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Evolution of arid landscape in India and likely impact of future climate change

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Thar Desert and Ladakh are two prominent arid areas in the Indian Subcontinent, representing the hot and the cold arid regions, respectively. Landforms in Thar Desert have developed over a relatively stable platform, and bear strong impressions of several cycles of late Quaternary climate change between warm wet and dry cool phases, which dictated the spatiotemporal distribution of the fluvial and aeolian processes and the typical disposition of the landforms. By contrast, Ladakh, located in the Trans-Himalaya, is mountainous and dominated by glacial, periglacial and fluvial processes, with fewer signatures of lacustrine and aeolian processes. Since ~44 ka, the area witnessed two major and one minor phases of aridity. Evidence for neotectonic, though expected very much in this suture zone between the Indian and the Eurasian plates, is not very common, and need proper investigation. Presently anthropogenic activities tend to have over-bearing influences on the process acceleration and land degradation in both Thar Desert and Ladakh. Since warming-related changes in climate have also started to impact the areas, sustainable land uses, backed up by land conservation measures are called for.

Introduction

Arid lands occupy 14 per cent of India's total land area, and include both hot and cold arid regions. While the major part of the hot arid region occurs in the state of Rajasthan that includes the sandy Thar Desert, the cold arid region occurs exclusively to the north of the Zaskar Range in the Trans-Himalaya, where it includes a vast swath of mountainous land from Ladakh in the southeast to Gilgit-Baltistan in the northwest (Fig. 1). Aridity here is quantified as a moisture availability index (Im, as defined by India Meteorological Department) of -66.66 to -91.00. Apart from the vast arid land in western India, small patches of hot arid areas also occur in the southern part of the country, especially in parts of Karnataka, Andhra Pradesh

and Maharashtra. The landforms in the hot arid region have largely developed on a dominantly stable Pre-Cambrian platform, except in Kachchh and Saurashtra where they bear strong impressions of recent tectonic activities along the continental margin. By contrast, the landforms in the cold arid region are mountainous, and have developed at the junction of the quasi-mobile Indian and the Eurasian plates. This factor, as well as the vast difference in thermal regime of the two regions, determines the types of subaerial denudation processes in the two regions, even though both the areas receive ~300 mm or less mean annual precipitation (Krishnan and Thanvi, 1977; Hobley et al., 2012; Fig. 2). Thus, while the hot arid region is largely dominated by wind erosion and/or sheetwash and periodic flooding by ephemeral streams, the cold arid region is subjected to glacial, glacio-fluvial and periglacial processes and mass wasting. Stream processes are more efficient in Ladakh due to the presence of many-glacial-fed large streams like the Indus and its tributaries. We describe below the landscape development in the two regions with examples from Thar Desert and Ladakh.

Thar Desert

The Thar, or the Great Indian Sand Desert, stretches between the foothills of the denuded Pre-Cambrian Aravalli hill ranges in Rajasthan state of India and the Indus River in Pakistan (Fig. 3). Although it lies at the eastern end of a vast arid land along the Tropic of Cancer that includes the hyper-arid Sahara, the Rub-al Khali and the Lut, Thar Desert has a much lower aridity than those extreme deserts due to its location at the transition of two major rain-bearing climate systems, the Indian summer monsoon (ISM) that brings about 100-500 mm rainfall, and a Mediterranean westerly system that sometimes brings showers of <100 mm during the winter and the spring. The land to its south, the Kachchh Peninsula and the Saurashtra Uplands in Gujarat, and that to its north, the thick sandy alluvium in the southern parts of Punjab and Haryana, also belong to the arid lands, but have lower aridity.

Present-day landforms

Most present-day landforms in Thar Desert bear strong imprints of fluctuating climate during the late Quaternary period, which dictated the relative dominance of fluvial and aeolian processes over time. Some landforms also bear the evidence of neotectonic movements,

Figure 1. Location of hot and cold arid regions. A: Cold arid region; B: Hot arid regions. 1: Ladakh Desert, India; 2: Thar Desert, India and Pakistan. Image on the right shows the DEM generated from SRTM30-GTOPO data at ~1 km resolution, with the boundaries superimposed.

Figure 2. Monthly precipitation pattern at (A) Sam, west of Jaisalmer, Thar Desert; and (B) Leh, Ladakh. The precipitation data is extracted from KNMI climate explorer for 36 years from 1981 to 2017. The dashed lines indicate 17, 83 and 97.5 percentiles and the bold grey line is for mean. (<https://climexp.knmi.nl/start.cgi>)

while strong signatures of human influences do also abound. Spatially, there exists presently a gradient of fluvial process efficacy from east to west, commensurate with the decreasing ISM rainfall in that direction (~500 mm in the east to 100 mm in the west), while the aeolian processes are stronger in the west and southwest, but become subdued towards east and north as the wind strength declines in that direction. This overall pattern is also dictated by strong seasonality of the weather. As the climate fluctuated between warmer wet and cooler dry phases at century to millennial scales, the process zonation and process efficacies also shifted, leaving their imprints in the sedimentary beds (Kar, 2014). The climate being arid, weathering processes are very slow in the region, but these prepare the materials for transportation and subaerial denudation. Based on the dominant processes the landforms could be broadly classified into fluvial, aeolian and lacustrine. The major fluvial landform sequence is: hills and uplands - rocky/gravelly pediments (and pavements) - colluvial plains - older alluvial plains - younger alluvial plains - river beds, which supply the aeolian processes materials for constructing over them the sand sheets, sandy hummocks and sand dunes of different types. Such complementary roles of the two processes continued throughout the Quaternary period, making most old land features polygenetic in nature. Because of insufficient drainage, deflation and land segmentation across stream valleys due to aeolian activities, as well as neotectonic activities, a number of salt playas (locally called the Ranns) of different shapes and sizes have also been formed within the desert (Kar, 1995). Based on the assemblages of landforms and their dominant characteristics, following seventeen major geomorphic provinces have been identified (Kar, 2014): (1) Aravalli Hills; (2) Alluvial plains of the north; (3) Star dune field; (4) Transitional parabolic dune field; (5) Luni alluvial plain; (6) Siwana Hills; (7) Transverse dune field of NW; (8) Parabolic dune field of NW; (9) Hamada landscape; (10) Gravel pavements with sand streaks; (11)

Parabolic dune field of south; (12) Nagarparkar Upland; (13) Saline alluvial plain of NW; (14) Transitional parabolic dune field of NW; (15) Rohri Upland; (16) Network dune field of west; and (17) Linear dune field with megabarchan fields in west (Fig. 3).

Plinth of the Quaternary landforms

A vast pediplaned surface, composed largely of Pre-Cambrian metasediments and igneous rocks in the east and on gradually thickening sedimentary beds of Mesozoic and Tertiary periods in the west, provided the basement for Quaternary landform development (Sinharoy et al., 1998). The oldest formation in the region is found in the Aravalli Hills tract as the Banded Gneissic Complex (BGC; Heron, 1953), which is dated to 3.5–2.5 Ga (Meert et al., 2010). It hosted the Delhi Supergroup of rocks (~2.00 Ga) that formed the Aravalli Mountain chain, or the Delhi Fold Belt (~1 Ga), as part of the Great Indian Proterozoic Fold Belt along the western edge of the ancient Rodinia Supercontinent (Ashwal et al., 2013). A series of volcanic events between 1700 Ma and 750 Ma along the south-western margin of the mountain produced the Sendra Granite, Erinpura Granite, Malani Igneous Suite, Mt. Abu Granitoids, etc., which extended the

continental margin of the period westward, and hosted the younger meta-sediments, including the Marwar Supergroup of sedimentary rocks (Meert et al., 2010, Ashwal et al., 2013, Davis et al., 2014). Northward wandering of the continent and sedimentation in four major segmented basins (i.e., the Nagaur Basin, the Jaisalmer Basin, the Barmer Basin and the Sanchur Basin) since then gradually built up the terrain through the Mesozoic and Tertiary periods to the early Quaternary stage and brought the desert to its present position (Sinharoy et al., 1998, Davis et al., 2014, Wadhawan, 2018). The oldest surviving Quaternary deposits over large parts of the desert are a mixture of sand and gravel, which hint at a dominantly fluvial landscape during the early Quaternary period. Partly-calcreted aeolian sand sheet deposits have also been found in patches to lie directly over the basement, especially in the central and western parts (Dhir et al., 2010), which suggest that the aeolian features were also an integral part of the landscape.

Fluvial landscape evolution

The ephemeral Luni River and its tributaries from the Aravallis constitute the major river system of the desert. A number of other

Figure 3. Geomorphic provinces, wind pattern and dune trend in Thar Desert. Details of geomorphic provinces 1-17 are given in text.

short ephemeral streams from isolated hills in the desert flow for shorter distances during the rains. The wide misfit valley of a Himalayan stream, the Ghaggar River, lies along the northern fringe of the desert. Its discontinuous segments have been traced along the desert's western fringe as the Raini, the Wahinda and the Nara (Fig. 3). C.F. Oldham (Anon., 1874), from his interpretation of topographical sheets and field observations first suggested anonymously that this misfit wide valley of the presently seasonal Ghaggar River, and some other abandoned valleys known as the Naiwals, were actually the former channels of a major Himalayan river, the Sutlej, which used to flow into the Arabian Sea independent of the Indus, and that the Ghaggar-Nara segment of the river was possibly the Saraswati River of the ancient Indian literature. This was the first major suggestion of a Himalayan stream draining the northern and westernmost parts of the desert. Satellite remote sensing helped to trace a maze of buried courses of that system through the plains of Punjab and Haryana, and then through the desert itself (Ghose et al., 1979; Kar and Ghose, 1984). Mica-rich sandy alluvium, vegetation banding, spatially arranged evaporite sequences, e.g., calcrete, gypsum and sodium salts, and shallow potable aquifer field-validated some of those satellite-derived palaeochannels through the dune-infested terrain.

Based on chrono-stratigraphic evidence from the Ghaggar palaeo-valley in India (Singh et al., 2016) it is now understood that ~155 kilo annum before present (ka), a thick aeolian sand sheet, intercalated with silty sand, covered the surface of the valley. Abundance of silt in some layers suggested either a sluggish flow or a dominant aeolian process reworking some of the older fluvial deposits. From ~75 ka the valley received the Satluj alluvium, the major influxes likely taking place around 70 ka and between 60 ka and 25 ka. Since the Last Glacial Maximum (LGM, 25-18 ka) the valley received only some intermittent flows from smaller seasonal streams with frequent aeolian intercalations. At the tail-end of the Ghaggar valley in Pakistan detrital zircon from the Yamuna River basin was traced in the >49 ka fluvial sand layer, and was interpreted as the Yamuna's westward flow (Clift et al., 2012). In the core of the desert, chrono-stratigraphic sequences in the lower part of the Luni River at Khudala revealed major pluvial phases during ~80-90 ka, ~55 ka, ~30 ka and 7-6 ka, which matched with the signatures of stronger monsoon elsewhere (Kar et al., 2001; Jain et al., 2005). All such pluvial phases accelerated the fluvial processes and stabilized the sand dunes. Climate simulation results suggest that the Eemian Interglacial (~127 ka) was a period of still higher rainfall in South Asia, but fluvial deposits of that period are yet to be properly dated and evaluated. An interesting but little-explored landform in the rocky terrain of Jaisalmer and in the northern part of the Luni alluvial plain is a series of palaeo-karstic features, including sinkholes, shallow dolines and uvalas that are partly buried under recent deposits. The features could have been formed during some of the past major pluvial phases. The pluvial phases were followed by major dry phases. The atmospheric conditions since the Eemian period and their likely influence on landscape processes are now being understood through climate simulation modelling and proxy studies (e.g., Shin et al., 2003; Groll et al., 2005; Caley et al., 2014; Dutt et al., 2015).

Aeolian processes and bedform evolution

The most dominant landforms in Thar Desert are the sand dunes which can be broadly classified into the 'old' and the 'new' ones. The

old dunes are typically 15-30 m high, stabilized with copious carbonate nodules and shrub vegetation, and belong mostly to the linear, parabolic, transverse, star, and network types. The axial trend of old linear and parabolic dunes broadly change from NNE in the westernmost part to NE in the central part to ENE in the easternmost part, as the summer wind speed declines gradually towards east and north. In the northern part of the desert, where critical sand-raising wind typically blows from WNW during late-winter and spring, and from SW in summer, the dune orientation tends to replicate both the wind vectors, and thus assumes either a network pattern, or a star shape in fern-leaf pattern (Fig. 3). The new dunes include the 1-8 m high barchans and the 20-40 m high megabarchanoids, which form naturally in the high wind energy regime in the west, as well as 1-3 m high nebkhas and sand streaks that form in the sandy plains anywhere in the desert, but normally abound around the settlements and the deep-ploughed sandy croplands. Linear to sinuous sand ridges (~2-5 m) form along the banks of many ephemeral streams as source-bordering dunes, where the channels supply much of the sediments through funnelling effect (Kar, 1993a). Such dunes in the northern alluvial plain now help to trace the palaeo-valleys of the Ghaggar and the Naiwals in a canal-dominated terrain. Under increased dryness and with adequate sand supply from upwind sources, the stream valleys gradually attract more aeolian sand as crescentic to transverse bedforms which tend to bury the valleys altogether. The transverse bedforms are efficient sand captors, while the source-bordering linear dunes act more as sand-passing bedforms (Kar, 1993b). Such complex fluvial-aeolian interactions explain the typical dune landscape along some of the major buried stream valleys to the west of Bikaner and Jaisalmer. The Aravallis and the other major hill fronts are draped with gullied obstacle dunes in the form of whalebacks and echo dunes, where alternate layers of aeolian sand and fluvial gravels record the cycles of the two processes at annual to millennial scales.

Normally aeolian activities are expected to increase with aridity, the peaks coinciding with extreme aridity (i.e., often during a glacial climate). OSL dating of sediments in Thar Desert, however, show that aeolian sand accumulation was higher during the transition from drier to wetter phases, i.e., from glacial to interglacial stages, especially during ~115-100 ka, 85-75 ka, 65-60ka, 55-50 ka, 30-25 ka and 14-7 ka, when the SW wind gradually strengthened with the northward shift of the ITCZ, but a vigorous monsoon regime was yet to be re-established (Kar et al., 2001, 2004; Singhvi and Kar, 2004). This synchronism between SW monsoon wind and aeolian sand accumulation is strikingly similar to the modern era summer wind dictating significant aeolian sand mobilization. It strengthens our previous process-based argument that the monsoon strength determined the efficiency of aeolian processes and dune-building activities in Thar Desert during the Quaternary period (Kar, 1993a).

Most sand dunes within the desert and beyond its eastern boundary recorded a strong phase of aeolian sand deposition during 14-10 ka, although the process started around 16 ka. The desert extended far to the east of its present limit and into the present-day semi-arid eastern Rajasthan (Goudie et al., 1973). By 10 ka increased monsoon rains stabilized the sandy landscape to the east of the desert, but within the desert the large-scale aeolian activities continued till ~7 ka (i.e., the Climatic Optimum). Available OSL dates suggest that aeolian activities within the desert picked up again from ~5.0 ka to 3.5 ka when monsoon rains had declined. Incidentally, it was during this phase that the misfit stream valleys along the desert's northern and western fringes hosted a large number of Harappan settlements (~4.5-3.9 ka). This was

followed by another phase of high aeolian activity during 2.0-0.6 ka, but the sandy landscape to the north, east and south of Thar Desert did not record much activity. Remnants of the pre-10 ka aeolian sand bodies beyond the present desert boundary now help to fix the approximate boundary of a Mega-Thar (Fig. 3). The latest phase of sand mobility in the desert started around 0.3 ka, when the rates of dune mobility and sand accretion began to surpass the geological rates due to increasing human pressure, especially in the post-independence era when large-scale shifts in land use took place from traditional animal-based mixed-farming to modern irrigated farming with tractor use (Kar et al., 1998, Kar, 2014).

Although the weak W to NW wind of LGM did not allow much aeolian activity within the desert, several fossil dunes beyond the desert's southern margin in Gujarat recorded high aeolian activity, especially in the Mahi and the Sabarmati river catchments, possibly due to a lower sea level during LGM, which exposed a wide stretch of coastal sand to a longer fetch of strong wind over a sparsely vegetated surface (Juyal et al., 2003). In the northernmost part, continuity of sand accretion and dune-building processes during weak monsoon phases cannot be ruled out, because the NW wind is stronger here than in the south. Presently the area experiences sand mobilization during both spring (NW wind) and summer (SW wind), which explain the multi-directional arms of the old star and network dunes.

Fluvial-aeolian interactions in Rann (playa) formation

Presently significant aeolian erosion of the rocky/gravelly tract can be noticed in the very dry hamada landscape of Jaisalmer-Ramgarh, where constant etching and grooving of the gentle NW-dipping soft limestone beds by strong sand-surcharged SW wind leads to the formation of small depressions with micro-scarps. Over the millennia, the small depressions gradually coalesce to form few large en-echelon depressions and then evolve into saline Ranns under a strong evaporative regime, as has been the case with Mithar Rann, Khara Rann, Kanodwala Rann, etc., near Jaisalmer (Kar, 1993b). A series of yardangs have also formed in the vicinity. Elsewhere in the desert, deflation hollows in the wake of isolated hills, flanked by linear dunes, capture and confine the seasonal run-off from surrounding areas to form ephemeral lakes, which subsequently evolve into saline Ranns (e.g., at Degana, Didwana, Jaidu; Kar, 1990). A few other Ranns appear to have evolved as tectonic basins (e.g., at Sambhar, Kuchor). All the major Ranns experienced a hypersaline environment during the LGM. Subsequently, most Ranns in the eastern part experienced freshwater conditions during stronger monsoons, but those in the extreme west either missed the event or experienced it for a brief period because rainfall did not fluctuate there appreciably after the LGM (Singh et al., 1974; Roy and Singhvi, 2016).

Neotectonic influences

Apart from the climatic fluctuations, tectonic activities during the Quaternary also played some role in the evolution of desert landscape, especially in the Luni alluvial plain where satellite images revealed a number of lineaments. Striking relationship was noticed between many of the NNE-SSW lineaments and drainage anomalies like sudden widening of channel beds, stream incision and angular bends, as well as small terraces. At least two terraces were identified along many streams, including the Luni to the south of Sindari (Kar,

1988). Signatures of a tectonic event at ~10 ka were found in the form of oblong mud balls within a fluvio-lacustrine bed of sand-silt at Khudala near the junction of the Luni with the Jawai. It suggested that the semi-viscous lacustrine deposit of the period was subjected to vigorous shaking, followed by northward tilting of the beds. Courses of both the Luni and the Jawai were affected (Kar, 2014).

Present-day human impact

The fragile landscape of Thar Desert is now under a high risk of sediment mobility, soil erosion and land quality degradation, due to high demand for food, fodder, water and other resources from the land. Destruction of natural plant cover on old dunes, flattening of small dunes and deep ploughing of sandy terrain to expand croplands has increased wind erosion and new dune formation. Misuse of canal water in the palaeochannel-dominated northern part has encouraged waterlogging and salinization. Gully erosion is increasing on many obstacle dunes in the Aravalli foothills as the land is opened up for irrigated cropping due to destruction of the natural shrub cover for cropping through groundwater irrigation, while construction of too many water reservoirs and anicuts in the Aravalli hills has severely restricted stream function in the sandy plains (Kar, 2018). Elsewhere, several isolated hills are being cut up for stone chips to construct road networks, so much so that many smaller hills have almost vanished. Coarse sand along many ephemeral streams is being indiscriminately scooped out for building material, which is badly impacting the hydrology of this water-poor region. Although some course-correction at stakeholder level is also taking place, especially where the trade-off between technology-mediated 'development activities' and conservation practices is becoming too costly to sustain, the apathy towards landscape health for better ecosystem services is abysmal.

Likely impacts of future climate change

The negative impacts of above human modifications to landforms are getting exacerbated by recent anthropogenic climate change. Briefly, the climate simulation studies suggest that by the end of this century monsoon rainfall in western part of the desert may decline by ~30%, but pre-monsoon rain, which was almost absent earlier, may increase by 30-50%. Temperature during summer and winter may rise by 3-5°C, while the summer wind speed may increase by 10-20% (Rupakumar et al., 2006). To understand the impact of such changes on aridity and wind erosion, Kar (2012) calculated the moisture availability index (Im) and wind erosion index (WEI) in the region, using the IPCC AR-4 simulation data for A2 scenario. Simulation data from GFDL 2.01 and ECHAM 5.01 matched well with the observed values, and suggested that WEI might increase during the next decade and then fluctuate at a much higher level than at present till the end of the century, even though the past records show a gradual decline in summer wind speed and WEI from 1951 to ~2000. Since then wind strength has started to show a slight increasing trend along the western and eastern margins (Kar, 2013), but the sand-reactivated areas have declined considerably over the first fifteen years of the present century (Kar, 2019). Additionally, a mid-May rain spell resulting from Western Disturbances is gradually becoming a boon for natural plant regeneration in the open rangelands and in effecting partial sand stabilization, while increased frequency of dust storms from the NW in early- to mid-summer with wet scavenging within

the desert, is providing opportunities for silt trapping in shrub-covered lands. It will be interesting to monitor if the trends are sustained over the coming decades, and if the inhabitants are able to take bold land use decisions to gainfully utilise the emerging opportunity. The likely feedbacks from such evolving phenomena to the atmospheric and land surface processes might moderate the future climate. In the worst case scenario, the arid boundary may shift to the east of Jaipur by 2040 and drought frequency may increase. Since the satellite-derived atmospheric dust load pattern mimics the WEI pattern, the GCM-derived higher WEI values during coming decades would mean higher atmospheric dust loads than at present, provided the predicted gradual increase in pre-monsoon rain does not suppress the dust emission (Kar, 2013, 2014). In case the dust transport from desert increases one may expect large-scale rainfall modification over northern India (Bollasina and Nigam, 2011).

Cold Desert of Ladakh

The cold desert of Ladakh lies to the north of the Zaskar Range in the Trans-Himalaya, where the Indian plate collided with the Eurasian plate and got subducted below the Kohistan-Ladakh arc along the southwestern margin of the Tibetan Plateau. Situated at an average elevation of ~3500 m above mean sea level, the region experiences two different weather systems: one associated with the cool westerlies from the Mediterranean during October to March when snowfall takes place, and the other bringing warm and moist winds of the ISM from June to September, when some rains occur. The arid boundary roughly runs along the summit of the Zaskar Range, the land to its south having a semi-arid climate. The mean annual precipitation at Leh is <150 mm (Lang and Barros, 2004), decreasing NE to ~40 mm. Strong winds blow throughout the year, but the stronger wind speed of ~6 m/s is recorded during March to June (Kumar et al., 2017). Palaeoclimatic reconstruction from the lacustrine sedimentary sequences in Ladakh reveal that all through the late Quaternary period stronger ISM favoured warm and wetter conditions with a tendency towards semi-arid condition, while the periods of stronger westerlies enhanced the aridity and cold climatic conditions (Demske et al., 2009).

Present-day landforms

Ladakh provides copybook examples of numerous glacial and periglacial landforms. In the active glacial areas it is common to find cirques with bergschrunds and arêtes near the summits, as well as hanging valleys and moraines (especially in the Zaskar Range, the Ladakh Range and the Eastern Karakoram), while the areas from where active glaciers have retreated reveal amphitheatre valleys, tors, roche moutonnees, drumlins, remnants of median, lateral and end moraines, etc. (Pant et al., 2005). In the areas where permafrost or seasonal frost occurs at ground and/or subsurface, a variety of periglacial features could be noticed. These include features of frost-shattered conglifractates, frost-heaved congliturbates, pingos, kettle holes, sorted stone polygons, etc. Normally, frost shattering during summer occurs to a depth of 5–10 cm, but during winter it occurs to 50 cm or more depth. This process, along with the high lightning strikes in the area, fractures the bedrock over large parts of the periglacial domain, and makes available material for erosional agents. Chemical weathering of the igneous rocks at lower elevation produces finer debris (Dietsch et al., 2014). Small pingo mounds, related to

subsurface seasonal ice wedges in the narrow alluvial plains of the Indus hinder cropping practices. Ladakh is also home to many fluvial, lacustrine and aeolian landforms, both present and past. Major fluvial landforms include the gravel-dominated alluvial fans along the hill slopes, strath terraces, valley-fill outwash terraces and lake-outburst terraces, as also the narrow sandy alluvial plains along the sluggish channels of the Indus and the Shyok. Typical aeolian landforms include the obstacle sand dunes along the hill slopes (also called the ‘sand ramps’, e.g., near Shey and Karu) and small crescentic dunes (e.g., in the Nubra valley). Examples of lacustrine features are the large and small lakes (e.g., Pangong Tso, Tso Kar). Chrono-stratigraphic records from the above landforms provide clues to the importance and time of endogenic and exogenic processes on the landscape development (Pant et al., 2005; Dortch et al., 2010; Sant et al., 2011; Bhutiyani, 2014; Dietsch et al., 2014; Juyal, 2014; Kumar et al., 2017; Kumar and Srivastava, 2017). At micro-level various physical and chemical weathering processes operate to either break down the solid material for the erosional agents, or to indurate the materials. The landforms appear to have their altitudinal niches. Thus, the glacial landforms are mostly found in the uppermost part of the mountainous terrain, followed at lower altitudes by the periglacial features, and then the fluvial, aeolian and lacustrine features near the valley bottom (Fig. 4).

Despite having an arid climate, Ladakh hosts the upstream reaches of one of the most important rivers of the Indian Subcontinent, the Indus, which originates from near Mt. Kailas in Tibet. Within Ladakh the Indus flows approximately in a SE to NW direction along a structural strike in the suture where the Indian and the Eurasian plates got locked, i.e., the Indus Suture Zone (ISZ). The river divides the barren and glaciated hill ranges in the north, composed essentially of the granodioritic batholiths of the Ladakh Range, the Khardung volcanics, the Pangong migmatites and the Karakoram crystalline complex, from the craggy subsidiary northern ranges of the Zaskar with colourful indurated molasses and flysch, as well as the sedimentaries and the crystallines of the lofty Zaskar Range and the High Himalaya further south (Thakur, 1983; Thakur and Misra, 1984). The Indus valley has evolved as an intermontane depression between the Ladakh Batholith and the Zaskar Range due to the persistent northward movement of the Indian plate since the early Eocene. Consequently it has suffered compressive deformation and progressive shortening (Garzanti and Van Haver, 1988).

The major tributary of the Indus in the district is the Shyok River from the north that flows almost parallel to it, and forms a barbed drainage pattern together with the Nubra River, suggesting river capture or back-tilting of the headwaters (Juyal, 2014). Smaller tributaries from the Zaskar Range in the south include the Zaskar and the Suru, which have deeply incised their beds in the Indus Molasse deposits along the ISZ, as the deposit has been subjected to a NE thrusting across the Indus valley since 14 Ma, resulting in a shortening of the Molasse width by ~36 km, uplift of the bedrock and base level adjustment by the streams across the deposit (Sinclair and Jaffey, 2001; Jamieson et al., 2004).

A number of glaciers occur in the region. Small cirque glaciers are numerous in the Ladakh Range, especially on its N-facing slopes, as well as in the Zaskar Range, while the longer ones occur further north in the Eastern Karakoram Range (>10 km long) and the Central Karakoram Range (>70 km long), the latter hosting the Himalaya's longest glacier, the Siachen, despite the fact that precipitation in the region decreases from SW to NE (Wallis et al., 2016). This apparently

Figure 4. Dominant geomorphic features along the Indus River valley near Leh and its surroundings, as mapped from field studies and satellite image interpretation. The moraines are both lateral and terminal. Other notable landforms in the area (but not shown) include an amphitheatre valley at Leh, and a host of periglacial, glacio-fluvial, fluvial and lacustrine features. Background image is a SRTM-90m DEM. Inset map shows the major terrain configuration of Ladakh district, as seen on SRTM-90m DEM.

paradoxical glacier distribution pattern is related to the terrain elevation and terrain uplift rates, which increase progressively northward from the Indus valley in response to the gradual crustal shortening and thickening of sediments from the ISZ northward. It has triggered higher exhumation rates of the bedrocks in that direction (i.e., 0.09–0.47 mm/y in Ladakh Range to 0.65–0.70 mm/y in Eastern Karakoram) since ~7.4 Ma (Wallis et al., 2016).

Past glacial cycles

Based on observations in the Shyok and the Nubra valleys, Dortch et al. (2010) identified three major glacial stages at ~45 ka (Deshkit-1), ~81 ka (Deshkit-2) and ~145 ka (Deshkit-3), and suggested that glacial advancement across the region was largely related to ISM precipitation. Compilation of results from several studies on moraine deposits, however, reveal ten periods of glacial

advancement (i.e., glacial stages) in the Leh and Nubra valleys (Burbank and Fort, 1985; Owen et al., 2006; Dortch et al., 2010, 2013). The Indus valley glacial stage is one of the oldest, dated to ~430 ka (Owen et al., 2006). The moraines of Leh valley glacial stage are dated to ~311 ka. Deshkit-3 stage in Shyok valley, Kar glacial stage and Skardu glacial stage in Skardu valley (157±13 ka; Seong et al., 2007) appear to be synchronous (Owen et al., 2006; Dortch et al., 2010). The Ladakh-4, Deshkit-2 and Pangong-2 glacial stages are dated to ~80 ka, while the Bazgo glacial stage took place ~61 ka. Deshkit-1 and Pangong-1 glacial stages are dated to ~46 ka, Ladakh-2 glacial stage to ~20 ka (MIS-2), Ladakh-1 stage to ~13.9 ka, and Ladakh cirque and Pangong cirque stages to ~1.7 and ~0.4 ka, respectively (Owen et al., 2006; Dortch et al., 2010, 2013). In the Zaskar Range, evidence for four glacier advances was found (Sharma and Shukla, 2018). The oldest stage (SZS-4) was equivalent to MIS-4, while SZS-3 occurred during LGM, and SZS-2 during a post-LGM

glacial period (15.7–14.3 ka). SZS-1 has been dated to mid-Holocene (~6 ka). Thus, the periods of glacial advancement in the region are now found not to be restricted by exclusive summer or winter precipitations, but to the relative strength of both climatic forces. Nagar et al. (2013) found evidence for extensive glaciation in Nubra valley during the LGM, which was related to the winter precipitation from the westerlies.

Valley fill sequences

The glacial events generated enormous sediments within the region, which got slowly transported downslope by the streams as debris flow, outwash fan and valley filling (Fig. 5 A and B). As a result, the valley floors started to gradually fill up along the Indus and its tributaries from both north and south, and subsequently channel incision also took place through those in-filled valleys (Burbank et al., 1996; Leland et al., 1998; Phartiyal et al., 2013; Blöthe et al., 2014; Kumar and Srivastava, 2017; Jonell et al., 2018). At least three pulses of aggradation have been identified from sediment dating, centred at ~52 ka, ~28 ka, and 16 ka (Blöthe et al., 2014; Kumar and Srivastava, 2017). The aggradation and incision processes divided the Indus valley into two segments: (1) from Nyoma to Leh, characterized by one level of channel filling, and (2) from Leh to Dah Hanu, characterized by one fill and one strath terrace. Apart from the above, an older filling event along the Indus at ~200 ka and a younger filling at ~8–6 ka in the Zaskar rivers were also identified (Blöthe et al., 2014; Jonell et al., 2018). In the Karakoram, valley filling along the Tangste River took place during intensified monsoon at 48 ka and 30–21 ka, especially through glacio-fluvial, fluvial and lacustrine sedimentation (Phartiyal et al., 2015).

Lacustrine records

Dating of several lacustrine deposits revealed an interesting sedimentation pattern. Lacustrine deposits at Spituk is dated to 50–30 ka, while that at Lamayuru (Fig. 6 A) is >35 ka (Kotlia et al., 1997; Phartiyal et al., 2005). A string of palaeo-lake deposits along the downstream reaches of the Indus between Nimu and Batalik revealed dates of ~11 ka (at Saspol), 17–14 ka (Rizong), 15–5 ka (Khalsi), ~11 ka (Achinathang) and 14–6 ka (Biamah), which suggested that the

lake levels rose from 35 ka to 5 ka, but also that the rise in temperature and monsoon influences might not have been consistent over the period (Nag and Phartiyal, 2015).

Sand ramps and their palaeoclimatic records

The sand ramps of Ladakh (Fig 6 B) provide a composite record of aeolian deposition, hillslope debris and fluvial processes. Most of these occur along the hill slopes bordering the Indus, especially at Spituk, Leh, Saboo, Choglamsar, Thiksey, Shey and Stakna. Aeolian

Figure 5. (A) A valley fill sequence showing debris flow and fluvial deposits along the Indus River near Mahe village. (B) A panoramic view of the alluvial fan at Nurla.

sand is sourced from the adjacent Indus floodplain, especially during the hot and dry months of March-June when strong wind winnows the finer sand particles from the floodplain to deposit them along the hill slopes, especially where vegetation cover is low. Thus, the process efficiency depends on ample sediment availability, strong winds, and low vegetation cover (Kumar et al., 2017). Hillslope runoff during the subsequent summer tends to partly wash down the aeolian sand and deposit coarser fluvial materials from upslope on them. The process is continuing through the millennia, leading to mm-scale stratification of aeolian and fluvial deposits in the ramps. Thicker overall deposits of aeolian/fluvial deposits (but with smaller stratifications within) provide evidence for the duration of the enabling drier or wetter climate. Sedimentological analysis indicates increased precipitation and intra-dune lake formation at places during wetter climatic phases.

Dating of sediments in the sand ramps at Shey, Choglamsar, Saboo and Spituk reveal two major aeolian accretion phases: Phase-I during 25-15 ka and Phase-II 12-8 ka (Fig 7; Kumar et al., 2017). An older aeolian phase at $\sim 44 \pm 3$ ka was identified from a sequence near Shey. Phase-I (25-15 ka) includes several short-term, relatively wetter spells punctuating the overall dry phase of the Last Glacial Maxima (LGM). These increased the threshold moisture and possibly increased the plant cover for sand trapping. Studies on glacial moraines in Ladakh showed glacial advances during phase-I (Owen et al., 2006, 2008; Demske et al., 2009; Dortch et al., 2010, 2013; Phartiyal et al., 2013; Owen and Dortch, 2014). Phase-I sand accumulation has also been observed in the Chinese loess records (Porter, 2001).

The high occurrence of slope-wash and channel gravels in Phase-II (12-8 ka) sediments and the intra-dune lake deposits (~ 12 ka at Shey) suggest an overall wetter climate during their formation. The glacial and Tso Kar lake records suggest glacial expansion at 10.6 ± 0.7 ka and 8.3 ± 0.5 ka (Owen et al., 2006; Dortch et al., 2013), and an arid phase during 13.5-11.5 ka and 8.5-7.0 ka (Demske et al., 2009; Wünnemann et al., 2010).

Comparison with past aeolian phases in Thar Desert

To understand the climates of sand accumulation in the Thar Desert and the Ladakh Himalaya, their chronologies were compared with the chronologies for Guliya ice core (Thompson et al., 1997), effective moisture for the Himalaya (Herzschuh et al., 2006) and the Indian

Figure 6. (A) A landslide-dammed palaeolake deposit at Lamayuru. (B) A sand ramp at Nyoma.

Ocean sea surface temperature (SST) reconstructed from the Mg/Ca values of planktonic foraminifer *Globigerinoides ruber* (Saraswat et al., 2005). It reveals quite contrasting climatic phases for the two regions (Fig 7). While aeolian sand accretion in the Thar Desert took place mainly during the strengthening phases of the SW monsoon, that in Ladakh took place mainly during the cold arid phases.

Neotectonic activities

Information on neotectonic activities in Ladakh is scarce and spatially discordant. Dietsch et al. (2014) suggest that Ladakh Range is quiescent since mid-Miocene, while Phartiyal et al. (2015) inform that the Tangste river valley preserves some evidence for neotectonic activities along the Karakoram Fault. Along the Stok thrust on the SW margin of the Indus valley Sinclair et al. (2017) have calculated from terrace dating and structural mapping, a horizontal displacement rate of ~ 0.21 m per ka since 45 ka, which has constricted the valley by ~ 0.1 m per ka and migration of the river channel towards the NE direction. Evidence for recent tectonic activities has also been gathered from the strath terraces along the Indus and the Zaskar (Blöthe et al., 2014; Munack et al., 2014; Kumar and Srivastava, 2017).

Figure 7. The proxy data for paleoclimate is compared with the sand accumulation for both cold and hot deserts in India. The dashed black line indicates atmospheric temperature changes from Guliya ice core (Thompson et al., 1997), the solid black line shows effective moisture (Herzschuh et al., 2006) for Tibetan Plateau, and the dash and dot grey line indicates sea surface temperature in the Arabian Sea, reconstructed from *Globigerinaruber* (white) Mg/Ca ratio (Saraswat et al., 2005). The top-most bars on glacial stages represent the timing of glacial extension in Ladakh (Owen et al., 2006; Phartiyal et al., 2013). The bars on Thar Desert represent the timing of sand accumulation in Thar Desert (Kar, et al., 2001, 2004; Singhvi and Kar, 2004; Kumar et al., 2017), while the bars on sand ramps in Ladakh Himalaya indicate the periods of sand accumulation in Ladakh.

Present-day human impact and likely future

As development activities are increasing in Ladakh, incidence of encroachments on the natural systems are also increasing. Construction of roads and buildings on unstable slopes, or across the ephemeral drainage pathways on the fan deposits, has made the landscape more vulnerable to landslide, sheetwash and flooding, with consequent damages to the infrastructures. A recent example is the catastrophic flood in Leh and surrounding areas during August 2010, which was related to a cloud-burst (Juyal, 2010; Ziegler et al., 2016). Although such high rainfall events takes place at periodic intervals, the recent construction spree on shallow channels of the alluvial fans and along the debris-covered hill slopes started to block the natural drainage system on the alluvial fan deposits, especially around Leh and Choglamsar. The high run-off generated during the cloud-burst got obstructed by the new infrastructures and, finding no natural escape routes, destroyed whatever came downslope. Added to this problem is the impact of recent anthropogenic climate change that shows a warming trend with reduced number of days of precipitation, but with increased incidence of high-intensity rains. Such a scenario may lead to increased incidence of drought and flood (Chevuturi et al., 2018). Geo-hazard mapping, risk assessment and preparedness may help to mitigate such events (Hart and Hearn, 2018).

Conclusions

It is evident from the above review that the arid landscapes of

Thar Desert and Ladakh provide very interesting clues to their respective evolutionary histories, but that the landscapes are very dissimilar in the two areas, despite the fact that the landscape histories of both the areas are related to the fluctuating SW monsoon. While Thar Desert is part of the hot arid region, and has its landforms developed on a stable platform, Ladakh is a part of the cold arid region where the terrain is mountainous. Aeolian processes are dominant in Thar Desert, but glacial and periglacial processes dominate in Ladakh. Even the past climatic phases for aeolian process acceleration in the two deserts were dissimilar during the past. The landscape of both the regions, however, is vulnerable to excessive human pressure and future climate change, which may lead to accelerated soil erosion and land quality degradation. This calls for judicious use of the land resources for long-term sustainability.

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