

Space-based observation of a high-altitude red-coloured glacial lake in Ladakh, Northwest Himalaya, India

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The present study reports the existence of a unique and unusual feature of the Zaskar valley, Ladakh, India – a proglacial ‘red/brown-coloured lake’ observed from space-based remote sensing data. The lake has not changed in colour and size over the years. Here we report observations from 2004 onwards till recently. The local geology plays an important role, and iron-dominated lithology of the region interacts with snow and glacial meltwaters and subsequently deposits red/brown-coloured suspended silt in this proglacial lake. Spectral analysis of reflectance data from Sentinel-2 images in visible–infrared region of electromagnetic spectrum suggests that the colour of the lake is due to high concentration of suspended solids, having dominant reflectance at 660–700 nm and thus causing the red/brown colour of the water.

Keywords: Proglacial lake, remote sensing, space-based observations, suspended solids.

THE Zaskar valley, Ladakh, India lies between the Karakoram Range in the north and the Great Himalayan Range in the south, and offers surreal landscapes (such as glaciers, glacial lakes, saline lakes, permafrost features and dunes) and fascinating geology. Climatologically, the region (Zaskar) lies in the transitional zone of two most important atmospheric circulation systems, viz. the Indian summer monsoon and the mid-latitude westerly winds, and where the earth surface/geomorphic processes are known to sensitively respond to precipitation and temperature changes. Hence the region has preserved evidences of past climate variability that may help in ascertaining climate processes and their regional and global correlations¹⁻⁴. This arid part of the Indian Himalaya is least populated due to harsh and extreme climate, and scanty vegetation. A fair number of studies pertaining to the climate of the region⁵, change in glaciers⁶, glacial lakes⁷ and diverse landforms due to permafrost, glacial activity, etc.⁸ have been carried out in the region. However, owing to the extreme high-altitude environment of the region with lower oxygen levels, higher ultraviolet (UV) radiation and extreme cold weather, most of the remote locations in Ladakh remain unexplored and unknown.

The ongoing global warming has resulted in continued glacier melting and the formation and expansion of glacial lakes in the Himalayan region⁹⁻¹¹. One such glacial lake, which is ~30 km southwest of Lamayuru – ‘moon land of Ladakh’, Leh, shows a unique reddish/brownish colour. The glacial lake is located at 34°0.280’N and 76°43.295’E, at an altitude of ~5060 m amsl (Figure 1)^{12,13}. The distance of the lake from the nearest road and village Photoskar (~4200 m amsl) is ~11 km. This lake is dominantly fed by meltwater from its northeasterly-facing mother glacier. The morphometry analysis shows that the lake covers an area of ~0.19 km², perimeter of ~1.19 km, length of ~700 m and width of ~300 m. The orientation of the lake is northeast and slope between the mother glacier and the red lake is about 20°. The shape index reveals a near circular shape of the lake (shape index 0.75). Analysis of the time-series images of the red/brown lake (red lake henceforth) indicates that the size and colour of the lake have not changed over the years (Figure 2). The water body of the lake remains frozen during winter season spanning from November to April.

According to various reports available in the public domain, there are only 29 pink lakes in the world¹⁴. Lake Hillier in Western Australia is one of the famous pink lakes and the colouration is considered to be due to the algae *Dunaliella salina*, which grows well in salty environment only¹⁵. Recently, the water of Lonar Lake in Maharashtra, India has turned pink due to large presence of the salt-loving Haloarchaea microbes¹⁶. However, the pink colour of Dusty Rose Lake in British Columbia, Canada, which is a glacial lake, is due to its surrounding rocks and not due to algae¹⁷. Similarly, the Blood Falls of Taylor Glacier, Antarctica, contains a diverse microbial community that is metabolically active, and influences weathering and gives a reddish colour to the meltwater¹⁸⁻²⁰. Due to the discovery of such unique environments, the subglacial environments have become important for scientific research²¹⁻²³; however, such research is largely lacking in the Himalayan region.

The red lake identified in the Ladakh Himalaya is a high-altitude lake located at ~5060 m amsl, average surface temperature of which varies from ~-16°C during winter to ~6°C during summer. The study area is located on the transition of Zaskar Tethyan Zone which formed during the progress of India–Asia collision that has resulted in the closure of the Neo-Tethys Ocean at ~55 Ma (refs 13, 24–27) and Spontang ophiolite complex (SOC) which is an ophiolite klippe that overlies the volcano-sedimentary mélange^{25,27,28}. The meta-sedimentary rocks of the Zaskar Range contain ‘ferruginous formation’ rich in ironstone²⁴. The NE-facing glacier and catchment area feeding the red lake are located on these rock formations of Zaskar. Therefore, we propose that the persistent red and brown colour of the meltwater is likely due to the soluble iron complexes derived from weathering of

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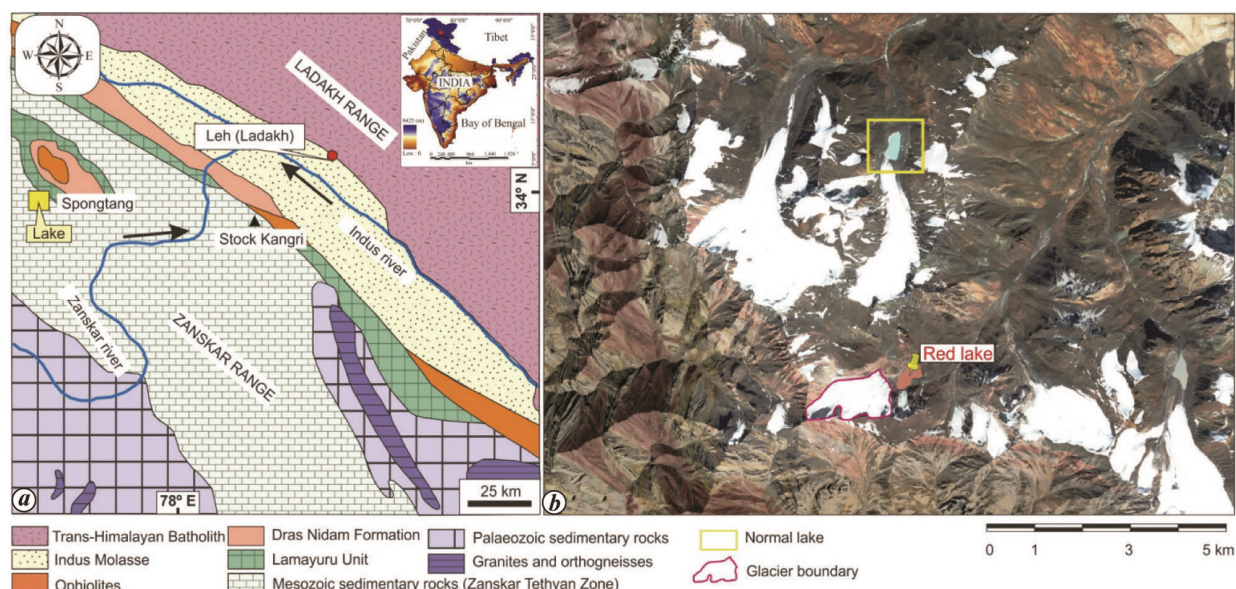


Figure 1. *a*, Geological map of the red lake area and its surroundings (modified after Thakur¹² and Schlup *et al.*¹³). Location of the lake is shown as a yellow square. *b*, Google Earth image dated 17 October 2017, showing the red lake and adjoining normal blue-coloured proglacial lake.

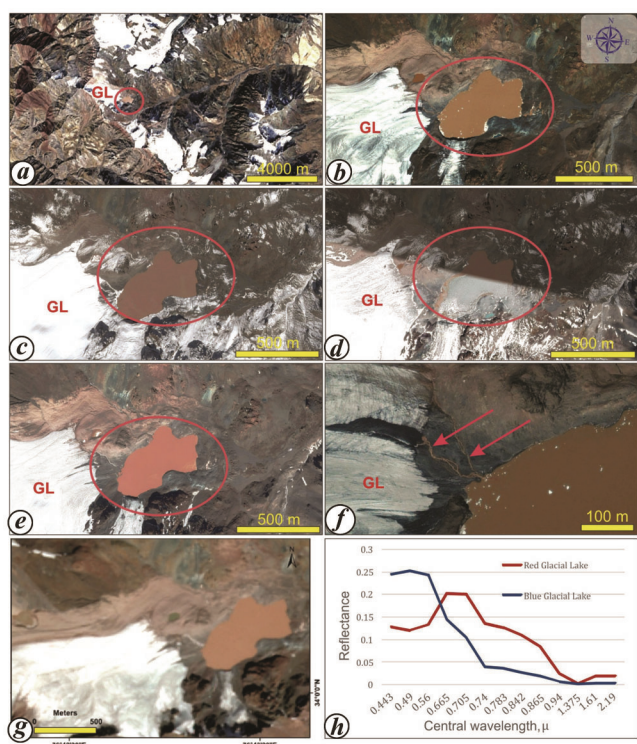


Figure 2. Time series images obtained from Google Earth Pro showing the mother glacier (GL) and the colouration of the red lake in *(a)* 2000; *(b)* 2004; *(c)* 2013; *(d)* 2014; *(e)* 2017; *(f)* Close-up of the 2004 images showing the colour (red arrow) of melt water; *(g)* Natural colour composite (bands 4, 3, 2) of Sentinel 2A dated 4 October 2020 showing the red lake; *(h)* Spectral response curves of the red glacial lake and the nearby blue glacial lake (shown in Figure 1 *b*) obtained from Sentinel 2A dated 30 August 2020.

iron-rich bedrock. Besides, the SOC comprises of mantle-peridotites (Iherzolites, harzburgites), dunites, gabbro, diorites and plagiogranites in form of numerous boulders

(peridotites), dykes (gabbroic), lenses (dunites) interbedded with volcanoclastic deposits²⁹. The characteristic mineralogy of these mafic and ultramafic rocks being dominated by olivine and pyroxenes makes them metastable at surficial conditions, especially in the presence of aqueous fluids. Dissolution of primary olivine and pyroxene is accompanied by precipitation of secondary phases in the form of clay minerals, carbonates and iron oxide and hydroxides. Therefore, the red coloration of the lake may be imparted by the formation of hematite and goethite as a result of near-surface aqueous weathering of iron-bearing mafic and ultramafic rocks. It has been reported that the glacier meltwater in the Himalayan regions is rich in chloride (Cl^-), bicarbonate (HCO_3^-) and sulphate (SO_4^{2-}) ions³⁰ which can form stable soluble complexes with Fe^{2+} at pH ranging between ~ 7.0 and 8.0 (ref. 31). The release of Fe^{2+} in the meltwater could have been enhanced by interaction of Cl^- -rich meltwater with frozen iron oxide-rich fluids in the sub aerial sections of the catchment area. Besides, microbially induced weathering of sub-glacial bedrock minerals could be another viable source of Fe^{2+} . However, differences in water residence times, water–rock ratios, refreezing at the water–ice interface, basal geologic conditions, and biological processes can produce different water chemistries³², and hence need further studies.

Due to the above described geochemistry, the lake is expected to have high concentration of suspended solids. A spectral analysis of the red glacial lake water compared to a typical blue glacial lake water (Figure 2 *h*) using Sentinel-2 images dated 15, 25 and 30 August 2020 revealed marked difference in the spectral response of water of the red lake. The peak reflectance of the spectrum of the red lake occur at 660–700 nm ($0.66\text{--}0.7\ \mu\text{m}$)

wavelength range, compared to the peak of the blue water lake at 0.49–0.55 μm . This marked difference gives the lake its unique red/brown colour.

The colour of this high-altitude glacial lake might be affected due to snow/ice meltwater interaction with local lithology. It will be worthwhile to study this phenomenon and geochemical processes by conducting extensive field campaigns during the next summer season in this region. Therefore, we propose a systematic study of this lake that will provide important insights in understanding the ecology of such sub-glacial environments along with the geochemistry and glacier dynamics in the Himalaya.

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ACKNOWLEDGEMENTS. P.P. thanks Dr Shovanlal Chattoraj and Supriya Sharma (Indian Institute of Remote Sensing, ISRO, Dehradun) for help and support. S.N.A. thanks the Director, Birbal Sahni Institute of Palaeosciences, Lucknow for encouragement and support.

Received and accepted 19 November 2020

doi: 10.18520/cs/v120/i2/429-431