2007

Late Quaternary bedrock incision in the Narmada river at Dardi Falls

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Recommended Citation

Gupta, Avijit; Kale, Vishwas S.; Owen, Lewis A.; and Singhvi, A. K.: Late Quaternary bedrock incision in the Narmada river at Dardi Falls 2007.
https://ro.uow.edu.au/scipapers/4896

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Abstract

Fluvial incision in bedrock is common in many rivers of the Indian Peninsula. We investigated a site in the gorge of the Narmada river at Dardi Falls that displays geomorphic evidence of intense bedrock erosion. We report here a terrestrial cosmogenic radionuclide date from an eroded rock surface in Peninsular India. Terrestrial cosmogenic radionuclide dating of the rock surface adjacent to the inner gorge indicated that the minimum age of the gorge is 40 ka. We suggest that the present gorge has developed in two phases, separated by a period of large-scale aggradation that filled the gorge with alluvium. Gorge formation is most likely associated with tectonic activity in the SonNarmada- Tapi lineament zone. Erosion at this scale also requires large palaeodischarges with high unit stream power. This study illustrates the powers of combmmg newly developmg geomorphic, DEM and geochronological methods to elucidate the dynamics and nature of landscape evolution.

Keywords

GeoQUEST

Disciplines

Life Sciences | Physical Sciences and Mathematics | Social and Behavioral Sciences

Publication Details

Gupta, A., Kale, V. S., Owen, L. A. & Singhvi, A. K. (2007). Late Quaternary bedrock incision in the Narmada river at Dardi Falls. Current Science: a fortnightly journal of research, 93 (4), 564-567.

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Received 23 June 2006; revised accepted 11 May 2007

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Fluvial incision in bedrock is common in many rivers of the Indian Peninsula. We investigated a site in the gorge of the Narmada river at Dardi Falls that displays geomorphic evidence of intense bedrock erosion. We report here a terrestrial cosmogenic radionuclide date from an eroded rock surface in Peninsular India. Terrestrial cosmogenic radionuclide dating of the rock surface adjacent to the inner gorge indicated that the minimum age of the gorge is 40 ka. We suggest that the present gorge has developed in two phases, separated by a period of large-scale aggradation that filled the gorge with alluvium. Gorge formation is most likely associated with tectonic activity in the Son–Narmada–Tapi lineament zone. Erosion at this scale also requires large palaeodischarges with high unit stream power. This study illustrates the powers of combining newly developing geomorphic, DEM and geochronological methods to elucidate the dynamics and nature of landscape evolution.

Keywords: Bedrock erosion, cosmogenic radionuclide dating, DEM, gorge, Narmada.

THE erosion-dominant landscape of the Indian Peninsula is characterized by rivers downcutting into underlying bedrock. Many large rivers of Peninsular India flow through scablands, rock gorges and knickpoint-related waterfalls. However, the dates of such downcutting or rates of erosion are not known for any of the Peninsular rivers, with the exception of the pre-Holocene Tapi Gorge[1] and the historical evidence of rapid bedrock erosion by the Indrayani river[2]. We report here a ^{10}Be terrestrial cosmogenic radionuclide surface exposure age determination for the Narmada Gorge at Dardi Falls and discuss its significance in terms of regional geomorphology and bedrock erosion.

The 1300-km long Narmada river in Central India flows through three major bedrock gorges separated by alluvial basins. In the downstream direction these are the Marble Canyon near Jabalpur, Punasa Gorge near Khandwa, and Dhadgaon Gorge west of Badwani[3]. The present study is on the Punasa Gorge, where at Dardi (22°18′49″N and 76°21′11″E) the Narmada river (Figure 1) has eroded a >100 m deep and 1–7 km wide gorge with an inner canyon[4] (Figure 2). A ca. 10-m high waterfall occurs at the head of the inner canyon. Thick (>50 m) alluvial deposits of late Quaternary age overlie the bedrock on the right bank (Figure 2 *a*), whereas the left bank rises to a set of strath terraces with abraded and water-polished rock surfaces. The back of the terraces is covered by riverine alluvium and soil. Similar rock surfaces are likely to extend below the alluvium that occurs on the top of the right bank.

Quartzites of the Vindhyan Supergroup constitute the local bedrock. To the south, a major fault runs parallel to the Narmada river[5] (Figure 1 *c*). The river flows through the large tectonic feature of the Son–Narmada–Tapi (SONATA) lineament zone characterized by neotectonism, moderate seismicity[5–7], and several longitudinal fault-bound blocks with an episodic history of vertical and lateral movements[6]. The resulting river morphology demonstrates tectonic and structural control as illustrated in Figure 1 *c* and *d*, which is a digital elevation model (DEM) of the Dardi Falls area

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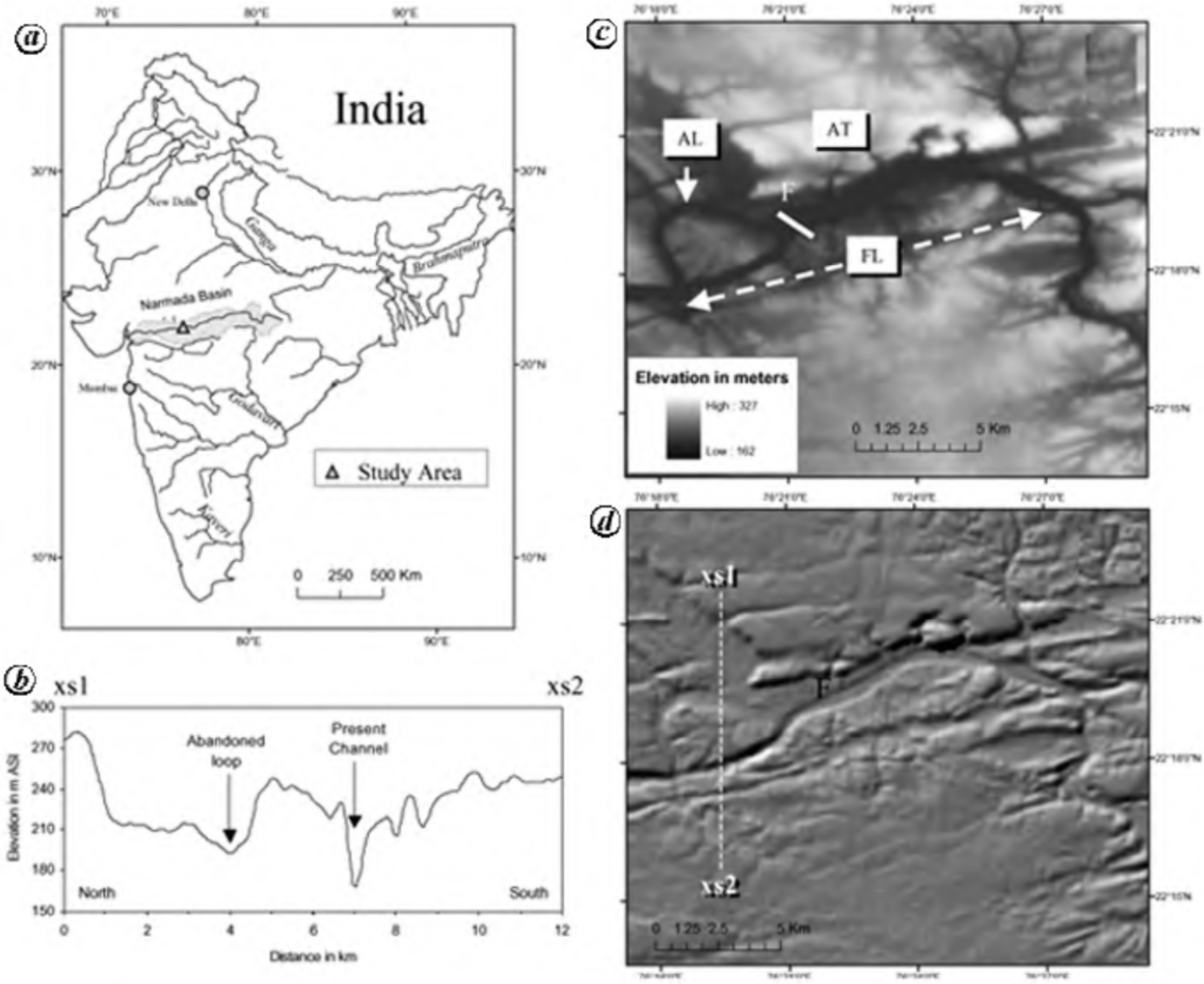

Figure 1. ***a***, Location of the study area. ***b***, Cross-profile across the abandoned loop and the modern channel of the Narmada river. ***c***, Digital elevation model. ***d***, Shaded relief map of the Dardi Falls area based on 90-m SRTM data. AL, Abandoned Loop; AT, Alluvial Terrace; F, Dardi Falls and FL, Major south fault. Location of the cross-profile is shown in ***d***.

Figure 2. ***a***, A view of the channel scabland area around Dardi Falls, the inner channel, and thick alluvial deposits on the right bank (view upstream). ***b***, Inner channel of the Narmada river.

that was generated using 90 m Shuttle Radar Topography Mission (SRTM) data. An abandoned channel loop is present immediately downstream of the falls (Figure 1 *c* and *d*). The elevation of the abandoned channel is about 25 m higher than that of the present bed of the Narmada (Figure 1 *b*). This association suggests that the abandonment of the river loop, creation of the waterfall, and the inner gorge eroded by upstream retreat of the falls are interlinked. DEM analysis reveals yet another abandoned channel bend in the rock, ca. 9 km downstream of the Dardi Falls.

Samples were collected and processed for ^{10}Be terrestrial cosmogenic radionuclide surface exposure dating from the flat rock terrace surfaces away from the vertical walls of the gorge. Two sites on the left bank were selected for sample collection, one on the flat rock surface close to the low water level of the inner gorge (DF1) and another on the shoulder of the inner gorge (DF3). At each site an *in situ* river-polished slab of quartzite, ca. 5 cm thick, was collected from the surface with hammer and chisel.

Following crushing and sieving, quartz was separated from the 250–500 μm size fraction using the method of Kohl and Nishiizumi[8]. The hydroxides were oxidized by ignition in quartz crucibles. BeO was then mixed with Nb metal prior to determination of the ^{10}Be/^{9}Be ratios by accelerator mass spectrometry at the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory. Isotope ratios were compared to ICN ^{10}Be standards (K. Nishiizumi, pers. commun.) using a ^{10}Be half-life of 1.5×10^6 years. The measured isotope ratios were converted to ^{10}Be concentrations in quartz using the total Be in the samples and the sample weights. Radionuclide concentrations were then converted to zero-erosion exposure ages using the scaling method of Stone[9], and were corrected for shielding and geomagnetic field variations as described by Farber *et al.*[10]. The sample DF1 could not be processed because quartz had too many impurities and requires resampling. However, DF3 provided reasonable concentrations. The age data for the ^{10}Be terrestrial cosmogenic date are shown in Table 1 and in the following paragraphs we discuss the possible implications of this age, so as to initiate more research on the timing of bedrock incision in the region.

Table 1. Terrestrial cosmogenic surface exposure date and age for sample DF3

Sample number	DF3
Latitude (°N)	22.31
Longitude (°E)	76.35
Altitude (m asl)	190
Thickness of sample (cm)	5
Quartz mass (g)	15.1965
^{9}Be mass (g)	0.9808
Conc. ^{9}Be (mg/g)	0.437
^{9}Be/^{10}Be (10^{-14})	6.130 ± 1.184
^{10}Be concentrates atoms/g SiO^2 (10^4)	11.40 ± 2.20
Shielding factor (Skyline 60° for 180° azimuth)	0.604347
Age not corrected for variations in palaeomagnetic field (ka)	47.5 ± 9.3
Age corrected for variations in palaeomagnetic field (ka)	39.7 ± 9.7

The exposure age of DF3 sample is at least 40 ka. This integrates in it the shielding effects of later burial and exhumation. During gorge formation, the river obviously had adequate power to sculpt large-scale fluvial forms in quartzite. The sample was from the rock terrace above the inner channel allowing us to infer that the inner gorge is younger than the determined date as it is cut into the sampled bedrock.

Remnants of the alluvial valley-fill deposits on the right bank of the Narmada river (Figure 2 *a*) indicate large-scale aggradation. No local radiometric dates of these alluvial deposits are available, but numerous radiocarbon dates from the central Narmada Basin[11,12] suggest that this alluvium is late Pleistocene in age, ca. 9–40 ka. This alluvium occurs along the Narmada and has been identified from stratigraphic evidence seen as the deposits of a mobile, meandering river that carried large quantities of sand[4]. At Dardi, this alluvium filled at least partially a valley in quartzitic sandstone that varies in width between 1 and 7 km and is 100 m deep. The alluvium was then eroded to expose the present Punasa Gorge.

At this stage, based on a single age, we were not able to reconstruct the timing or origin of the canyon-like inner channel of the Narmada. We can consider two possible scenarios (Figure 3). In the first scenario, the inner gorge could have been formed in the same downcutting event as the entire gorge. The gorge subsequently was filled by alluvium of the meandering palaeo-Narmada, and later exposed by the river in a second downcutting episode of post-Pleistocene age when most of the alluvial cover was removed. Alternatively, the Narmada downcut a wide valley at >40 ka ago, which was then filled by late Pleistocene alluvium followed by a Holocene excavation during which the river had enough power to remove the alluvium and excavate the inner gorge in the rock.

Tectonically steepened gradient of the river may explain part of the incision[13,14], but substantive amount of water needs to flow down the Narmada on a steepened gradient in order to downcut a wide and deep channel in quartzite. The standard stream power equation directly relates power with both slope and depth of a river. This implies a time of large floods. The present Narmada is capable of moving at least 2 m boulder slabs in large floods (Figure 2 *b*). Past floods must have been bigger, as active gorge formation does not happen at present.

Hypothesis 2 (Figure 3) suggests that the following events occurred in succession: (i) Principal gorge downcutting event probably during isotopic stage 3 (60–40 ka), a period more humid than the present, seen in several records in India[15–19]. (ii) Sediment production, transport and infill by a meandering palaeo-Narmada. (iii) Removal of sediment and downcutting of the inner gorge.

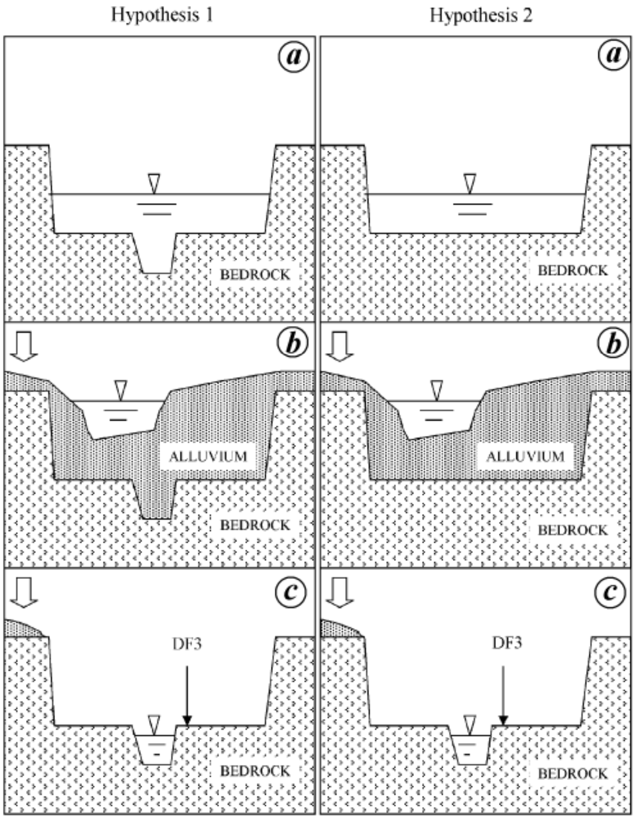

Figure 3. Diagrammatic sketch of two hypotheses of gorge formation at Dardi. See text for explanation. DF3, Dated sample.

The gorges of the Narmada apparently had complex history of tectonic movements and hydrological changes[20]. Near Jabalpur, like the loops at Punasa, the river has abandoned a meander to flow into a straight 3-km gorge downstream of a waterfall in marble[21]. It is possible that in the past the river flowed across bends and excavated tectonics-related lineations in rock to form gorges. Abandonment of previous loops and course-straightening could be due to both tectonic triggers and large floods. Excavation of the gorge required deep floods with high velocity along weakened rock. Once confined in a gorge, a river does not change its course. We need more dates to properly reconstruct the evolution of the Narmada gorges, but it seems likely that besides tectonic control, gorges are the result of periods of flood-prone river hydrology. The intermediate channel-filling alluvium was deposited by a meandering river[4] during a period of low floods and weak monsoon.

This is an initial study of the powers of combining newly developing geomorphic, DEM and geochronological techniques to help understand the dynamics and evolution of landscapes in the Indian Peninsula. It is hoped that this will stimulate similar future research in the region and regions outside India.

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Received 18 August 2006; revised accepted 12 April 2007

Landslide-dammed lakes in the Alaknanda Basin, Lesser Himalaya: Causes and implications

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We present observations on landslide-dammed lake deposits located in the vicinity of the E–W and NW–SE trending, south-dipping North Almora Thrust, in the Alaknanda Basin around Srinagar Garhwal. Preliminary observations suggest that activation of crumpled and unstable phyllite dominated slopes led to temporary damming of second and third order tributaries of the Alaknanda river. Sedimentary styles of the succession indicate deposition under the transient lacustrine environment, with seasonality. Luminescence chronology suggests that the lakes were formed after the Last Glacial Maximum (LGM) and probably continued till the Mid-Holocene. Lake formation is attributed to the reactivation of phyllite-dominated slopes following the reestablishment of the southwest monsoon after the LGM. Presence of contorted laminas is interpreted as episodic events of seismic activity. Finally the lakes disappeared due to large-scale slope reactivation around Mid-Holocene.

Keywords: Alaknanda Basin, landslide-dammed lakes, optical dating.

CLIMATE change at variable timescales exerts profound control on hill slope and fluvial transport processes and hence the landscape development[1,2]. However in the case of the Himalaya, additionally the role of tectonics remains equally important[3]. Climatic and rainfall variations are major forcing factors behind orogenic deformation in the Himalaya[4]. Therefore, it is important to understand the past climatic changes and associated sediment generation and deposition in different climato-tectonic domains of the Himalaya.

In the Alaknanda Basin evidences pertaining to the landslide damming of the rivers are limited to the Higher Himalayan ranges around the Main Central Thrust (MCT). The zone of the MCT is not only seismically active, but also coincides with the zone of intense southwest monsoon[5]. Away from the MCT towards the south, there is no reported evidence for river damming in the geological past. In view of this, the observations presented here are important.

Activity along the North Almora Thrust (NAT) is manifested by the presence of highly fractured phyllites that are precariously resting on moderate to steep slopes around Srinagar town. During the prolonged monsoon phases, increased pore-water pressure creates favourable conditions for deep-seated landslides, which are evidenced along National Highway no. 58. Here, the results of our preliminary investigations on four lake sequences coupled with geochemistry and Optically Stimulated Luminescence (OSL) chronology have been used to determine the timing of landslides and to explore the records of palaeoclimatic changes.

The area investigated lies in the Alaknanda Basin of Garhwal Lesser Himalaya (lat. 30°15′–30°18′32″N and long. 78°42′–78°50′E). After traversing a narrow valley, the Alaknanda river enters the wide open valley (~6 km long) around Srinagar town, where six levels of aggradational river terraces can be seen. Geomorphic features, viz. fossil river course, entrenched meanders, river gorges, raised aggradational and degradational terraces, and slip-off slopes indicate tectonic activity in the past[6]. Climatically the area bears subtropical climate with a mean annual rainfall between 1000 and 1500 mm, of which 80% occurs between mid June and mid September. During this period the Alaknanda river and its tributaries carry maximum water and suspended load. The vegetation is dominated by *Pinus roxhburghi* (1400–700 msl), *Dalbergia sissoo* and *Acacia* spp. (700 m) and its distribution is governed by the altitude and slope aspect.

The dominant lithology in the study area is low-grade upper Proterozoic phyllites and flaggy quartzites equivalent of Garhwal Synform[7] (Figure 1 *a*). The phyllites are

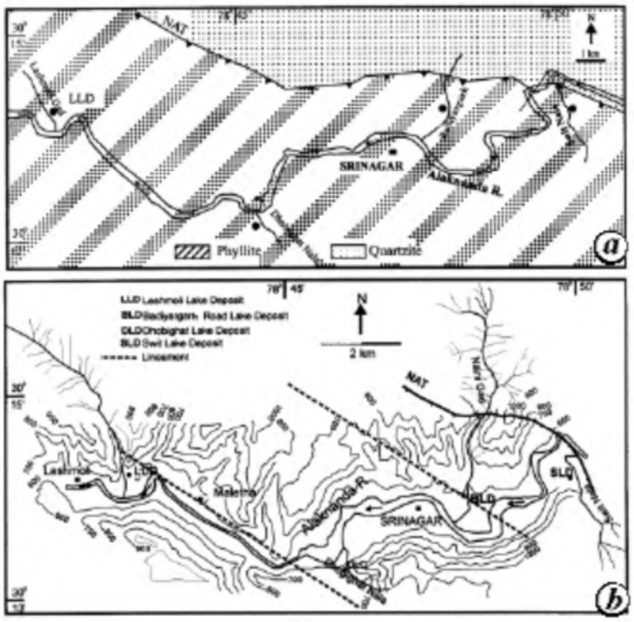

Figure 1. ***a***, Major lithology of the study area along with location of lake deposit sites. ***b***, Map showing the valley morphology, major lineaments and location of lake deposits.

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