharashtra Plateau, India: A review and new observations. Journal of Palaeosciences 70(2021): 289–303.

The Maharashtra Plateau dominantly displays an erosional landscape and the Quaternary alluvial deposits in the valleys are remarkably limited in areal extent and thickness. The only exceptions are the infilled basins/valleys downstream of bedrock gorges with knickpoints. Earlier studies have inferred a good correspondence between the major changes in the monsoon regime and the fluvial activity (aggradation and incision/excavation) on the regional–scale during the last ~10^3–10^5 years. However, geomorphic evidence suggests that some of the mid to late Quaternary aggradational events may not be directly related to known climatic events and the fluvial activity in some of the tributaries did not correspond with the recognized regional behavioural pattern. Basin–specific tectonic activity as well as alterations in the isohyetal pattern in the rainshadow zone appear to be the plausible reasons for the observed variations in the fluvial responses. The relationship between Quaternary climate changes and the fluvial activity, even in this area of uniform lithology, appears to be a complex one.

Key–words—Godavari, Krishna, Aggradation, Incision, Infilled basins and valleys, Gorges, Knickpoints, Isohyetal pattern.

INTRODUCTION

A number of studies in the last few decades have recognised changes in the river regime and fluvial activity in the Indian Peninsula in response to climatically–induced changes in the catchment and river hydrology during the late Quaternary (Rajaguru 1969; Corvinus *et al*., 1973; Williams & Clarke, 1984; Kale & Rajaguru, 1987; Chamyal *et al*., 2003; Jain & Tandon, 2003; Mishra *et al*., 2003; Nagalakshmi & Achyuthan 2004; Juyal *et al*., 2006; Williams *et al*., 2006; Patnaik *et al*., 2009). Comparison of the fluvial sedimentary records and available palaeoclimate proxy records (marine and lacustrine) indicates that the river systems in central and western India have, by and large, responded to the major changes in the monsoon regime during the late Quaternary (Kale & Rajaguru, 1987; Juyal *et al*., 2006; Williams *et al*., 2006). In general, aggradation was associated with the cooler and/or drier Marine Isotope Stage or MIS 5/4 transition, the Last Glacial Maximum (LGM) and the mid–Holocene, and river incision and excavation dominated the warmer and wetter Holocene Climatic Optimum and the late Holocene stage (Kale *et al*., 2003; Kale *et al*., 2004; Williams *et al*., 2006; Juyal *et al*., 2006 and the references therein).

While the periods of aggradation and excavation/incision on the regional–scale appear to broadly correspond with the recognized major periods of climate change during the last ~10^3–10^5 years, the available geomorphic, chronological and archaeological evidence from the upper Godavari and Krishna basins suggest that some of the mid to late Quaternary aggradational events may not be directly related to the fluctuations in the monsoon strength and some of the tributary streams experienced out–of–phase alluvial sedimentation (Mishra *et al*., 2003; Kale, 2007; Kale & Shejwalkar, 2008). In this paper, an attempt is made to review and interpret the available multivariate data on sedimentary fluvial archives, to understand the possible role of the past changes in the isohyetal (precipitation) pattern and area/basin–specific tectonic activity on the allochthonous river systems of the Maharashtra Plateau. The focus of this paper is especially on the upper Godavari and Krishna rivers and their major tributaries within the Deccan Traps region (Fig. 1).

GEOMORPHIC AND CLIMATIC SETTING

The Maharashtra Plateau constitutes a major part of the vast Indian Peninsula. The nearly 1–km high Western Ghat Escarpment (*Sahyadri*) defines the western margin and the Tapi Rift forms the northern boundary of this eastward–sloping elevated plateau. Horizontal to sub–horizontal Deccan Traps basalt flows of Cretaceous–Eocene age (~65 Ma) cover a major part of the plateau. Only in the eastern part, older rocks are exposed. The nearly 700–km long Western Ghat Escarpment (within the Deccan Traps), with orographically induced southwest monsoon precipitation (June to September), is the source of three principal rivers, namely the Godavari, Krishna and Bhima, and many of their higher order tributaries (Fig. 1). All the main–stem rivers and their major tributaries have remarkably low channel gradients and occupy unusually wide, box–shaped valleys, right from the source (Kale & Shejwalkar, 2008).

The monsoon–fed rivers of the study area fall under two major hydrological types. Allochthonous or allogenic rivers, such as the Godavari, Bhima, Krishna and their major tributaries (Pravara, Kukadi, Nira, etc.), that originate in the high relief (~1000–1600 m ASL) and high rainfall zone (~3000–6000 mm) of the Western Ghat (or its major offshoots), but flow through the semi–arid, rainshadow zone (~1000–500 mm) for tens to hundreds of kilometres (Kale, 1990; Kale & Rajaguru, 1987). These Western Ghat rivers commonly sustain flows for a longer duration, in spite of the fact that the autochthonous tributaries of the rainshadow zone do not contribute much discharge downstream. The autochthonous streams, in comparison, are sourced almost entirely from within the rainshadow zone. Such non–Ghat tributary streams are highly seasonal or ephemeral in nature, and carry water for a short duration after wet–spells during the monsoon months.

Presently, all the rivers within the area under review are partially to deeply incised in bedrock or late Quaternary

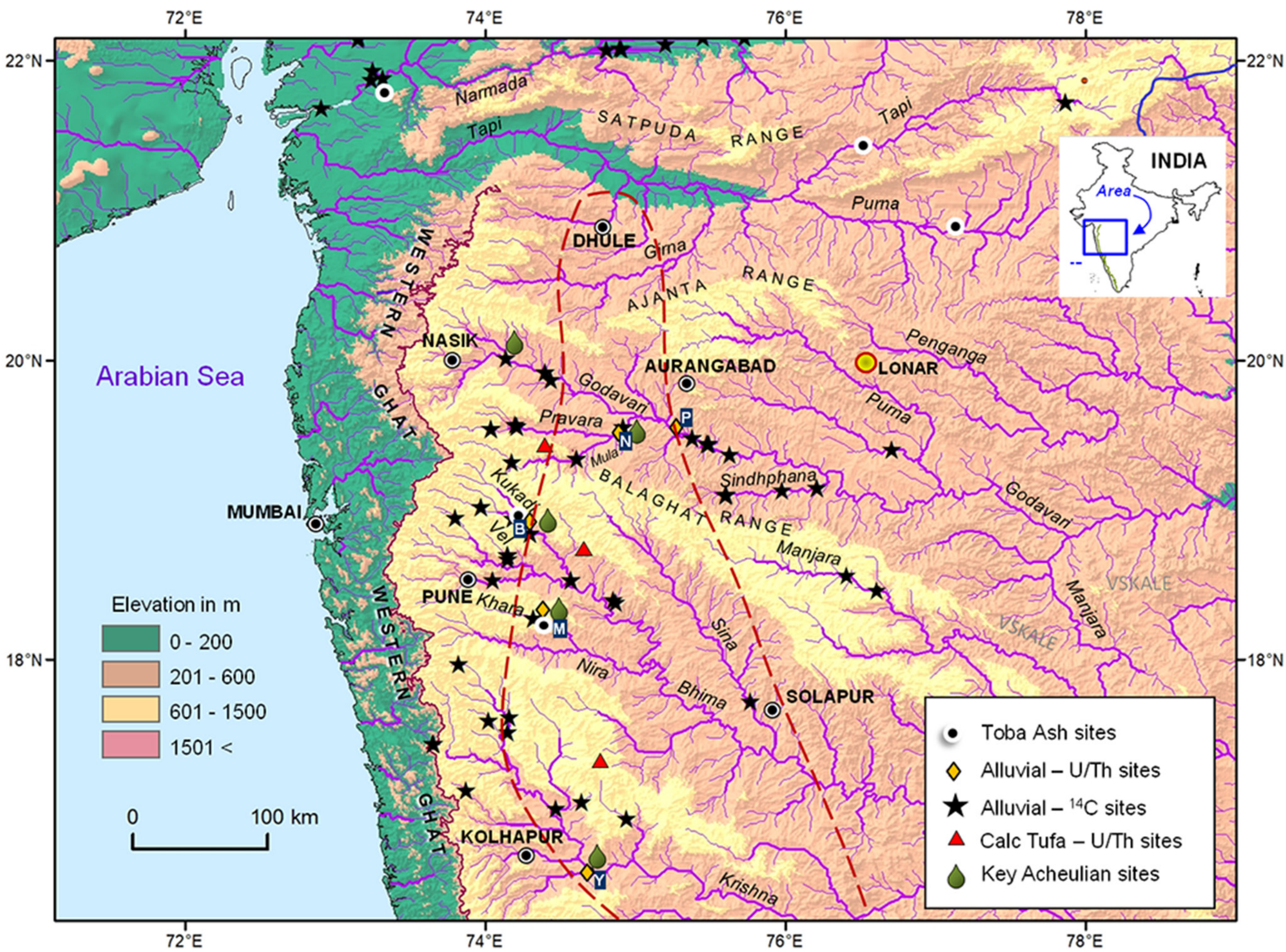

Fig. 1—Map of western India, showing some important geomorphic and archaeological sites over the Maharashtra Plateau mentioned in the text. Some ^{14}C dated sites in the Narmada and Tapi basins are also shown. The area enclosed by the 700 mm isohyet (dashed red line) represents the core dry zone (CDZ) with < 500–700 mm annual rainfall. Some important sites shown are–Paithan (P), Nevasa (N), Bori (B), Morgaon (M) and Yedurwadi (Y).

alluvium and are, therefore, devoid of significant floodplains. In the alluvial reaches, the river channels are bounded by high alluvial cliffs (~3–5 m), which are presently undergoing erosion by undercutting or by bank gullies.

QUATERNARY SURFICIAL DEPOSITS

The Maharashtra Plateau dominantly displays an erosional landscape (Kale & Rajaguru, 1987). Bedrock landforms and rocky channels are more common than depositional features and alluvial rivers. In comparison with the alluvial river reaches associated with the Narmada–Son–Tapi (SONATA) rift zone and the Cambay Rift (Mahi and Sabarmati), the Quaternary alluvial fill deposits in the valleys of the upper Godavari, Krishna and Bhima rivers are remarkably limited in areal extent and thickness (Rajaguru, 1969). The only exceptions are the infilled basins/valleys in the upper reaches of some tributaries of the Godavari and Bhima rivers. In general, the wide, box–shaped valleys generally display a two–alluvial fill and two–terrace combination in valley alluvium (Rajaguru 1969; Kale & Rajaguru, 1987) (Fig. 2A).

It is pertinent to mention here that two noteworthy geological events occurred during Quaternary in the study area. The first major geological event occurred around 570 ± 47 ka in the form of a meteor impact at Lonar (Fig. 1) in the middle Godavari domain (Jourdan *et al.*, 2011). Then at about 75 ka ago, volcanic ash from the Toba Volcano in Sumatra, Indonesia was deposited in many valleys of the Indian Peninsula. These tephra deposits, identified as the Youngest Toba Tuff (YTT) and considered as a useful stratigraphic marker, are exposed at two localities in the study area (Kale *et al*., 2004 and references therein). The occurrence of YTT within alluvial deposits and at or close to the modern bed level has important implications for reconstructing the Late Pleistocene fluvial as well as Quaternary tectonic history of the region. Although there is no evidence to suggest that the ~150 m deep and nearly ~1.8 km wide crater–forming event at Lonar had an impact on the Late Pleistocene fluvial activity at the local or regional scale, the Lonar Lake sedimentary record has provided valuable information on the changes in the monsoon regime over the core monsoon zone during Holocene (Prasad *et al*., 2014). Archaeological evidence from the middle Godavari Basin suggests that this extremely

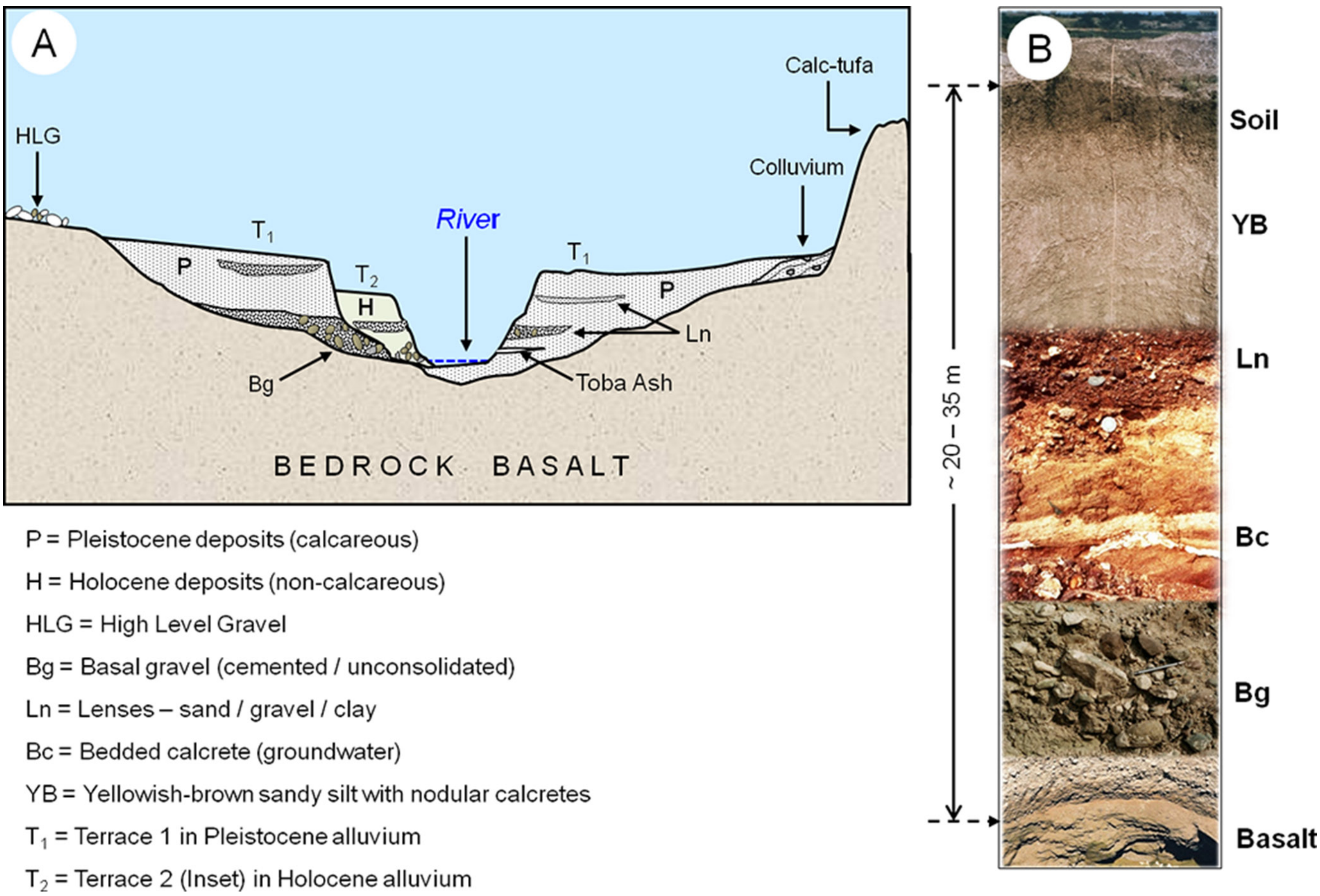

Fig. 2— (A), Generalized valley cross–section showing the two alluvial–fill and two–terrace combination in valley alluvium in the upper Godavari and Krishna basins. Section not to scale; (B), A composite litho–section of the Pleistocene alluvial fill deposits based on field photos.

rare geological event was most likely witnessed by hominins occupying the region.

The exposed Quaternary sedimentary sequences (Figs 3–6) in the upper Godavari and Krishna basins have been the focus of several studies since mid–1960s due to the occurrence of mammalian and reptilian fossils, datable molluscan shells and abundant archaeological material (Rajaguru 1969; Corvinus *et al*., 1973; Kale & Rajaguru, 1987; Rajaguru, *et al*., 1993; Mishra *et al*., 2003). During the last 3–4 decades, borehole data from dam sites and field investigations of the exposed bank sections and dug wells have provided ample information about the distribution and spatial variations in the thickness of the alluvial fill deposits. These investigations indicate that the thickness and lateral extent of the alluvium is remarkable in some parts of the upper Godavari and Bhima basins (Rajaguru, 1969), particularly downstream of bedrock gorges with knickpoints. Geo–archaeological studies have provided enough evidence of the presence of ancient channel bed and bar deposits at multiple locations in this bedrock dominated landscape.

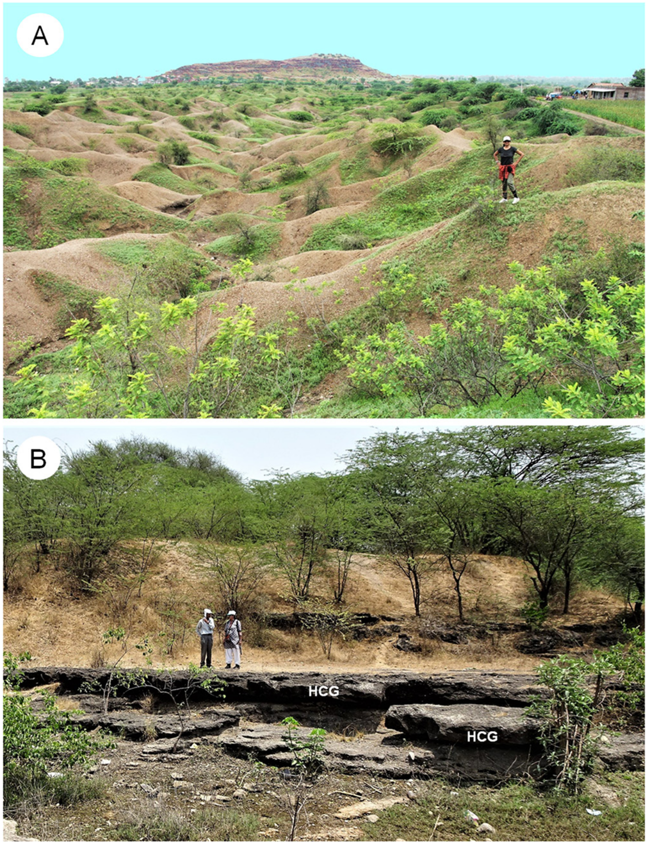

Fig. 3—(A), A view of the infilled Adula–Mahalungi Basin located to the NW of Sangamner Town. See Fig. 8 for location. The deposits are presently undergoing dissection by gullies; (B), Yellowish brown sandy–silts overlying heavily cemented and indurated cross–bedded, sandy–pebbly gravel beds (HCG), exposed on the left bank of the Kukadi River at Bori. See Figs. 1 and 8 for location. Fossil bones and early Acheulian artefacts (Fig. 6B) were collected from this ancient point bar deposits (Kale *et al.*, 1986a). U–series analyses gave an age of ~200 ka for the gravel cement (Atkinson *et al*., 1990).

Two types of Quaternary surficial deposits: alluvial and colluvial have been recognized in the Godavari and Krishna valleys. The Quaternary alluvial fill deposits are fairly widespread and are divisible into two main types–the Pleistocene alluvial fill deposits and the Holocene inset deposits (Fig. 2A). Apart from age, the two types of alluvia differ in many respects: in the thickness and lateral extent, in the mean texture, in the carbonate nodule formation, in the degree of soil development, in the degree of cementation as well as in the associated archaeological material and fossils. The Late Pleistocene deposits form a higher terrace (T_1) and the Holocene sediments occur as discontinuous, inset terraces (T_2) (Rajaguru, 1969) (Fig. 2A). Colluvial sediments (Fig. 5C), of variable thickness and extent, occur in the foothill zones in many river basins (Fig 2A), particularly in the semi–arid parts. A brief description of the Quaternary surficial deposits is given below.

The Pleistocene Alluvial Fill Deposits

Exposures along the channels and borehole data from multiple dam sites indicate that these older fluvial deposits are up to 35 m thick and comprise of yellowish–brown, sandy–silty units (Figs 3B, 4B) with coarse gravel at the base (Fig. 2B) (Rajaguru, 1969). The thicker, massive sandy–silty units sometimes contain lenses of sandy–pebbly gravels (Fig. 2B). These older formations often contain nodular and tubular calcretes and sometimes carbonate cemented sands and gravels in the lower units (Kale *et al*., 1990). Incipient to well developed soil horizons (vertisols or red soils) are not uncommon (Fig. 2B). Crudely bedded coarse–grained alluvium at the base, dominated by pebbles and cobbles (Fig. 4C), is exposed at multiple locations. Heavily cemented and indurated cross–bedded, sandy–pebbly gravel beds are exposed in the bank sections at several locations (Figs 3B, 5A), particularly in the Godavari and Bhima basins (Kale *et al.*, 1990), and indicate the antiquity of the deposits in this rocky and tectonically stable terrain. These indurated gravel beds have yielded animal fossils and Palaeolithic artefacts (Fig. 6B).

Some of the oldest fluvial deposits, occurring high above the modern bed level, have been reported from the upper Godavari Basin. These rounded to sub–rounded, coarse channel deposits, designated as 'High Level Gravel' (HLG) by earlier workers (Joshi *et al.*, 1979; Corvinus, 1981), have been observed at Paithan on Godavari and at Nevasa on Pravara (Fig. 1). At both the sites, the HLG occurs about 15–20 m above the modern channel bed, and several tens to hundreds of meters away from the banks (Fig. 2A). The < 2 m thick gravel deposits, dominated by weathering– and erosion–resistant siliceous rocks (chert and chalcedony) and compact basalt, are directly resting over the bedrock. The high elevation

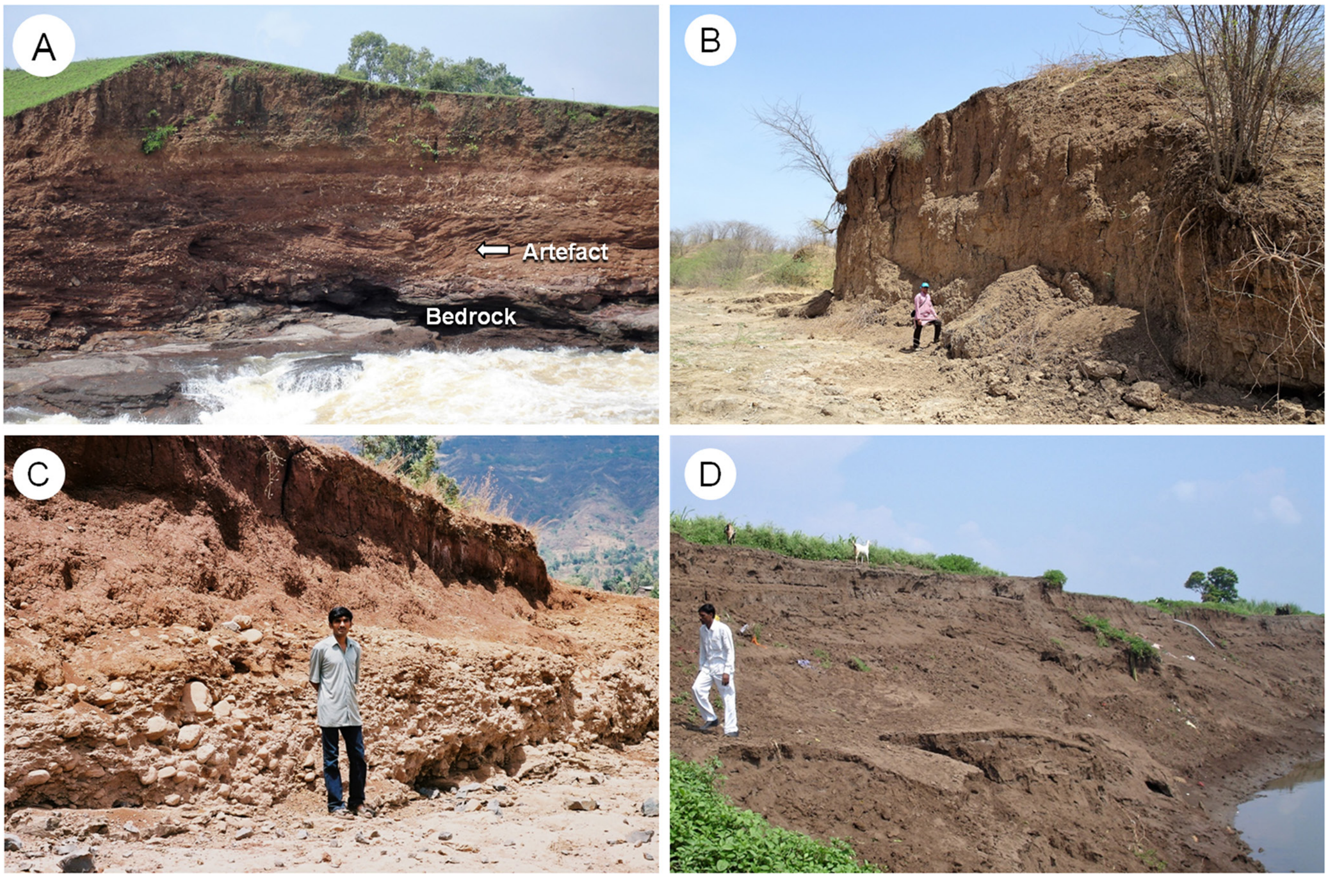

Fig. 4—Late Quaternary sedimentary deposits. (A), Artefact–bearing Pleistocene deposits (~ 2–3 m) at Gangapur on the right bank of the Godavari River. Artefact and section reported by Deo *et al.* (2018); (B), Yellowish brown, calcareous sandy–silt deposits of Godavari exposed at Nandur Madhmeshwar; (C), Reddish sandy–silty alluvium overlying thick bouldery gravel bed on the right bank of the Krishna River, upstream of Wai; (D), Dark brown, non–calcareous Holocene sediments exposed on the left bank of the Godavari River at Kalavi near Nashik. Photo A and D courtesy of P. S. Hire.

(~15–20 m) indicates that the gravels were deposited prior to the channel incision in bedrock. This suggests the antiquity of these gravel deposits. Mishra (1995) has assigned a pre–Pleistocene age based on geomorphic and archaeological evidence. The gravels have survived because of the dominance of weathering–resistant chert and chalcedony pebbles/cobbles.

Based on sedimentology and sedimentary structures of the alluvial fills, two main types of depositional environments are apparent–overbank and channel. The coarse gravelly units generally represent channel bed, near channel or bar (mid–channel or point bar) deposits, whereas the finer members, sometimes with sandy/gravelly lenses, appear to be overbank, flood or floodplain deposits. The pool deposits in the bank sections are represented by black fissured clays (Kale *et al*., 2004). During the September 1969 extraordinary monsoon flood on Godavari, Mujumdar *et al*. (1970) observed deposition of ~20–90 cm thick silty–sandy sediments by over–bank flows and clayey sediments in the pools. Interestingly, no coarse sediments were deposited over the banks during this rare, extreme hydrological event.

A range of dates has been established for the Pleistocene alluvial deposits based upon ^{14}C determinations of shells (bivalve and ostrich) and a few samples of fossilized wood and charcoal (Corvinus *et al*., 1973; Rajaguru & Kale 1985; Kale & Rajaguru, 1987: Mishra *et al*., 2003; Kale, 2007). For a long time, the alluvia were thought to have been deposited during the prolonged interval of aggradation roughly coinciding with the Last Glacial Maximum (LGM) arid phase based on radiocarbon dates (Corvinus *et al*., 1973; Rajaguru & Kale, 1985). However, it is apparent from the ^{14}C ages of the basal units that the lower units are beyond the range of radiocarbon dating. The occurrence of the 75–ka Youngest Toba Tuff (YTT) within the Pleistocene alluvial sequences (Fig. 6C), at several localities in western and central India in general and at two sites within the study area in particular (Fig. 1), indicated that the rivers were also aggrading during MIS 5/4 transition (Kale *et al*., 2004). Furthermore, a few U/Th dates of the gravel cement from the indurated sandy–gravelly units, a fossilized tree trunk and a tusk of *Elephas* sp. (Fig. 6A) suggest that some of the exposed fluvial deposits could be older than 100 to > 350 ka and thus are likely to be at least Middle

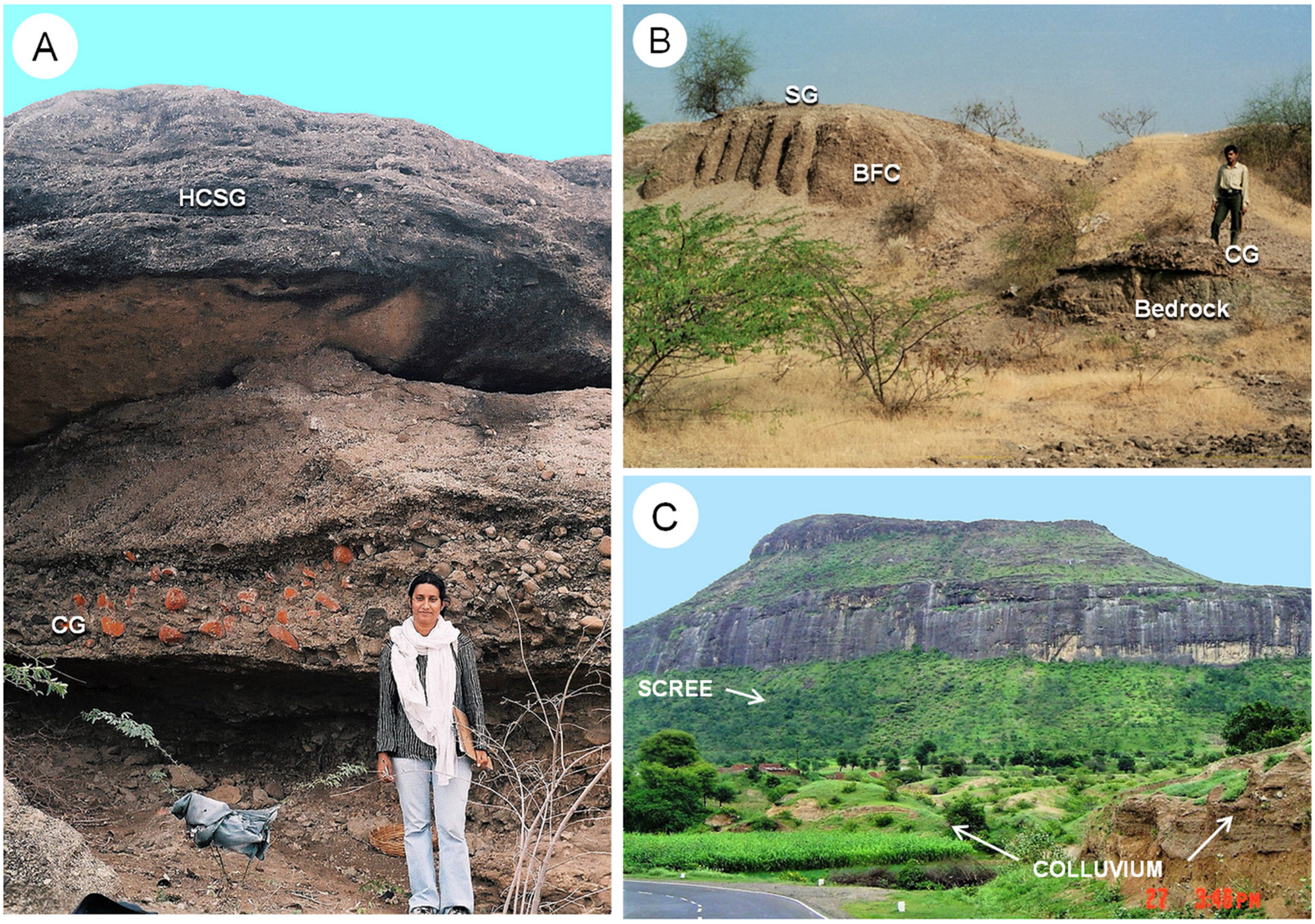

Fig. 5—(A), Heavily cemented sandy gravel (HCSG) with cross–bedding and cemented pebbly–cobbly gravel (CG) units exposed on the left bank of the Karha River near Morgaon; (B), Thick, heavily calcretized, black fissured clays (BFC) covered by a thin veneer of loose sandy–pebbly gravel (SG) containing microliths and shells near Morgaon; (C), Colluvial deposits in the Chandanapuri Valley. See Fig. 8 for location. Note the dissection and gully erosion in the foothill deposits.

Pleistocene in age (Kale *et al*., 1986b; Atkinson *et al*., 1990). These observations were further supported by relative dates based on fluorine–phosphate ratio ($100F/P_2O_5$) of the fossil bones from multiple localities (Kshirsagar, 1993). The Middle Pleistocene (or possibly even Early Pleistocene) ages of some of the exposed alluvial units cannot be ruled out completely because of the occurrence of *in situ* early Acheulian artefacts within the coarse alluvium at a few sites (Corvinus *et al*., 1973; Kale *et al*., 1986a, b; Mishra *et al*., 2003; Deo *et al.*, 2018) (Fig. 6B). In this context, it is important to note that about 1.7 to 1.1 Ma old Acheulian artefacts have been reported from the southern part of the Indian Peninsula (Pappu *et al*., 2011). To summarize, it is reasonable to deduce on the basis of archaeological evidence and limited number of radiometric dates that, although the bulk of the finer alluvial deposits were laid down during Late Pleistocene, some of the coarser sedimentary units in particular are much older and may have been deposited during different time intervals since the Early or Middle Pleistocene.

The Holocene inset deposits

The Holocene alluvial deposits are present in many valleys as discontinuous, inset aggradational terraces (Rajaguru, 1969) (Fig. 2A). The Holocene sediments are up to 15 m thick, and are generally non–calcareous, often structure–less, dark brown to reddish sandy–silts (Fig. 4D), sometimes with gravelly units at the base. Evidence of pedogenesis is conspicuously absent. The Holocene sediments appear to be reworked Pleistocene sediments (Kale & Rajaguru, 1987). Driftwoods, bones, hearths, potsherds and artefacts of Mesolithic–Chalcolithic age occur within these deposits (Kale & Rajaguru, 1987; Mishra *et al.*, 2003). The inset nature and the sedimentological properties of these younger sediments suggest that this was a relatively minor, low–magnitude aggradational event (Kale & Rajaguru, 1987).

Radiocarbon ages, ranging from ~11.7 to 3.1 ka BP, were reported by Kale & Rajaguru (1987), Mishra *et al.* (2003) and others. The summed probability distribution plot of the

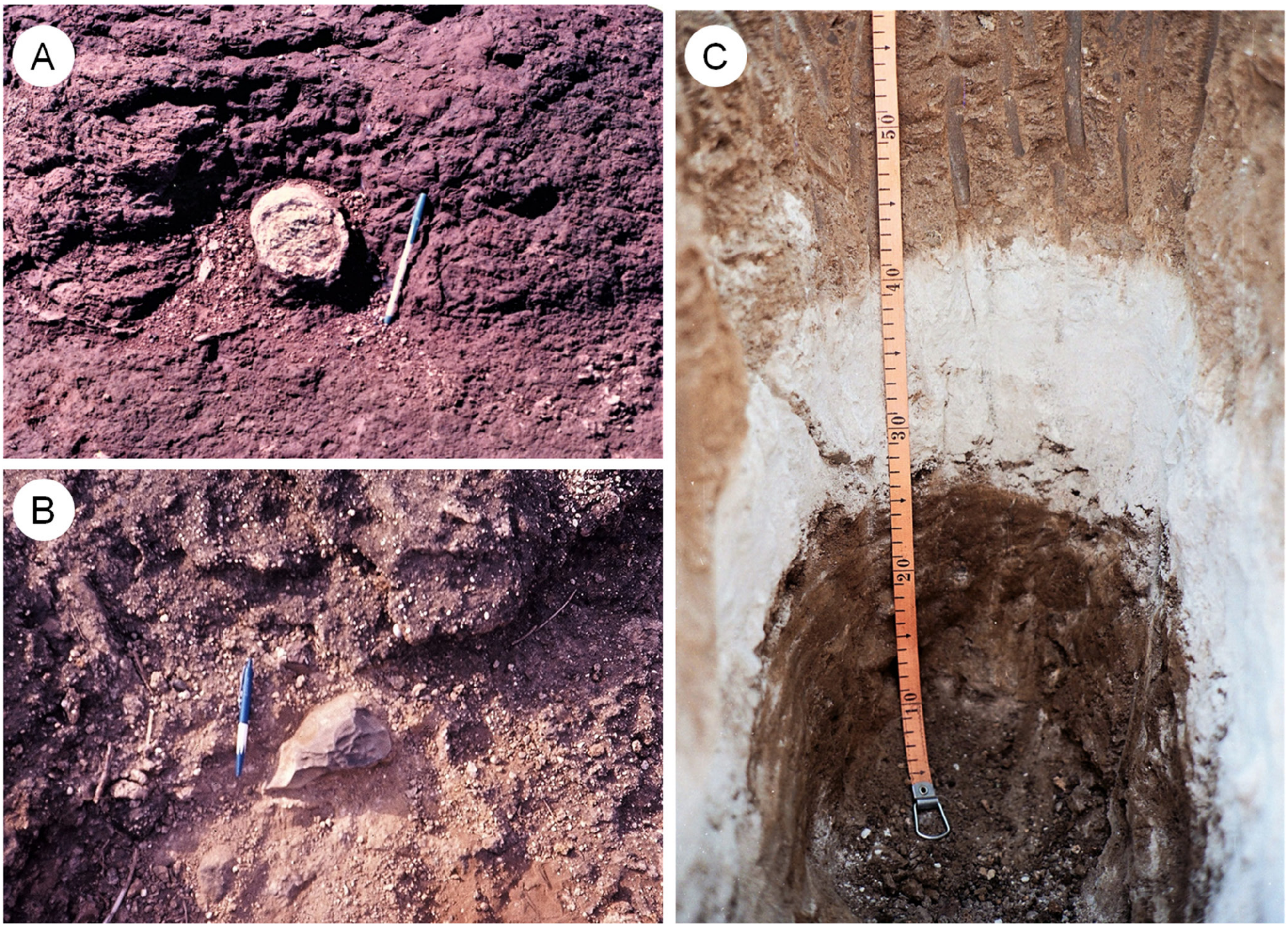

Fig. 6—Mid to Late Pleistocene fluvial deposits; (A), *In situ* tusk of *Elephas* sp. within calcareous reddish silts at Yedurwadi, in a link–channel (chute) of the Krishna River (Kale *et al.,* 1986b). The tusk has been dated to ~81 ka by U/Th technique (Kale *et al.*, 1988); (B), *In situ* early Acheulian handaxe occurring within the heavily cemented sandy–pebbly gravel unit at Bori on the left bank of the Kukadi River (Kale *et al.*, 1986a)(Fig. 3B). U–series analyses gave an age of ~200 ka for the gravel cement (Atkinson *et al*., 1990); (C), The ~75 ka Toba volcanic ash or YTT (~15 cm thick) overlain by yellowish brown sandy–silty unit and underlain by dark brown clayey unit seen in an excavated trench at Morgaon on the left bank of the Karha River. The dark clays represent pool deposits and the overlying sandy–silts are overbank deposits.

calibrated radiocarbon dates from the upper Godavari and Krishna basins shows distinct periods of alluviation during Holocene at ~12.6–10.5, ~9–7 and ~5–3.7 cal ka BP (Fig. 7). Although the bulk of the inset deposits belong to mid to late Holocene, some of the tributaries in the rainshadow zone provide evidence of a phase of alluviation between ~17 and ~8.5 cal ka BP (Mishra *et al*., 2003). This time interval roughly coincides with stronger summer monsoon (~10–6 ka; Sarkar *et al*., 2015), when all the main–stem Western Ghat rivers and their major tributaries were incising and excavating (Kale & Rajaguru, 1987; Rajaguru, *et al*., 1993).

The Colluvial deposits in the foothill zones

As expected, the colluvial deposits with large range in grain size are confined to the foothill zones, especially in the semi–arid parts of the valleys (Joshi & Kale, 1997). The deposits (up to 10 m thick) generally occupy footslopes and the gently inclined pediment slopes or narrow tributary valleys in the rainshadow zone. At a number of localities, the colluvial accumulations are deeply dissected by gullies, giving rise to badland–like topography (Fig. 5C). The infilling of colluvial and fluvio–colluvial sediments in narrow foothill valleys is observed in the Pravara Basin, particularly in the Chandanapuri Valley (Fig. 8).

The colluvia are unconsolidated to consolidated poorly sorted, admixed gravels, sands, silts and clays. Presence of crude to well–bedded (horizontal to cross–bedded) units and evidence of cut–and–fill activity indicate local reworking and re–deposition of the hillslope material by gullies and ephemeral streams. Calcium carbonate in diffused or nodular form is common in the colluvial deposits. As a result, some of the units are slightly to highly consolidated. Although Mesolithic flakes, cores and tools have been located on the surface of the deposits, the sedimentary sequences are generally devoid of artefacts and fossils. U/Th dates of carbonate nodules from two sites have yielded ages of 14 and 75 ka (Atkinson *et al*., 1990). These dates suggest that the accumulations have persisted in the foothill zones for thousands of years. Based on geomorphic and archaeological evidence, the colluvia are thought to have been initiated during periods of hillslope instability induced by a reduction in the vegetation cover during Late Pleistocene arid phases (Kale & Rajaguru, 1987; Joshi & Kale, 1997).

LATE QUATERNARY FLUVIAL ACTIVITY: BASED ON RADIOCARBON CHRONOLOGY

The regional–scale changes in the river activity during the late Quaternary could be determined by deriving the summed probability distribution plots of the calibrated radiocarbon dates. In a summed probability distribution plot, periods of alluviation and erosion are represented by clusters of calibrated ^{14}C dates and gaps between the clusters, respectively (Kale, 2007 and references therein). All the ^{14}C dates from the upper Godavari and Krishna basins were assembled and analyzed in OxCal 4.4 program. It should be mentioned here that some of the late Pleistocene and late Holocene ^{14}C dates are on materials buried below the channel bed sediments at dam sites, and thus do not necessarily represent period(s) of alluviation. Another point to be noted here is that the gaps between the clusters do not necessarily imply erosion or break in aggradation. The gaps could be simply due to absence of ^{14}C dates of this time interval (Kale, 2007 and references therein).

Fig. 7A shows the plot of ranked uncalibrated radiocarbon ages of 45 samples (older than 1 ka BP) from the alluvial units in different basins. Clustering of radiocarbon dates and distinct gaps in the alluviation over the past ~30–40 ka are apparent from the simple plot. The clusters and gaps are better reflected in the summed probability plot of calibrated dates (Fig. 7B). Three high–probability radiocarbon clusters within the Holocene (~12.6–10.5, ~9–7 and ~5–3.7 cal ka BP), and multiple, low–probability clusters during the Late Pleistocene period are easily recognizable.

Proxy data from the Lonar Lake reveal that while wetter conditions prevailed during the first half of the Holocene (~10–6 ka cal BP), severe arid conditions occurred between ~4.8 and 4.0 cal ka BP (Sarkar *et al*., 2015). U/Th dates of calc–tufa deposits (Fig. 2A) from the semi–arid parts also indicate significantly higher monsoon rainfall between 10 and 6 ka in the present rainshadow zone (Pawar *et al*., 1988; Atkinson *et al*., 1990). Even a cursory glance at the probability plot will reveal that ^{14}C clusters occur during both types of climatic phases (Fig. 7B). Further, during severe aridity (for example close to the LGM peak and between ~4.8 and 4.0 cal ka BP) one would expect the drainage systems to become almost defunct and incapable of any activity (even aggradation), particularly in the rainshadow zone. Apparently, there is no robust evidence of such a phase of complete fluvial inactivity either from the probability plot or from other types of archives in the study area or elsewhere.

Nevertheless, the probability–based analysis provides sufficient indications that the response of fluvial systems, even in an area of uniform lithology, is much more complex than the simple, but widely accepted pattern of aggradation during colder and/or drier phases and incision during warmer–wetter stages (Kale, 2007 and references therein). It will become evident from the discussion in the following section that apart from regional climate, several other geo–environmental factors determine the fluvial activity and river responses.

OVERVIEW AND DISCUSSION

From the description of the spatio–temporal characteristics as well as the types and ages of the Quaternary surficial deposits in the upper Godavari and Krishna basins, it is apparent that the sediments in the valleys have long residence time. It is also evident that the fluvial sediments occurring in the valleys did not accumulate during a single region–wide aggradational phase, but were deposited during different time intervals. Apart from climate (monsoon strength), non–climatic factors may have been responsible for the inter–or intra–basin differences in the fluvial responses and activity in this area of uniform lithology. Further, in spite of good amount of geochronological and archaeological data, the major Quaternary aggradation and degradation events are not yet chronometrically well constrained. It is also apparent from the review that there are still a number of facts about aggradation and degradation that have not been yet adequately understood and explained.

Nevertheless, two noteworthy facts emerge from the information presented in the preceding sections that need some more discussion and explanation–(a) infilled valleys and basins with unusually thick accumulations of sediments in the headwaters of the Pravara and Kukadi basins, and (b) out–of–phase deposition in some eastern tributaries of the Godavari and Bhima rivers within the Early Holocene. Here an attempt is made to understand the probable reasons for these two striking anomalies.

The infilled basins and valleys *vis–à–vis* bedrock gorges

Geomorphic investigations in the valleys during the last 5–6 decades by many workers from the Deccan College, Pune have revealed that the thickness and the lateral extent of the alluvial sediments is remarkably high in the Pravara Basin (a southern tributary of Godavari; Fig. 1) and its two northern tributaries, namely Adula and Mahalungi, (Fig. 8). The wide Adula–Mahalungi–Pravara infilled basin (Fig. 3A), between Akola and Sangamner (Fig. 8), in the upper Pravara Basin has been reported and investigated by earlier workers

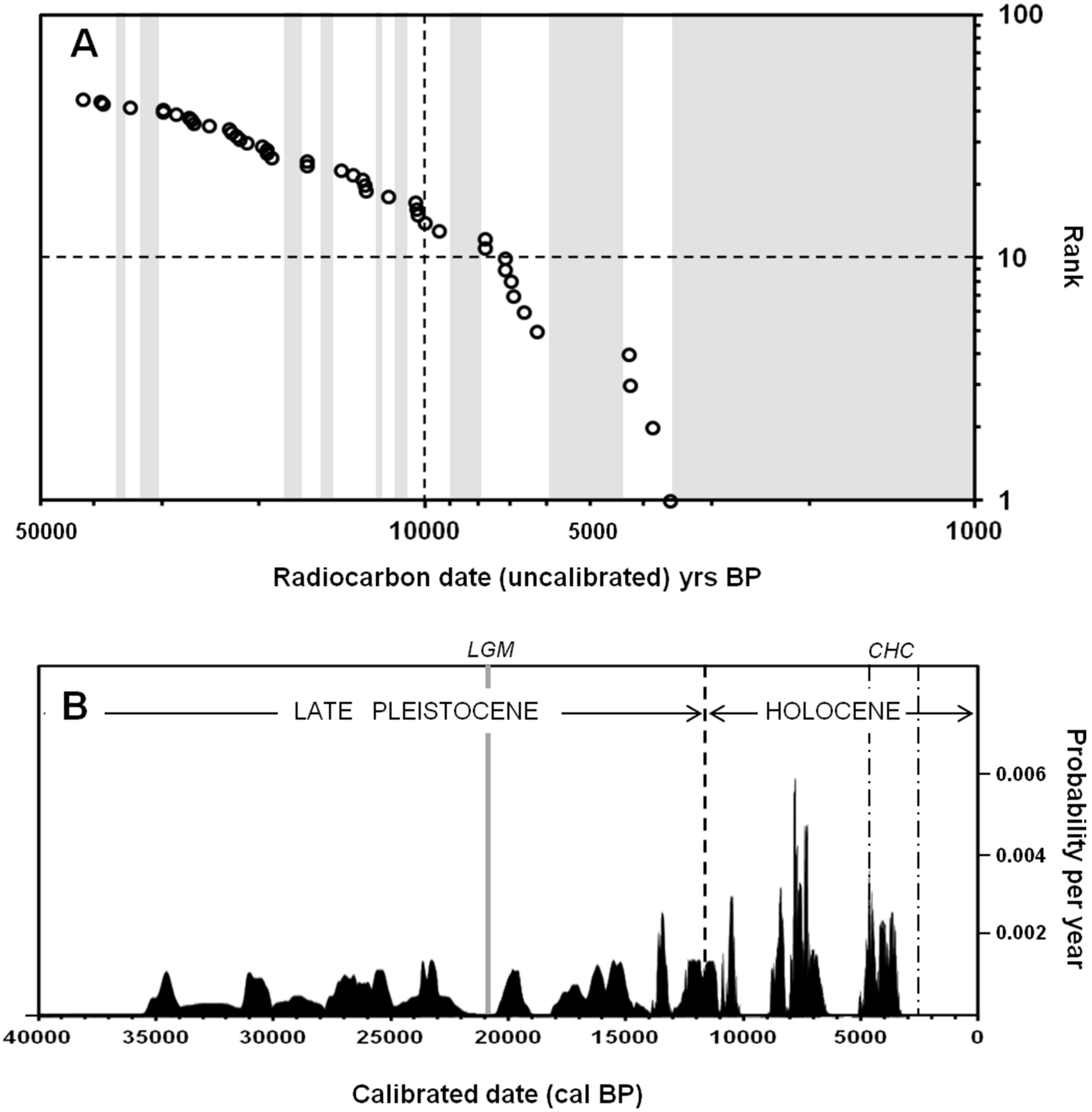

Fig. 7—(A), Plot of the ranked uncalibrated radiocarbon dates (>1 ka BP). The shaded areas represent gaps in the uncalibrated radiocarbon dates. As the x–axis is on the logarithmic scale, the pre–10 ka BP gaps appear to be smaller than the late Holocene gaps. (B), Summed probability distribution plot derived using OxCal version 4.4 program for ^{14}C dates (> 1 cal ka BP). LGM = Last Glacial Maximum (~21 ka); CHC = agriculture–based Chalcolithic Cultures (~2000–600 BCE) in western India. Source of basic data: Corvinus *et al*., 1973; Rajaguru & Kale 1985; Kale & Rajaguru, 1987: Mishra *et al*., 2003 and other sources.

(Rajaguru, 1969; Gupte & Rajaguru, 1971; Corvinus *et al*., 1973). The infilled Adula–Mahalungi–Pravara basin covers an area of > 250 km^2. Two other equally noteworthy infilled bedrock valleys were subsequently identified–one on the Kas River, downstream of the Bota Gorge and second one on the Mandvi River in the headwaters of the Kukadi River (Fig. 8).

An important point to note here is that these infilled valleys and basins are located immediately downstream of meandering bedrock gorges (entrenched meanders) with knickpoints at the gorge–head (Fig. 8). For instance, upstream of Akola, the Pravara River flows through a nearly 20 km long, lineament–controlled, sinuous and deep (~60 m) rocky gorge

(Fig. 8). A 50–m waterfall (the Randha Fall) is located at the head of the Pravara Gorge. A 45–m waterfall is also present on its northern tributary, the Adula River. Similarly, the infilled valleys of Kas and Mandvi occur downstream of sinuous bedrock gorges, with knickpoints (Fig. 8). Alluvial deposits are found resting against the vertical walls of the lower gorges (Rajaguru, 1969; Gupte & Rajaguru, 1971) indicating that the gorges were also partially filled by sediments produced upstream. Presently, the sediments in the infilled valleys and basins are undergoing intense gully erosion and denote sediment supply–limited conditions. The badland–like terrain (Fig. 3A) suggests that sediment production via intense bedrock erosion in the gorge sections has almost ceased, and the gorge extension by upstream propagation of knickpoints is no longer active. This headwater area in the Pravara and Kukadi basins, roughly located between two major peaks, namely the Kalsubai peak (1646 m ASL) in the north and the Harishchandragad peak (1422 m ASL) to the south, is henceforth referred as the Kalsubai–Harishchandragad Block or KH Block in brief (Fig. 8).

The association between sinuous bedrock gorges upstream and infilled valleys/basins downstream clearly indicates that the sediments have been derived by the headward recession of knickpoints and vertical erosion of the bedrock gorges. Earlier workers have invariably attributed these anomalies to tectonic movements in the area (Gupte & Rajaguru, 1971; Corvinus *et al.*, 1973; Rajaguru & Kale, 1985). Tectonically steepened gradient of the rivers may explain the radical incision and knickpoint retreat in meandering bedrock rivers, rather than a simple, direct hydro–climatic explanation. It is now a well recognized fact that a fall in the erosional base-level (due to rock uplift or lowering of sea level) has a more dramatic effect on the channel gradient, stream power and fluvial activity than the base-level rise (Ethridge *et al*., 2005). Flume experiments have shown that rapid incision induced by a fall in the base-level concentrates stream power in a narrow, deep valley that extends rapidly up valley (Koss *et al*., 1994; Ethridge *et al*., 2005). As the area under review is a thousand km inland, the influence of sea level fluctuations on the gradient could be completely ignored. Channel profile adjustments due to rock uplift is the only alternative and plausible explanation. Apart from incised bedrock meanders and knickpoints, other geomorphic evidence such as the presence of the highest peak (Kalsubai, 1646 m ASL) in the Deccan Traps as well as the deepest embayment in the Western Ghat Escarpment (Fig. 8) supports the hypothesis of local or block uplift in this part of the Deccan Traps (Kale & Shejwalkar, 2008). However, besides prominent lineaments, no other geological or geophysical evidence of tectonic uplift or deformation is known from the KH Block. Multiple, prominent ~N–S oriented lineaments are clearly visible on the satellite images.

Other related issues deal with the role of monsoon climate and the timescale of gorge formation. It could be argued that radical erosion and gorge development in bedrock was initiated or dominantly occurred under wetter monsoon phases (MIS 3 or MIS 5e, for example), characterized by increased magnitude and/or frequency of geomorphically effective floods. However, it has been shown that extraordinary floods are not a prerequisite for major erosion events, and even moderate–magnitude floods are capable of intense erosion in resistant bedrock (Anton *et al*., 2015). Further, estimation of peak flood power for several Indian rivers reveals that large rivers with higher peak flood discharges (between 10^4 and 10^5 m^3s^{-1}) but low channel gradients have very low values of unit stream power (Kale, 2003) and thus, are incapable of bedrock erosion and/or coarse sediment transport. Without a significant increase in the channel gradient (and flow depth), intense erosion in bedrock cannot be initiated and sustained. This is because the boundary shear stress ($\tau = \gamma RS$), a measure of flood power, is directly proportional to the product of channel slope (S) and hydraulic radius (R) (Kale, 2003 and references therein).

Another fact to be noted here is that as the anomalous geomorphic features (entrenched meanders, knickpoints and infilled basins/valleys) are confined mainly to the KH Block, the regional monsoon climate does not appear to be the sole or dominating controlling factor. If climate would have been the main forcing factor, such gorges and/or infilled valleys should have been observed in other basins of the Deccan Traps region as well. Furthermore, the role of tectonics seems very likely because within the Indian Peninsula some of the thickest alluvial fills are observed along the Narmada, Tapi, Mahi and Sabarmati rivers, which occupy ancient structural depressions (Cambay Graben and SONATA rift zone) with a long history of tectonic and seismic activity (Chamyal *et al*., 2003; Juyal *et al*., 2006; Copley *et al*., 2014 and references therein). Any climatic forcing on gorge incision and formation in the study area is, thus, considered less likely. It is therefore, reasonable to state that the unusually thick alluvial deposits occurring immediately downstream of the meandering bedrock gorges in the KH Block are not directly linked to known major Quaternary climatic phases, but to tectonically induced episodes of bedrock erosion. Of course, it is very likely that some of the incision episodes may have coincided with known major climatic events.

In the absence of exposure ages of the rocks exposed on the gorge walls and at the knickpoints, estimating the rates of bedrock erosion and reconstructing the erosional history of the Pravara, Kas and Mandvi bedrock gorges unambiguously remains a difficult proposition. Approximate estimation of the volume eroded from the Pravara Gorge–considering the length (~20 km) and the average width (~200 m) and mean depth (~60 m) of the gorge–indicates that about 0.25×10^9 m^3 of rock mass was eroded to create the gorge. This is equivalent to 10 m thick deposits spread uniformly over an area of 25 km^2. The eroded material was deposited immediately downstream of the gorge in a wide, open Pravara–Adula–Mahalungi Basin (Fig. 8) due to elevated sediment supply, sudden loss

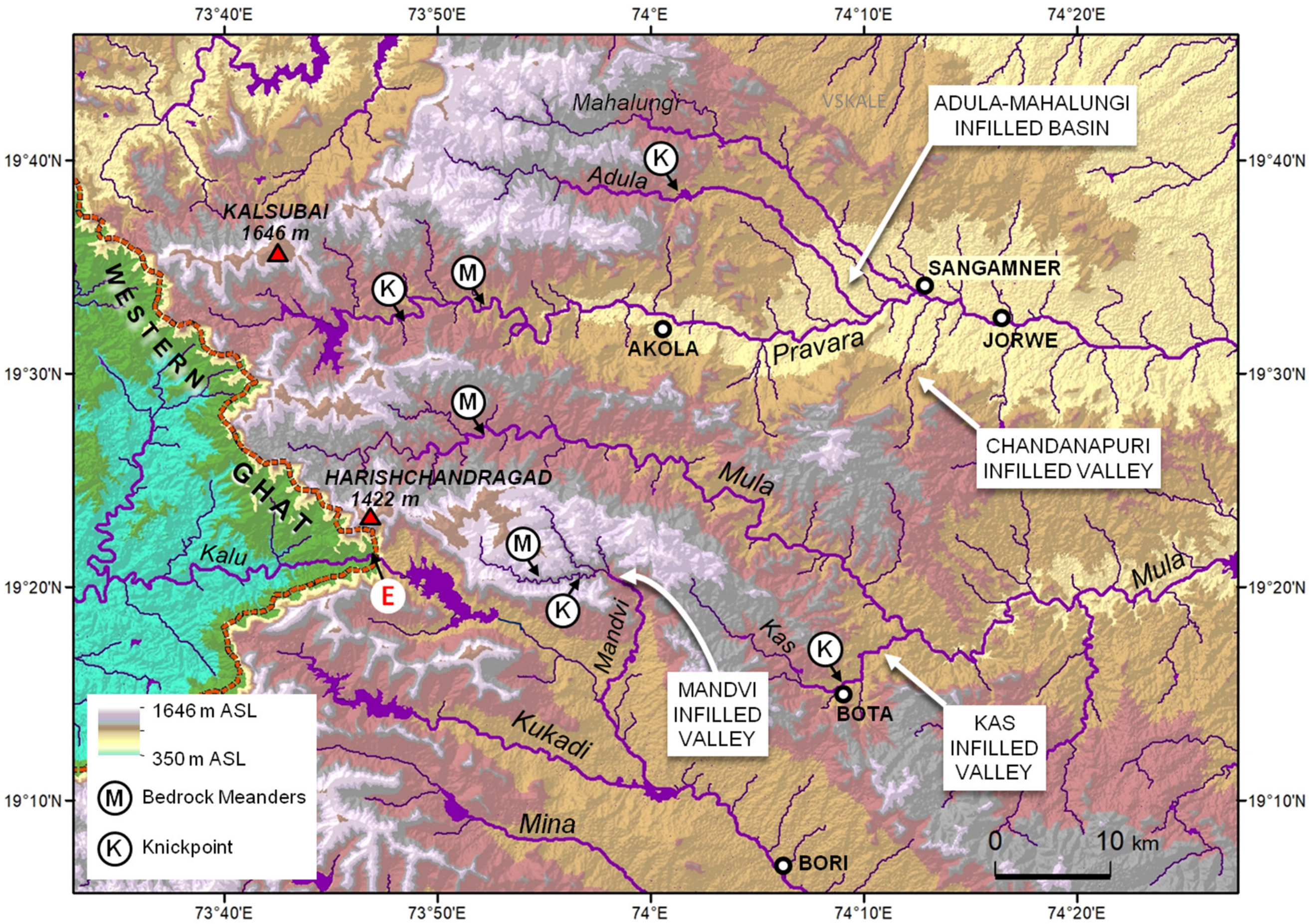

Fig. 8—Map showing the infilled valleys and basins in the Kalsubai–Harishchandragad (KH) Block. The Mula River is the principal tributary of the Pravara River, with comparable length and drainage area. The map also shows the location of incised or entrenched meanders (M) and knickpoints (K) in the area. Note the deepest embayment in the Western Ghat Escarpment at Malshej Ghat (E) formed by rapid headward erosion by the west–flowing Kalu River. There is evidence of a river capture by the Kalu River in the Malshej Ghat.

in the stream power and transport–limited conditions. This is a typical alluvial fan setting. Such a large fan, with an axial length of ~23 km and dominated by coarse alluvium, is present downstream of the Dhadgaon Gorge on the Narmada River (Chamyal *et al*., 1997). Intense, prolonged erosion in the Dhadgaon Gorge was most likely induced by rift–related tectonic activity in the SONATA rift zone (Chamyal *et al*., 1997).

The occurrence of thick alluvial deposits all along the Pravara channel downstream up to its confluence with Godavari indicates that a sizable proportion of the gorge sediments was subsequently reworked and transported downvalley under favourable hydrological conditions. The deposition then propagated up valley (Koss *et al*., 1994) into the lower–order tributaries, such as in the Chandanapuri Valley (Fig. 8).

The approximate minimum time required to erode the ~20 km long Pravara Gorge could be roughly estimated by considering the average rate of siltation in the existing reservoirs created by dams in Maharashtra. Analysis of the hydrographic survey data, available for nearly 40 dams within Maharashtra (CWC, 2020), reveals that the average sedimentation rate is approximately 1.27 x 10^3 m^3/km^2/yr. Needless to say, the current soil erosion rates are significantly elevated because of increased anthropogenic activities in the catchments. The Lonar Lake record also shows a dramatic increase in the sedimentation rate (2–6 mm/yr) in the modern period than during the greater part of the Holocene (Prasad *et al.*, 2014). Thus, calculations using three parameters–(i) the average sedimentation rate in the reservoirs, (ii) the present approximate area of the Pravara Gorge, and (iii) the estimated volume of the rock eroded from the gorge and deposited downstream–indicate that it would have taken at least 50,000 years for the river to carve this narrow gorge at the current rate and under similar hydro–climatic conditions. As tectonically–induced bedrock erosion is quasi–continuous and episodic (Anton *et al*., 2015) and since the hydro–climatic conditions have fluctuated between wet and dry phases, the rough estimate simply indicates that the Pravara Gorge is not very young and the sediments stored in the infilled basins and valleys could be much older than the last glacial, and perhaps even beyond the range of U/Th dating. This may be plausible because the cemented fluvial gravel beds, containing early Acheulian artefacts, at Nevasa on the same river have yielded a U/Th age of >350 ka (Atkinson *et al.*, 1990). The aggradation perhaps continued until the terminal phase of Pleistocene, as indicated by radiocarbon ages of shells (Mishra *et al.*, 2003) and U/Th age of cement from the top unit (Atkinson *et al.*, 1990).

It is pertinent to mention here that the occurrence of a palaeo–channel of the Kukadi River, completely defined by the 75–ka Youngest Toba Tuff (YTT), at the level of the modern channel bed near Bori (Kale *et al*., 2004) and exposed palaeo–banks of the Karha River at Morgaon as well as the presence of the implementiferous–cum–fossiliferous channel/point bar deposits (>10^5 yrs BP) close to the modern channel bed at other places indicate that the Traps region, in general, is tectonically very stable. This observation is further supported by the DEM–based analyses of various well–established geomorphic indices of activity tectonics (Kale & Shejwalkar, 2008). Although knickpoints and tens of meter long inner channels are present on few other rivers in the study area, such as at Nighoj on Kukadi River and at Shelarwadi on Indrayani River, comparable alluvium filled basins or valleys downstream are conspicuously absent. Another point to be noted in this regard is that the Western Ghat rivers occupy unusually wide valleys right from the source. A vast period of tectonic stability is, therefore, indicated by the landscape over the Maharashtra Plateau (Kale & Shejwalkar, 2008). It is only in the Kalsubai–Harishchandragad (KH) Block, there is a compelling evidence of tectonically induced fluvial activity and sedimentation (Kale & Shejwalkar, 2008).

Out–of–phase aggradation vis–à–vis change in the isohyetal pattern

A few radiocarbon dates from two tributaries of the Godavari and Bhima rivers, namely Sindhphana and Vel, respectively (Fig. 1) indicate that the aggradation was the dominant fluvial activity in these streams during Early Holocene humid phase (Mishra *et al.*, 2003). On the regional scale, all the available palaeoclimatic data show that the monsoon during Early Holocene was stronger and the main–stem rivers responded to the increase in discharge by excavation and incision (Kale, 2007). The dated shells from the Vel River (Fig. 1) are associated with gravel–dominated units close to the confluence with the Bhima River (Mishra *et al.*, 2003). As the gravel is locally derived from an older gravel bed, and as the overlying sandy–silty unit is undated, no firm conclusion can be drawn regarding alluviation on this river during Early Holocene. Furthermore, a radiocarbon date from the middle Nandi River, a small tributary of the Bhima River located further east in the core dry zone, suggests deposition during mid–Holocene (Kale & Rajaguru, 1987) and not within the Early Holocene.

The Sindhphana River, a tributary of the Godavari River, is a non–Western Ghat river, with its source and catchment entirely to the east of the Core Dry Zone (CDZ) delineated by <700 mm annual rainfall (Fig. 1). Radiocarbon dates from the top and bottom of a terrace suggest that the Sindhphana River was aggrading between ~17 and ~8.5 cal ka BP (Mishra *et al*., 2003). This out–of–phase response is interesting and needs at least a tentative explanation. The focus of the following discussion is on such eastern tributaries of Godavari, Bhima and Krishna, which have their sources within or to the east of the CDZ. In the absence of radiocarbon dates from other such eastern tributaries, it is assumed that these tributaries may have also responded in the similar fashion during the Early Holocene.

Aggradational phases generally appear coincident with drier phases (Kale & Rajaguru, 1987; Kale *et al*., 2004; Williams *et al*., 2006). Logically therefore, this implies that during Early Holocene, drier conditions prevailed over the catchments of the eastern tributaries. Although Gill *et al.* (2017), on the basis of Pacific SST proxy records and modelling, have inferred that the summer monsoon rainfall on the eastern side of the Western Ghat (rainshadow zone) was ~10–30% less than present day, the reconstruction is not supported by proxy data from the area. U/Th ages of thick valley–side calc–tufas (with fossil leaves and/or impressions) from the present day semi–arid zone (Figs 1, 2A) suggest significantly higher monsoon rainfall and elevated groundwater levels between ~10 and 6 ka over the water–divides and interfluves of the Godavari and Krishna basins (Pawar *et al*., 1988; Atkinson *et al*., 1990). Today, the calc–tufa deposition has ceased at all but one site. Further, palaeoclimate proxy data from the Lonar Crater Lake, located further east (Fig. 1), provide evidence of significantly wetter monsoon than the present between ~10 and 6 cal ka BP (Prasad *et. al*., 2014; Sarkar *et. al*., 2015). The Sindhphana Basin is situated between the Lonar Lake and the roughly north–south orientated belt of dated calc–tufa sites (Fig. 9). In view of this, the out–of–phase response of this tributary during terminal Pleistocene to Early Holocene transition period could only be explained in terms of a change in the existing isohyetal pattern and not in the regional monsoon regime *per se*. Change in the isohyetal (precipitation) pattern here encompasses not only a shift in the geographical position of the core dry zone (CDZ) but also changes in the spacing and overall shape of the isolines of rainfall amounts (700, 600 and 500 mm isohyets). It should be noted here that the rainshadow zone and the observed precipitation (isohyetal) pattern over the plateau is the result of asymmetric topography on the western margin of the Maharashtra Plateau due to the presence of the ~1–km high Western Ghat Escarpment (Fig. 1). The topography is a non–climatic factor.

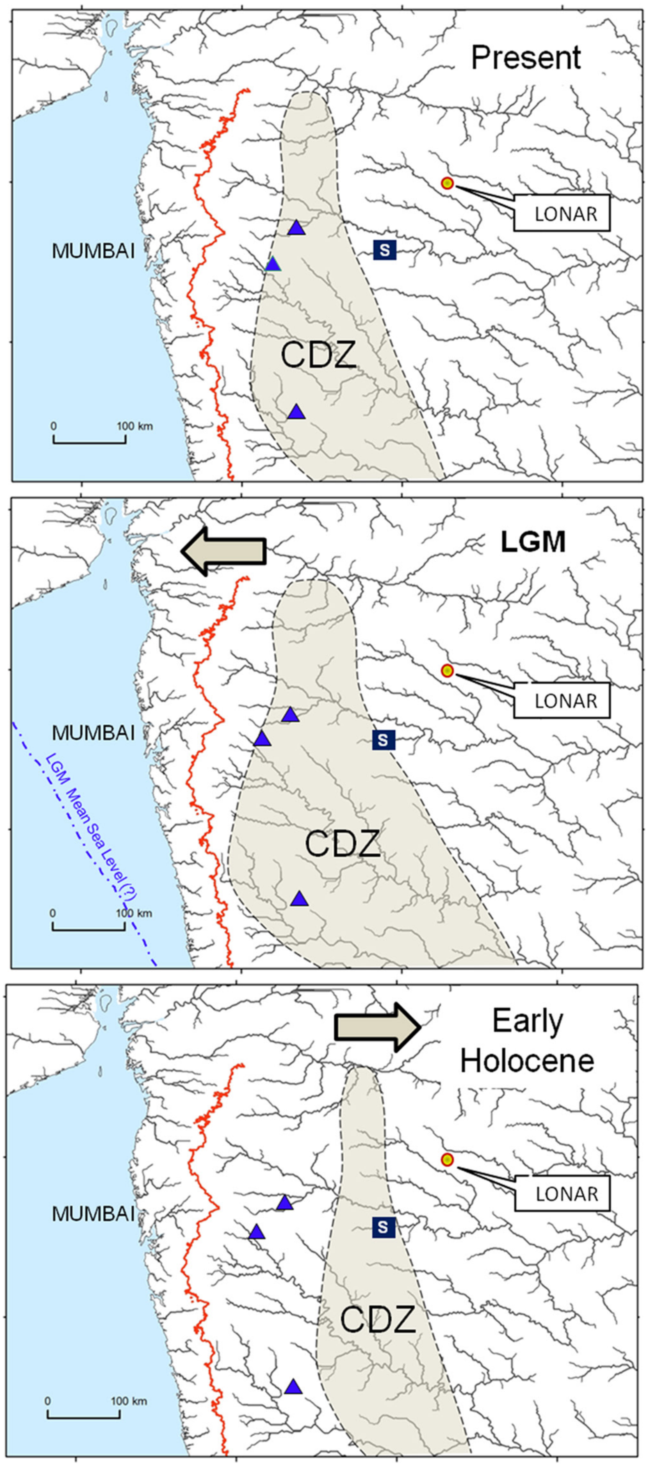

Fig. 9—Diagrammatic representation of the hypothesis of the shift in the Core Dry Zone (CDZ) during the LGM (middle panel) and the Holocene Climate Optimum (lower panel). The arrows show the direction of shift in the CDZ. The top panel shows the present area under CDZ defined by modern 700 mm rainfall isohyet (Fig. 1). The overall outline of the CDZ has been retained for the two other time periods. The Sindhphana River (S) with evidence of Early Holocene aggradation is also marked. The mean sea level during LGM roughly coincides with the 100 m isobath. Blue triangles represent dated calc–tufa sites.

Even a cursory glance at Fig. 1 will reveal that the dated calc–tufa sites are presently located within, but on the extreme western margin of the core dry zone (CDZ) demarcated by the 700 mm isohyet. During the Early Holocene wetter phase, the rainfall over the area was without doubt much higher than 700 mm. This implies that the tufa sites were no longer in the CDZ perhaps because the zone had shifted further eastward, that is, away from the Western Ghat. If this hypothesis of eastward shift in the CDZ is correct, the hypothesis could also explain, to some extent, why drier conditions prevailed over the eastern tributaries and why aggradation was the dominant fluvial activity in these basins around Early Holocene. Further, a similar shift in the CDZ in the opposite direction (westward) could also be postulated for the drier LGM phase, when aggradation was the dominant fluvial activity on the regional scale.

The proposed hypothesis of east–west shift in the CDZ since the LGM is presented diagrammatically in Fig. 9. It is proposed that during the Early Holocene, not only the CDZ shifted eastward but the geographical area of the CDZ also shrank. This is because of the evidence of higher precipitation from calc–tufas in the west and the proxy data from the Lonar Lake on the east. Lateral contraction would also lead to decrease in the spacing of isohyets and steepening of the precipitation gradient eastward. It is proposed that during Early Holocene, the narrow CDZ with rapid decline in rainfall amount towards east was located over the Sindhphana Basin leading to drier conditions and river aggradation.

Logically, reversal of this pattern could be visualized for the LGM. It appears that the widespread aggradation during LGM in the valleys was not only related to weakening of the southwest monsoon, but also to the westward shift and lateral expansion of the CDZ, and concomitant decline in the precipitation gradient towards the east. Westward shift in CDZ is likely, because this was the time interval when the mean sea level along the west coast was depressed by at least 100 m and the shoreline had receded by > 200 km (Fig. 9) leading to enhanced continentality and severe aridity over the Maharashtra Plateau (Kale & Rajaguru, 1987).

It therefore, appears that the out–of–phase behaviour of the Sindhphana River and possibly of all other eastern tributaries of the Godavari, Bhima and Krishna rivers was perhaps in response to a change in the isohyetal (precipitation) pattern and an eastward shift in the core dry zone (CDZ) during the Early Holocene. Needless to say, the proposed hypothesis requires further confirmation on the basis of high–resolution proxy data from multiple sites and a good number of radiometric dates of the alluvial deposits from other eastern tributaries, as well as application of palaeoclimate simulation models.

CONCLUSIONS

The main focus of this review was on some anomalous fluvial features as well as on the asynchronous late Quaternary fluvial response of some tributaries over the Maharashtra Plateau. Some of the noteworthy points emerging from the synthesis of multivariate data on the fluvial sedimentary records are summarized below:

1. The occurrence of 75–ka Toba volcanic ash (YTT) within the fluvial deposits, a few U/Th dates and nearly four dozen ^{14}C dates of the surficial deposits as well as the archaeological evidence from multiple sites suggest that the fluvial sediments on the valley floor of the rivers have long residence time, ranging from several tens to hundreds of millennia.
2. The incised bedrock channels of the Plateau rivers, presently buried beneath the alluvial cover in the alluvial reaches, are evidently older than the oldest fluvial sedimentary units. Since the oldest fluvial deposits are beyond the range of U/Th dating (>350 ka) and/or contain early Acheulian artefacts, it is reasonable to infer that the original channel incision into the valley floor may have been sometimes prior to the Middle Pleistocene.
3. The evidence of the last major and prolonged aggradational episode, roughly coinciding with the coldest phase of the last glacial cycle (around LGM), is comparatively better preserved in many valleys, in spite of the intense fluvial erosion and excavation initiated during Early Holocene in response to a significant increase in the monsoon intensity and concomitant rise in the river discharge and stream power. The channel inset deposits indicate a minor, low–magnitude phase of aggradation during mid to late Holocene. The Toba ash (YTT) unit and a U/Th date of colluvial deposits provides evidence of an aggradational phase around 75 ka or MIS 5/4 transition. The evidence of older aggradational phases is present only at some localities. Elsewhere the older alluvial formations may be still concealed under the Late Pleistocene alluvial cover. Since the aggradational events are not chronometrically well constrained, it is not possible to infer about the lags and leads in the river responses in the different river basins.
4. The probability–based analysis of ^{14}C dates as well as other geomorphic and archaeological evidence indicate that the response of fluvial systems, even in an area of uniform lithology, is much more complex than the simplified, but widely recognized pattern of aggradation during colder and/or drier phases (LGM, mid–Holocene) and degradation during warmer and wetter periods (Early and Late Holocene). The out–of–phase aggradation in the Sindhphana River and possibly in other eastern tributaries during Early Holocene may have been in response to a change in the isohyetal (precipitation) pattern and an eastward shift in the core dry zone (CDZ), rather than a shift in the regional monsoon regime.
5. The infilled basins and valleys downstream of the meandering bedrock gorges, within the Kalsubai–Harishchandragad (KH) Block, are anomalous fluvial features in this otherwise tectonically quiescent and basalt–dominated landscape. Rough calculations suggest that the gorge formation activity may have spread over a time span of, at least, several tens of thousands of years. The tectonically–induced incision of the gorges was primarily responsible for aggradation in the valleys downstream across several climatic phases. It is therefore reasonable to suggest that the aggradational event/events in these basins/valleys were not directly linked to known Quaternary climatic events.

This review illustrates the importance of field studies and field observations, as well as the advantages of combining field, geochronological, geo–archaeological and geographical data to understand the dynamics and complex response of river systems to different forcing factors. The main inference is that the relation between regional monsoon climate and river response (aggradation/incision) in this area of uniform lithology is a complex one, and the basin properties and non–climatic factors (tectonic movements, topography, etc.) also play an equally important role in determining the nature of fluvial activity and river responses. Several issues have emerged from the present review that remain less well understood or completely unanswered. Although there are now a good number of radiometric dates from the area, the major Quaternary incision and aggradation events are not chronometrically well constrained. It is hoped that this review will lead to resurrection of the field–based investigations of the fluvial sedimentary archives in these and other large rivers basins of the Indian Peninsula, before the limited records are destroyed completely by developmental activities and sand mining or permanently submerged by backwaters of numerous dams and weirs.

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