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Genesis of the Dhuadhar Falls, Bhedaghat, Madhya Pradesh, India

Dhuadhar Falls in Bhedaghat near Jabalpur, one of the most sought after tourist destinations in Madhya Pradesh, India, attracts thousands of tourists throughout the year. The mighty River Narmada drops (Figure 1 *a*) 30 m down into a deep gorge of marble rocks, creating one of the most beautiful natural sites. Although there is a lot of literature available describing the surrounding rocks like marbles and schists of Precambrian Mahakoshal group, Lamheta Formation of the Cretaceous and the Deccan Traps[1–3], there is hardly any work explaining the genesis of the Falls itself. The River Narmada flows almost in a straight line along the Narmada–Son Lineament (NSL) marking the boundaries of some of the important basins of India[4]. No Gondwana rocks (between late Paleozoic to Mesozoic age) are found to the North of the NSL and no Vindhyan supergroup rocks (~1700–800 Ma) are found to the south of the NSL[5]. This suggests that the feature has acted as a depositional basin boundary since Precambrian and continued until the deposition of Gondwana. The Deccan Traps rest directly over the Vindhyan supergroup in the north without any Gondwana rocks in between, which records a long hiatus in geological time. The Gondwana lies over the Archean basement and no Vindhyan supergroup is found to the south of the NSL. Hence, this too documents a long time gap in the geological record but at a different time interval. The NSL can be best defined as a narrow Archean/Bijawar strip which is faulted (EW strike), and it marks the boundary of the Vindhyans to the south and Gondwana to its north[6,7].

Here we document a few geomorphological observations which could throw some light on the possible mechanism by which the Dhuadhar Falls came into existence. One of the most common explanations amongst geologists is the presence of 'cross faults'[5] across River Narmada, related to the NSL, creating 'step'-like flow path of the river ornamented with several falls. This could be true for many other falls like the Ghughra Falls (Figure 1 *b*; situated 3 km upstream from Bhedaghat near Lamheta Ghat), but Dhuadhar certainly compels us to come up with an alternate explanation.

Figure 1 *c* shows the channel morphology of River Narmada in and around Bhedaghat. Channel A represents the current flow path, whereas Channel B shows the abandoned palaeo flow path of the river. It can be postulated from Figure 1 *c* that the Narmada once flowed through Channel B, but has changed its course and now flows through Channel A. We wanted to examine why such a change would have occurred and it left us with a possible explanation for the genesis of the Falls. We would now like to draw the reader's attention to the lineaments mapped (red lines, Figure 2 *a*) on the marble rocks in that area. These linear features are nothing but deep gorges formed by the weathering and

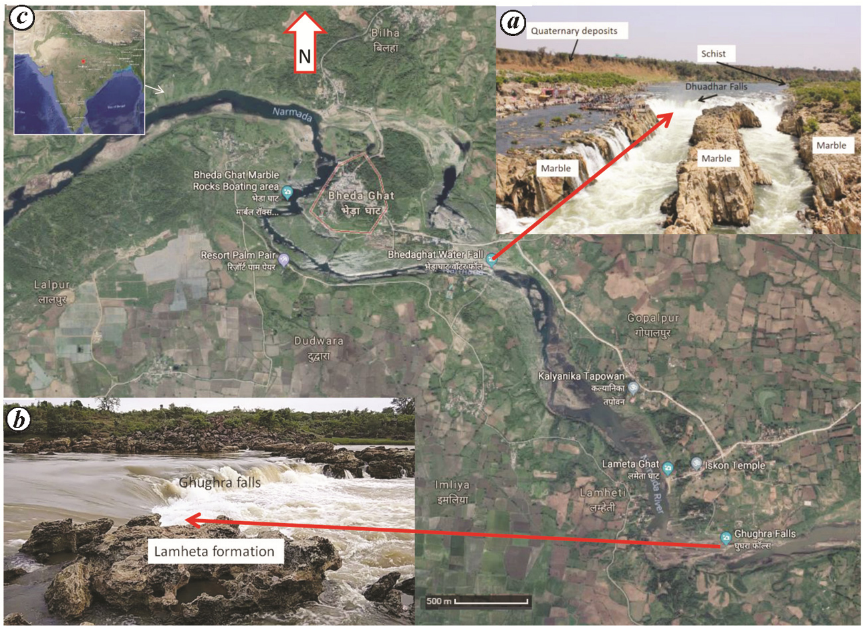

Figure 1. ***a***, Dhuadhar Falls in Bhedaghat near Jabalpur, Madhya Pradesh on River Narmada. ***b***, Ghughra Falls upstream of Dhuadhar falls near Lamheta Ghat. ***c***, Satellite image showing the relative positions of Dhuadhar and Ghughra Falls and flowpath of River Narmada near Bhedaghat (Courtesy: Google Maps).

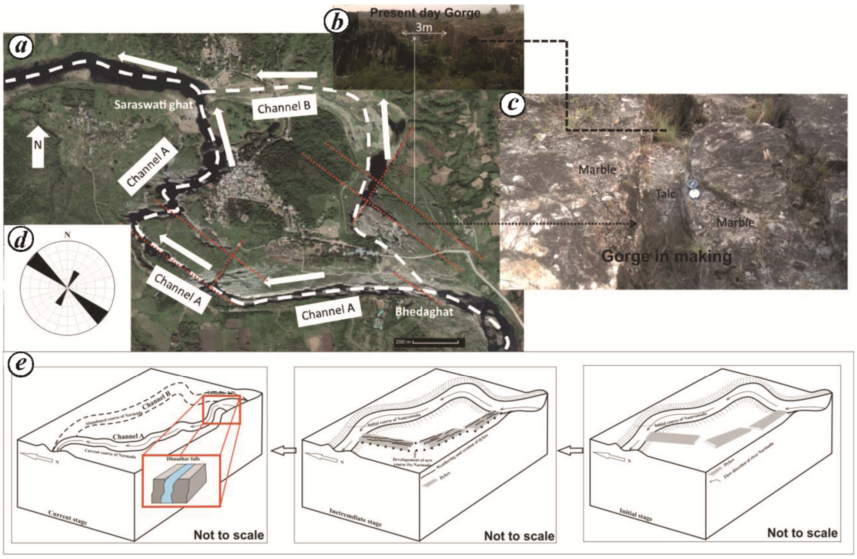

Figure 2. ***a***, Satellite image (Courtesy: Google Maps) showing the palaeo (Channel B) and current flowpath (Channel A) of River Narmada near Bhedaghat; red dotted lines represent gorges formed by weathering and erosion of Proterozoic dykes (Courtesy: Google Maps). ***b***, ***c***, Weathering of talcose materials that formed due to the metamorphism of older dykes and morphology of a gorge formed by such erosions or human excavation respectively. ***d***, Rose diagram showing distribution of orientation of such gorges. ***e***, Conceptual diagram explaining the erosion process of older dykes and corresponding change in the river flowpath. Initial stage: River Narmada flowing through older channel; intermediate stage: weathering and erosion of dykes; current stage: River Narmada flowing through the gorge created by the erosion of dykes, and hence changing its course now flowing through Channel A.

erosion of Proterozoic dykes. Figure 2 *b* and *c* shows examples where such a dyke is now being eroded forming a potential linear gorge with a sharp boundary with the country rocks both along and across its length. Mafic basaltic dykes have been metamorphosed to talcose rocks (schists) which are easy to erode and have a very high weathering potential. Talc can form by metamorphic transformation of mafic/ultramafic/dolomitic rocks in the presence of a fluid which is rich in silica and magnesium at a temperature ~750°C. Talc forms in the presence of a hydrothermal fluid at the expense of serpentine, which is a derivative of olivine and pyroxenes (components of mafic/ultramafic rocks) through metamorphic alteration. It could also form as a metamorphic product of impure dolomite. Lack of silica in the precursor rock or in the hydrothermal fluid will limit the growth of talc. It is often replaced by other minerals, and forms only when the pressure, temperature, precursor rock and enabling fluid composition are optimum. Otherwise, it might form chlorite, tremolite or phlogopite (Al, Ca or K in the precursor rock respectively). A basaltic dyke that has intruded pre-existing marble rocks forms a perfect precursor to such talcose rocks which are now present or have been eroded to form these linear gorges.

Figure 2 *d* shows trend distribution of such gorges. They are mostly oriented along NW–SE and NNE–SSW forming conjugate pairs. Most likely, they formed as shear joints in response to the palaeo stresses, where their acute bisector was oriented along the maximum horizontal stress (SH_{max}) azimuth ~ North South. Later, mafic lava used these fractures as conduits for emplacement forming dykes.

The current flow path (Channel A) of the Narmada from Bhedaghat (Figure 2 *a*), where the river deflects from its palaeo channel to Saraswati Ghat where the palaeo channel (Channel B) again meets the main course of the river, takes several kinks. The flow paths between two kinks are characterized by deep gorges and are often straight. Within the aforementioned interval of 2.5 km length, the river changes its flow direction from EW to ENE–WSW to NW–SE to ENE–WSW to NNW–SSE (Figure 2 *a*). It is clear that these local river paths are often parallel/sub-parallel to the gorges mentioned above.

The change in flow path of a river is mostly attributed to heavy flood events[8]. Rivers flowing from their sources to the sinks (ocean, lake or another river) do not necessarily take the shortest path[9]. It is often guided by the regional and local slope that develops with evolving topography. One of the primary factors that changes the local topography is preferential weathering. Often weathering and erosion of softer rocks form linear gullies allowing the river to flow through them.

We argue that the current flow path of River Narmada, between Bhedaghat and Saraswati Ghat is largely guided by the gorges formed due to erosion of Proterozoic dykes. The origin of the Dhuadhar Falls, is therefore, related to the preferential weathering of talcose material, which is the metamorphosed product of mafic Proterozoic dykes over the hard weathering-resistant marbles and schists. We summarize the hypothesis as follows: The Narmada once flowing gently in this region along its palaeo channel, guided by the basement rooted NSL, changes its path and falls into the deep gorges formed by weathering and erosion of metamorphosed dykes and forms the Dhuadhar Falls at its current location (Figure 2 *e*).

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Uranium mineralization in Kappatralla outlier of Gulcheru quartzite formation, Mesoproterozoic Cuddapah Supergroup, Kurnool district, Andhra Pradesh, India

In the eastern Dharwar craton, the crescent-shaped Cuddapah Basin forms a large intracratonic basin, comprising Meso–Neoproterozoic sedimentary sequence with volcanic rock components. The sedimentary environment of the Cuddapah Basin, in general, is comparable with peri-tidal complex with shallow marine carbonate shelf and beach environment. Systematic geological studies of the Cuddapah Basin are well documented[1,2]. The litho-units of the basin are mainly divided into older Cuddapah Supergroup and a younger Kurnool Group. The former is present throughout the basin, while the younger group is seen in its western and northeastern parts. The sediments of the basin overlie the Late Archaean–Lower Proterozoic granitoids intruded by basic and ultra-potassic dykes.

Investigations by the Atomic Minerals Directorate for Exploration and Research (AMD) resulted in identifying syngenetic strata-bound uranium mineralization at Tummalapalle, Andhra Pradesh (AP) and epigenetic unconformity proximal as well as fracture-controlled uranium deposits in Lambapur, Chitrial and Peddagattu areas of Telangana, India. The unconformity contact between the basement granites and overlying sediments of Cuddapah/Kurnool Groups is one of the potential targets for unconformity-type uranium mineralization along the northern and western margins of the arcuate Cuddapah Basin. Uranium mineralization has also been recorded in siltstone and quartzite of Gulcheru Formation associated with E–W fault near Gandi[3] and Tipparajupalle and Cheruvula Bodu areas of Cuddapah district[4] along the southern margin of Cuddapah Basin.

Here we focus on uranium mineralization in the outlier of the Gulcheru Formation near Kappatralla, Kurnool district, AP.

The Geological Survey of India[5] reported an isolated outlier of Gulcheru quartzite with an aerial extent of about 3.5 km^2 near Kappatralla village (15°34′35″N; 77°36′19″E, Survey of India toposheet no. 57 E/10), which is situated about 35 km west of Veldurthi, Kurnool district, India.

In the Kappatralla outlier, the Gulcheru quartzite rests as a cover rock above the basement crystalline rocks. The basement is composed of granite gneiss, granodiorite, diorite and intrusive granite equivalent of Closepet Granite. The intrusive granites are medium- to coarse-grained, grey biotite granite with several pegmatite and aplite veins intruded by NW–SE and E–W trending dolerite dykes (Figure 1). The NW–SE trending fractures in the granitoids are filled by chlorite, hematite and sericite due to hydrothermal alteration along fractures.

The unconformity contact between the basement granites and overlying Gulcheru quartzite approximately follows 540 m RL contour and the highest elevation of the outlier is 567 m. The thickness of Gulcheru sediment thus varies from 10 to 25 m. The Formation commences with lower pebbly feldspathic quartzite at the base which is successively overlain by ferruginous quartzite, grey sub-feldspathic quartzite, exhibiting current bedding and ripple marks with intercalation of carbonaceous, purple and greenish-grey shale, buff-brown quartzite and pebbly quartzite at the top with pebbles of quartz. Figure 2 shows the litho-facies diagram of Gulcheru quartzite in the study area. The strike of the formation is 45°–50°N with 4°–6° dip due SE. Uraniferous sub-feldspathic Gulcheru quartzite is light grey, composed of moderately sorted quartz grains with angular feldspar grains. They also contain bands, laminae and lenses of carbonaceous