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Prospects of Astrogeology and Astrobiology researches in India: Ladakh as an example

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ABSTRACT

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Ladakh sector of the Trans–Himalayan region in India shows a strong fidelity as an analogue of Mars. It is dry, cold arid desert, has abundant rocky ground with dust devils, loose rock blanketing the mountain slopes, segregated ground ice/permafrost, rock glaciers, sand dunes, drainage networks, catastrophic flooding sequences, making it geomorphologically similar as an early Mars analogue. Even for the geochemical fidelity in Ladakh volcanic rocks (basalt); serpentinites, saline lakes, active and fossil hydrothermal systems exist which can give a clue to the processes and chemistry of the Martian grounds. As far as exobiological fidelity is concerned we have permafrost (evidence of water in the past), increased UV and cosmic radiation flux, reduced atmospheric pressure, hot springs (some rich in boron). Hence, Ladakh environment, characters by freezing temperatures, limited precipitation, open water in rivers and lakes, comparatively low atmospheric pressure, thermal springs, and relatively high ultraviolet flux, is an analogue for the Noachian epoch on Mars. Ladakh is surely a treat for geographers, geologists and in recent years also for the astrogeologist's and astrobiologist's as well, with its lunar/martian landscapes; exposures of sedimentary, metamorphic and igneous rock types; glacial, fluvial lacustrine sediments and active climatic and tectonic processes. This article demonstrated the many opportunities for Mars analogue research, mentioning the sedimentary deposits of Ladakh with examples from the variety of sediment exposures along the Indus River and explores possibilities for the future astro work sites–be it the landforms carved from the glacial, fluvial, lacustrine and aeolian deposits to study the sedimentary processes, the hyper saline lakes, the permafrost and the hot springs to study the extremophiles or the million year emplacements of the rocks to study the geochemical constituents.

Key–words—Ladakh, Cold–arid desert, Mars analogue research, Astrobiology, Astrogeology.

INTRODUCTION

PLANETARY geological and geomorphological research can be understood and well interpreted only if the comparable processes on the surface of our planet are well studied and understood. Mars has cratered highland of moderate to high relief mostly in the Southern Hemisphere, as well as isolated knobs and massifs of rugged mountainous materials especially on crater rims. There are also extensive tracts of smooth and channelled plains (Baker, 1981) with surficial deposits of rounded pebbles and cobbles locally indurated into conglomerates (Grotzinger & Milliken, 2012). The largest former fluvial system is the 1,500 km–long outflow channel system of Reull Valles. Extensive subsurface ice deposits and evidence of mass movements, landslides, catastrophic floods, active fluvial action, and landforms are indicative of erosional and depositional eolian, glacial, and lacustrine processes (Baker, 1981; Grotzinger & Milliken, 2012). While the martian crust is predominantly basaltic (McSween *et al.*, 2009), remote sensing reveals the presence of occurrences of high silica rocks imply locally differentiated parent materials (Wray *et al.*, 2013; Bandfield *et al.*, 2004).

Terrestrial geologists and geomorphologists can make significant contributions to space exploration of the Moon or Mars because of their background and experience with analogous terrestrial forms, constituents, and processes. The Himalayan region, especially Ladakh, which we describe in this paper, holds a good prospect for the analogue studies with particular relevance to early (Noachian) Mars which was characterised by higher temperatures, water activity, pressures and atmospheric oxidation than at present.

THE TRANS–HIMALYAN AND LADAKHI CONTEXT

The Himalayan topography is characterized by horizontal compression of the lithosphere, topographic uplift, erosion and sedimentation ever since the collision of the Indian Plate with Eurasia. Due to the Hindukush–Karakoram–Pamir knot in the extreme northwestern side of the Himalayan mountain chain, thrusts along the 2500 km long east–west trending Himalaya, viz. Himalayan Frontal Fault, Main Boundary Thrust, Main Central Thrust, and Karakorum Fault as well as the Indus Suture Zone (ISZ) and Shyok Suture Zone (SSZ) (Fig. 1), make the entire area tectonically active. ISZ is recognized as the collisional boundary between the Indian and the Eurasian plates. The continental collision took place at ~55 Ma involving the rocks of active asian margin and passive Indian margin that was separated by once existing Neothethys Ocean (Brookfield and Andrew-Speed, 1984; Rowley, 1996). With the gradual subduction of the Indian Plate, the closure of Tethys sea took place followed by later stages of uplift, exhumation and unroofing (Dhital, 2015). As the continental collision proceeded, the suture belt thus evolved from shallow marine setting to fore arc basin to intermontane basin and tectono-stratigraphically divided into Zanskar Zone, Indus Suture Zone, Shyok Suture Zone and the Karakoram Zone from south to north (Fig. 1A, B).

The Trans–Himalaya constitute of high mountain ranges, wide valleys, narrow constricted gorges occupied by rivers: Indus, Shyok, Nubra, Tangtse, Hanley, Yapola, Markha, Tsarap–Lingti, Zanskar, etc; big lakes (Tsokar, Pangong Tso, Tso Morari); glacial valleys (with glaciers, ice patches, moraines, etc.) and several proglacial lakes occupying the crest of the Ladakh range (Phartiyal *et al.*, 2005, 2018) (Fig. 2). Apart from being tectonically dynamic, the Himalaya also determines the physiographic distinctions of the Indian landmass, where it acts as a barrier for the northward moving moisture laden monsoon winds during the summer season (Summer Monsoon) and also restricts the entry of icy winds (Westerly) coming from the north during winter season.

Being situated in the rain–shadow zone and with altitudes more than 3000 m above sea level, Ladakh is a high altitude cold desert. The dominant source of precipitation in Ladakh is westerly disturbances during winter months, which produce precipitation as snow. A secondary source of precipitation is the summer monsoon invasion from the south. The spatial extent and strength of these two systems is governed by the positioning of the Inter Tropical Convergence Zone. The Himalaya also modulates the Earth's surface temperature by weathering and erosional processes whereby it consumes a significant component of the global carbon dioxide.

The Indus River, in Ladakh follows the Indus Suture Zone which is one of the spectacular examples of active orogen building and climatic forcings. The region reveals interplay of tectonics and climate in its multiple levels of fluvial terraces, colluvial and alluvial deposits, palaeolakes, slope deposits, landslide driven damming, etc. and hence an apt Mars analogue site.

Glacial Records

This low to mid–latitude cold region above the treeline is one of the harshest ecosystems on the Earth and a part of the Third Pole (an area encompassing Himalaya–Hindukush and Tibetan Plateau). The entire Third Pole region is the most glaciated region outside the Polar regime. Snow and glacial melt are important contributors in hydrologic processes, which are strongly influenced by changes in temperature and precipitation. Glaciers are the important and intertwined ecological entities in this region, however the glaciers of the Ladakh range are being lost and an increased number of glacial lakes are causing a drastic turnover of the hydrology, ecology and micro floral/faunal diversity. The soil is exposed on dry

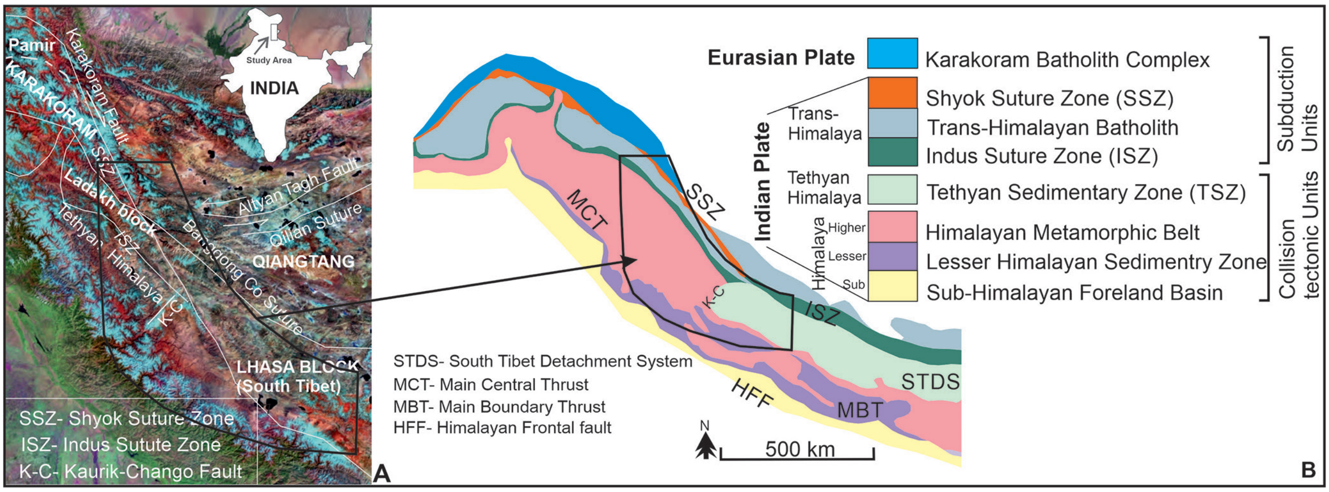

Fig. 1—Map showing the major active faults across the Himalayan syntaxes and geological map of northwest Himalaya.

lake beds, moss mounds, grazing grounds and the lowering of the permafrost is noticed as well.

The Indus River Valley is flanked by the Ladakh batholiths (north/right bank) and the sedimentary rocks of the Zanskar Range (south/left bank). The ranges host several glaciers, which presently occupy only the summits of these ranges (Fig. 3A), some only as residual ice patches. Five glacial stages of progressively decreasing glacial extent on the southern Ladakh Range are recorded: Indus Valley Glacial Stage, Leh (MIS 6), Kar (MIS 5), Bazgo (MIS 3) and Khalling (Early Holocene) (Owen *et al.*, 2006). Moraines at altitude at 3300–3650 m asl of Leh Stage is the oldest and show maximum glacial advance while the youngest moraine complex is formed at 4950–5200 m asl (Burbank & Fort, 1985). The Leh–Ganglass moraine (Fig. 3B) dates to 90 ± 15 ka (Brown *et al.*, 2002). Dotch *et al.* (2013) elaborated the five local glacial stages (GS) of Ladakh Range–Ladakh 4 GS at 81 ± 20 ka, Ladakh 3 GS, Ladakh 2 GS at 22 ± 3 ka, Ladakh 1 GS and Ladakh cirque GS at 1.8 ± 0.4 ka. The 21–23 ka moraines equivalent to Ladakh 2 GS have also been reported by Phartiyal *et al.* (2013) between Pathir Sahib and Nimo villages. The wide U–shaped amphitheater valleys along the tributary catchments bear the testimony of Quaternary glaciations.

Today the glacial equilibrium line altitude lies between 5200 to 5400 m asl, however the extent the glaciers have varied considerably throughout the Quaternary Period. However, nowhere in the trunk Indus Valley are glacial deposits recorded. Tributary valleys do have signatures of glacial advances but those advances were limited within those channels. Several proglacial lakes have been formed as a result of this receding. In the Zanskar Range there are some glaciers today but the Ladakh range is almost/nearly glacier free only with a chain of small glaciers along the highest part of the range. The largest glacier in the area today is Siachen, towards the north beyond the SSZ, the Nubra River takes its origin from the main tongue of the Siachen Glacier and the Shyok River from the Rimo tongue of the same glacier.

Fluvial Records

Alternating with these glacial advances, aggradational landform features that include huge alluvial fans, fan terraces and major palaeolake deposits were formed. Fluvial terraces are formed by both the incision of bedrock (strath terraces) and incision of valley fill (aggradational terraces) (Fig. 4A–C). At Leh, two levels of alluvial fan terraces (older T1 at 3250 masl and younger T2 at 3200 masl) are reported (Sangode *et al.*, 2013; Sinclair *et al.*, 2017), and can be traced downstream, for a few kilometers. The older terrace is deformed by thrusting, folding and extensive, irregular soft sediment deformation and is dated to be 50 to 31 ka (Sinclair *et al.*, 2017). T2 terrace yielded ages of 22 ± 1.3 ka, 19.1 ± 0.7 ka and 11.7 ± 0.7 ka and similar age range is also reported for terraces downstream Nimo and Basgo (Sinclair *et al.*, 2017). Six strath terraces with mean rate of the incision along the valley are described–

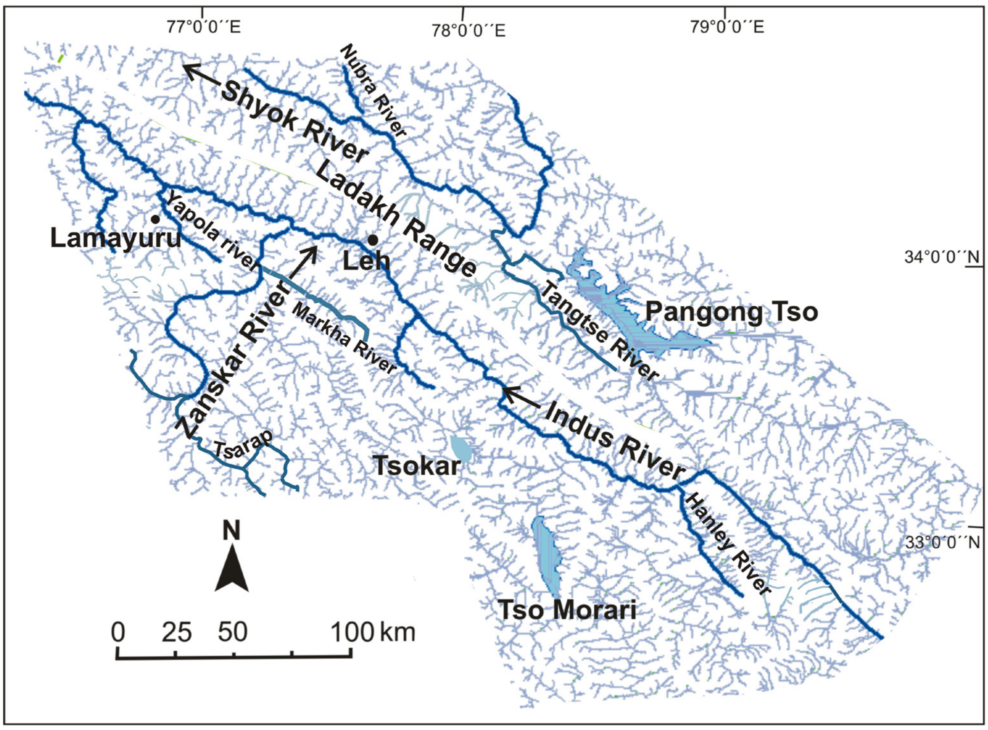

Fig. 2—Drainage network of the Indus River in the Ladakh region; Shyok River joining Indus on Skardu (Pakistan) is the main right bank tributary of River Indus with Nubra and Tangtse rivers as its tributaries; main left bank tributaries are Hanley, Zanskar and Yapola rivers.

terraces with ages > 60 ka have slow mean incision rate (0.4 ± 0.04 mm/yr) while strath terraces with ages < 15 ka have relatively fast mean incision rate (~ 1.1 ± 0.9 mm/yr) (Dortch *et al.*, 2011). Fluvial terraces at ~200–300 m aprl are ~200 ka while those occurring ~30–40 m aprl are ~50–20 ka (Blöthe *et al.*, 2014). Between Nimo–Dah older terraces at ~134 m aprl is dated to ~62–72 ka and younger terraces at ~45 m aprl to ~44–52 ka (Kumar & Srivastava, 2017). The process involved, surficial patterns formed, geomorphology and landscape evolution of the Quaternary deposits of Ladakh region can be used to compare and validate the geomorphological features on the surface of Mars and to validate them time and space.

Quaternary lacustrine deposits and aeolian deposits

Lakes in Ladakh region are basically of three types: closed basin lakes e.g., Tsokar Lake, Tso Morairi (Tso=lake in Ladakhi); open valley lakes e.g., Pangong Tso and glacial lakes e.g., Tsoltak, North Pulu, Yaya Tso, etc. and the other category is the palaeolakes e.g., Lamayuru, Spituk–Leh, Saspol–Khalsi, etc. (Fig. 5A–D). Most of the palaeolakes were formed by the blockage of the Indus River drainage due to tectonic and/or climatic effects. Palaeolakes are formed when climatic or tectonic disturbances mobilize the enormous sediment debris that lies loose on the high angled slopes, which then block the river at its narrow stretches forming open valley lakes with an inlet and outlet for the main drainage.

Palaeo–lacustrine deposits consist of sand, silt and clay units/beds (Fig. 6A–C). They can be seen at Shey, Spituk, Gupuk, Rizong, Saspol, Nurla, Khalsi, Sanjak, Bhima, Achinathang, Dah, Batalik and Lamayuru villages. Morphological reconstruction of Spituk palaeolake revealed 106 km^2 areal extent and ~40 km length (Sangode *et al.*, 2007; Phartiyal *et al.*, 2013; Mujtaba *et al.*, 2017). The Lamayuru palaeolake (Fig. 5A)(commonly known as Moonland) that existed ~35-26 ka years ago has an aerial extent of 3.524 km^2. The palaeolake comprises of mudstone, siltstone and sandy shale facies resting over the prelacustrine fanglomerate (Fig 5D). Breaching of Lamayuru palaeolake along the Yapola River (a tributary of Indus) at the closure of LGM (Fort *et al.*, 1989; Kotlia *et al.*, 1997a, b, 1998; Nag & Phartiyal, 2015; Móga *et al.*, 2020) generated a huge amount of debris which choked the main Indus River channel leading to formation of ~55 km long lake upstream called the Khalsi-Saspol palaeolake, having a surface area of 370 km^2 (Nag & Phartiyal, 2015; Nag *et al.*, 2016). Further downstream at Achinathang

Fig. 3—(A) View of Leh Town overlooking the snow–clad Zanskar Range; (B) Broad 'U' shaped valley formed by glacial sculpturing and lateral moraines at Ganglass Village (upper side of Leh Town) an evidence of glacial advances in the past.

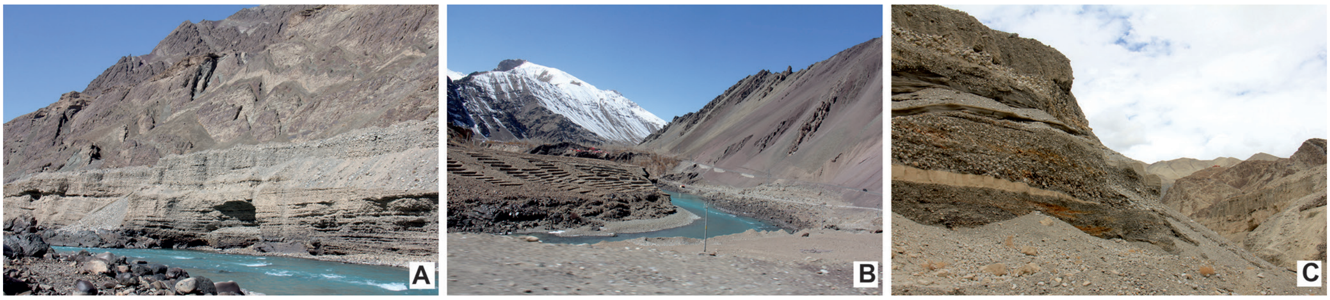

Fig. 4—(A) Aggradational fluvial terrace formed as the Indus River incised the through the valley fill; (B) Bedrock incised by Indus River forming an unpaired strath terrace occupied by people for agricultural activity; (C) Fluvial fill capped by colluvial debris near Nurla Village on the right bank of River Indus.

(2892 masl), Hanuthang (2816 masl), Bhima (2750 masl), Dah and Batalik (2688 masl) several deposits are seen. Perhaps these lakes in the past, were the reason for the humans to settle in this rugged part of the Trans–Himalaya.

Several sand ramps are seen in Ladakh range (Shey, Sabu, Leh) which are being used for sand mining (Fig. 7). Sedimentary architecture as deduced using vertical and lateral cut sections suggests that the sand ramps are composite records of aeolian, hill slope gullying and interdunal lacustrine activity. Aridity and aeolian activity was dominant in Ladakh during 25–17 ka and <12–8 ka and wetter phase prevailed at ~12 ka and 7 ka as revealed from interdunal lake phase (Kumar *et al.*, 2017).

Present day Lake sites

Several lakes, viz. Pangong Tso, Tsomoriri, and Tsokar are found in the region apart from the numerous glacial lakes

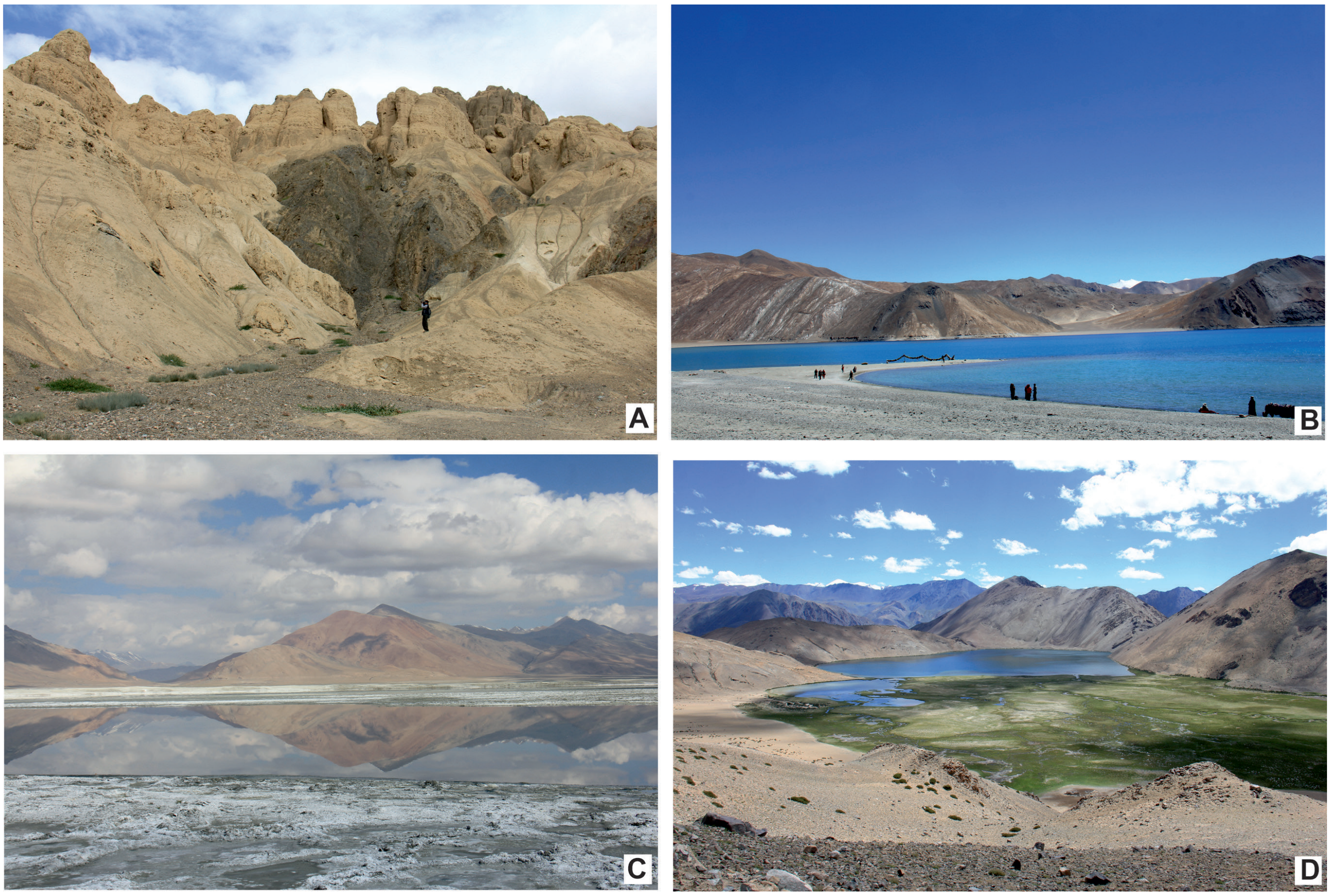

Fig. 5—Photographs of some different types of lakes in Ladakh; (A) Lamayuru palaeolake deposit commonly known as the Moonland; (B) Pangong Tso (Tso=lake) a brackish lake situated in the eastern part of Ladakh at 4300 m asl; (C) Salt water lake Tsokar surrounded by the Zanskar Range of mountains situated at more than 4500 m asl; (D) A glacial lake, Yaya Tso situated in the Chumathang region of east Ladakh at 4697 m asl surrounded by sedge meadows and hills.

in the Ladakh Range in addition to several proglacial lakes in the Ladakh Range.

Pangong Tso (Fig. 5B) is situated at an altitude of 4267 m and has a catchment area of 28,700 km^2, Pangong Tso Lake is the largest lake in the area and occupies a long, submerged valley which has been dammed to the west by a ridge formed by tectonic activity associated with the Karakoram strike slip faulting (Huang *et al.*, 1989) or by a moraine deposit during Last Glacial Maximum (Norin, 1982). During high stands the lake drains into the Shyok River (Fig. 2). The lake is a chain of five basins separated by shallow sills (Hutchinson, 1937; Norin, 1982) and which thus evolves as a series of lakes connected by rivers. It had a sixth basin which extended to the Tangtse Valley during a part of Holocene (Phartiyal *et al.*, 2015).

The Tsokar Lake (Fig. 5C) is situated within the Taglang La Formation of the Tso Moriri Crystalline Complex, assigned as an accreted unit of the ISZ. Thick piles of Quaternary lacustrine sediments are present as a cover deposit underlain by permafrost. Tso Kar receives water from the discharge through a shallow overflow of another river–fed lake Startsapuk Tso, situated in the same catchment. Many geomorphologic features developed by glacial, fluvial, aeolian, periglacial, lacustrine and permafrost activity are observed in the basin as reported in earlier findings (Dimri *et al.*, 1983; Wünnemann *et al.*, 2008, 2010). Small glacial cirques at the north–eastern and south–western side of the basin, terminal moraines along the eastern side of the basin, a lateral moraine on the western side of the basin and hummocky landscape with polished and striated clasts are the distinct glacial landforms (Pandey *et al.*, 2019). Another most striking feature is the several raised palaeo–shorelines suggesting gradual shrinkage in lake level since its time of formation. The hydrological evolution and climate changes of the lake are very well studied and attributed to the interplay of climate and tectonics (Sekar *et al.*, 1994; Demske *et al.*, 2009; Wünnemann *et al.*, 2008, 2010). Thermokarst forms, frost mounds, possible 10 m high lithalsas, thermal contraction crack polygons, permafrost mounds with thick ice lenses and reticulate cryostructures are the features which show this area is under the permafrost activity. Earlier investigations support the discontinuous permafrost due to the presence of many small and medium–sized ponds near to the frost mounds and larger ones in isolated thermokarst depressions (Dimri *et al.*, 1983; Wünnemann *et al.*, 2008, 2010). The study of the microbiota of these depressions would be helpful in the astrobiology studies.

The other major lakes in the area are the TsoMorari (4500 m), Kyun Tso and the Kyun Tso lakes, the twin lakes (west of TsoMorari) and Mipdpy Tso, Yusup Tso and the Kyuie Tso. Of these, the TsoMorari and the TsoKar lakes are very large lakes compared to the other lakes of this region. However, in the recent years, the TsoKar Lake has shown signs of receding water levels.

The high passes of the Ladakh Lake have several lakes. The Changla Pass houses the Tsoltak pro–glacial lakes. The surrounding area is occupied by undulating moss mounds, patterned ground and boulders with lichen growth a typical feature of the glacial terrains. Permafrost layer is seen at 110 cm level in the mounds while in other places at 40 cm. These layers are very good to study the microbes and microbiota adapted to the extremely low temperatures. The Khardungla Pass hosts the South Pulu and the North Pulu lakes and has been studied for diatoms and palynofacies along with the other physical and chemical proxies (Phartiyal *et al.*, 2020a, b; 2021). While Yaya Tso (Fig. 5D) is situated on the eastern flank of the Ladakh Range on the way to Horla in the Chumathang region, a region well known for its famous sulphur hot springs, travertine deposits, geysers and hydrothermal deposits.

Hot Springs

Geothermal features (Fig. 8) occur at a number of locations in Ladakh, most notably at Panamik, Chamuthang, and Puga (Craig *et al.*, 2013). The springs are fed by deeply circulating water along major thrust faults. Comparable high altitude springs occur in Chile (Fernandez–Turiel*et al.*, 2005) and China (Aitchison *et al.*, 2003). Some springs (e.g. Puga) are enriched in boron, and these are of considerable interest therefore to questions associated with early life habitats and prebiotic processes (Stellar *et al.*, 2019; Djokic *et al.*, 2017; Cossetti *et al.*, 2010). The antiquity of the hot spring biota, the significance of them as potential sites for the origin of life,

Fig. 6—Photographs of major palaeolake deposits, which are the best terrestrial archive for studying the continuous palaeoclimatic records; (A) Palaeolake section at Shey; (B) Spituk; (C) Lamayuru (Moonland).

and their known occurrence on Mars (Ruff & Farmer, 2016) as led to terrestrial hot springs including those of Ladakh, being studied as Mars analogues (Barbieri & Cavalazzi, 2014).

One major issue effecting the study of these springs has extensive anthropogenic impact on almost all of them from centuries of human use and more recent uncontrolled tourist development (Craig *et al.*, 2013; Pandey *et al.*, 2019). Development of geothermal resources for power generation (Craig *et al.*, 2013) also has the potential for significant impact if not managed correctly. Without such protections the cultural and scientific value of these sites will be severely degraded.

Ultraviolet effected soils

Soils and surficial deposits in Ladakh (Pant *et al.*, 2005) will inhabit a diverse range of environments due to variable temperature, moisture, and freezing regimes, different geological substrates, and variable ultraviolet fluxes due to altitude and aspect. Ultraviolet flux increases by approximately 10% over sea level values for every 1000 m gain in altitude (Blumthaler *et al.*, 1997). At the altitude of Leh, ultraviolet levels are therefore ~35% higher than at sea level, at that of Tso Kar ~45% higher, and at the altitude of the highest passes (~5,600 m) such as Chang La, Kardung La, and Taglang La ~56% higher. Snow free areas on the top of the Ladakh Range will receive 60% more ultraviolet than at sea level. There is also a parallel increase of the higher energy ultraviolet wavelengths to the surface with increased altitude. Čapková *et al.* (2016) and Řeháková *et al.* (2011) studied this variability and environmental dependencies in soil microbes from a combined total of six sites in Ladakh.

MARS ANALOGUES

The Mars analogue potential of the Ladakh region was introduced by Pandey *et al.* (2019). While a summary, this paper demonstrated the many opportunities for Mars analogue research. Here we further compare and nominate particular geomorphological and geological features of the Ladakh region as analogues for specific classes of features on Mars (Table 1).

One advantage of the Mars analogue features of Ladakh is their comparatively small scale. This makes them easier to study and to use as field teaching examples. They are also effective analogues for smaller scale features on Mars, especially those that are studied by surface missions.

More generally, the Ladakh environment, characters by freezing temperatures, limited precipitation, open water in rivers and lakes, comparatively low atmospheric pressure, thermal springs, and relatively high ultraviolet flux, is an analogue for the Noachian Epoch on Mars. The Noachian of Mars also featured much higher atmospheric pressures that those that pertain at present, episodic warming periods that allowed open water bodies, including rivers, catastrophic floods, and lakes (Wordsworth, 2016). Manganese concentrations in Noachian rocks suggest higher level of oxygen in the atmosphere at this time (Lanza *et al.*, 2014). Early Mars was characterised by alternation of warmer and colder conditions, at least partly comparable to the strong variations in the Ladakh climate through the Quaternary, and recorded in the sedimentary record. Simultaneously Ladkah also parallels current Mars with active periglaciation, glaciation, and aeolian activity.

This diversity of sites and environments provides a valuable framework for Mars–relevant astrobiological research. Biota and organic matter and their preservation, taphonomy, and diagenesis within the diverse lake environments of Ladakh will, as they have elsewhere (Cabrol *et al.*, 2018) guide the interpretation of martian lake deposits of the Noachian and early Hesperian epochs of Mars and possibly the selection of landing sites for future missions. The thermal springs of the Ladakh region, boiling at a much lower temperature than those of most other locations on Earth, provide insights into the potential adaptations of microbes to low pressure but boiling

Fig. 7—(A) Aeolian deposits–Sand ramp seen in the Ladakh Range near Leh; (B) These sand ramps are an important source of sand for construction purpose hence mined largely; photograph of sand ramp at Shey.

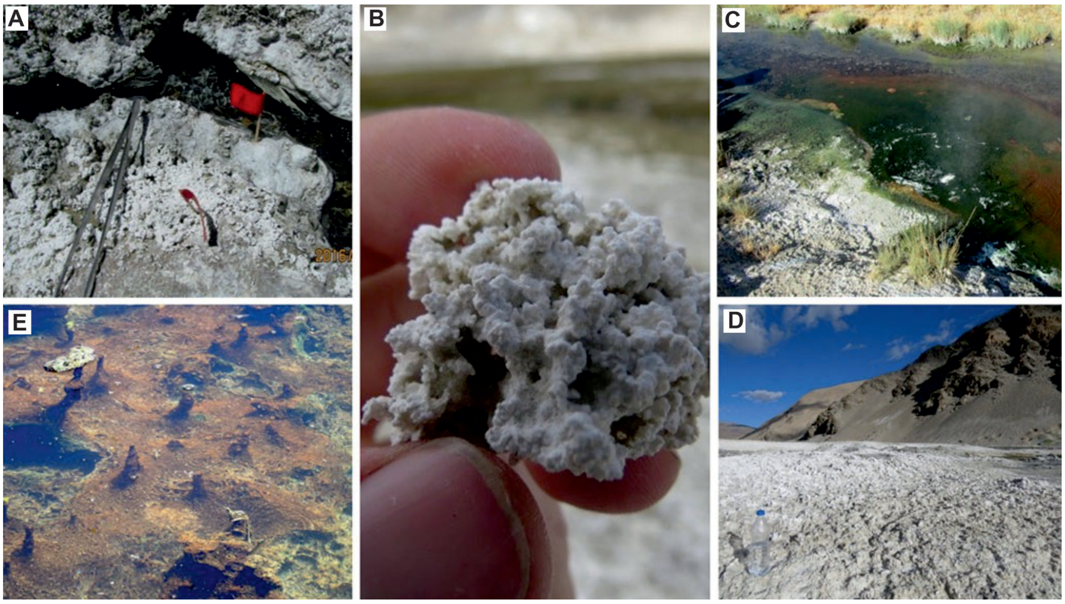

Fig. 8—Geothermal features from Ladakh (from Fig. 12 in Pandey *et al.,* 2019); (A) Puga Hot Spring crusts sample site; (B) Soluble puffy white crust in Puga Valley; (C) Differing coloration in biofilm mats at sampling sites; (D) White borate crust deposits in Puga Valley; (E) Conical algal mats from Puga Hot Springs (Photo Credits: UNSW ACA and BSIP).

aqueous environments in the martian past and, perhaps, on the icy moons of the solar system. Characterising the facies and textures associated with these deposits and comparing them with other high altitude spring systems such as those of Chile (Barbeieri & Cavalazzi, 2014) may aid in recognition of low temperature boiling environments in the terrestrial past as well as on Mars.

The high ultraviolet flux in Ladakh, which increases by approximately 10% over sea level values for every 1000 m gain in altitude (Blaumthaler *et al.*, 1997), also provides an opportunity to study adaptations to this environmental stressor in cold, arid, and icy environments. At the altitude of Leh, ultraviolet levels are therefore ~35% higher than at sea level, at that of Tso Kar ~45% higher, and at the altitude of the highest passes ~55% higher. There is also a parallel increase of penetration of higher energy ultra violet wavelengths with increased altitude. Häder and Cabrol (2018) have shown the value of comparing terrestrial ultraviolet fluxes this with those on Mars, using the Andean Altiplano region as an analogue. This region has a similar climate and altitude range to Ladakh. Comparable studies in Ladkah would complement and enhance the studies from regions such as the Altiplano and test the hypothese derived from them.

CONCLUSIONS

Ladakh is a recent addition to the range of potential Mars analogue regions on Earth. It's diverse geology and geomorphology offers many potential locations and features for comparing and contrasting with those on Mars. In particular Ladakh offers features of scales comparable to those encountered by surface exploration and analogues for early (Noachian) Mars in its lakes, rivers, catastrophic flood events, thermal springs and Quaternary climate oscillations. Modern martian environmental analogues can be found in the dunes and glacial, and periglacial features. It is our view that the Mars analogue potential of Ladakh will be increasingly valued amongst Indian scientists as the nation expands it planetary science capabilities and will provide opportunities for collaboration with foreign scientists interested in new and sites for Mars analogue research and astrobiology and for comparison with sites in China (Tibet) and South America (Altiplano) with comparable high altitude, cold desert environments.

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Table 1–Comparison of selected geological and geomorphological features of Ladakh and potential Martian counterparts.

Geomorphic/ geologic feature or process	**Ladakh examples**	**References**	**Martian examples**	**References**
Palaeo–lake sediments	Spituk; Saspol; Khalsi; Lamayuru; Tangtse/ Shachukul	Burbank & Fort 1985; Kotlia *et al.*, 1997; Phartiyal *et al.*, 2015; Nag & Phartiyal, 2015; Nag *et al.*, 2016, 2021; Móga *et al.*, 2020	Holden crater, Juventae Chasma; Jezero crater; Gale crater	Cabrol & Grin, 2010; Fukushi *et al.*, 2019; Hurowitz *et al.*, 2017
Hot springs	Puga; Chumathang; Panamik	Craig *et al.*, 2013; Shukla *et al.*, 2017; Tiwari *et al.*, 2016; Steller *et al.*, 2019	"Home Plate" Gusev crater	Ruff & Farmer, 2016
Catastrophic flooding	Chumathang/ Saboo; Leh floods; Zanskar palaeofloods	Juyal, 2010; Rasmussen & Houze, 2012; Thayyen *et al.*, 2013; Sangode *et al.*, 2017; Sinha *et al.*, 2018; Sarkar *et al.*, 2019; Chahal *et al.*, 2020	Ares Vallis; Galilaei Crater	Pacifici *et al.*, 2009; Goudge *et al.*, 2018; Coleman, 2015
Periglacial processes	South Pulu; North Pulu; ChangLa	Ali *et al.*, 2018; Phartiyal *et al.*, 2020a, b, 2021	Athabasca Vallis; Phoenix landing site	Balme & Gallagher, 2009; Mellon *et al.*, 2009
Glacial processes	Ganglass moraines	Brown *et al.*, 2002; Shukla *et al.*, 2019	Protonilus Montes, Phlegra Montes; Ascraeus Mons	Brough *et al.*, 2019; Conway & Mangold, 2013; Kadish *et al.*, 2008
Aeolian features	Sand Ramps; Indus Valley; Barchans dunes Hunder	Kumar & Srivastava, 2017; 2018a, b; Clarke *et al.*, 2020	Gusev crater; Gale crater; North polar erg	Diniega *et al.*, 2017; Chan & Netoff, 2017; Greeley *et al.*, 2006
UV effected soils	All soil above 3500 m	Čapková *et al.*, 2015	Variable through time across entire surface	Hader & Cabrol, 2018

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