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THE GEOMORPHOLOGICAL SURVEY OF THE PSEUDOKARST IN THE AREA OF LAMAYURU PALEOLAKE BADLANDS (MOONLAND), LADAKH REGION, INDIA

Abstract: Móga J., Kohán B., Csüllög G., Strat D., Kiss K. & Suresh M., T*he geomorphological survey of the pseudokarst in the area of Lamayuru paleolake badlands (Moonland), Ladakh region, India.* (IT ISSN 0391-9838, 2019).

Lamayuru Badlands have developed in the area of lacustrine sediments of a former lake from Ladakh region, North-West India that was set up 35-40,000 years BP at 3,600 m above sea level due to a catastrophic landslide triggered by the neotectonic activity on the Indus Suture Zone. After disappearance of lake, around 1000 years ago, the exposed sediments, which had thicknesses up to 200 m and consisted of alternating beds of mud, clay, mud-clay, silt clay, sand, breccia, and carbonate rich beds, were partially removed by fluvial erosion. Also, due to lithological characteristics of the sediments, neotectonic activity and climate conditions a peculiar badland landscape within a cold dry mountainous desert was created. The badland landscape, which evolved under natural conditions, is dominated by dissected east-west valleys and interfluves whereon overlap the semi-carbonate karst landforms expressed by a dense sinkholes network that resulted into topographic surface with egg crate morphology.

Key Words: Lamayuru paleolake, Ladakh, lacustrine sediments, cold arid climate, badlands, pseudokarst.

INTRODUCTION

Pseudokarst was defined as karst-like landforms, such as caves and sinkholes, which were primarily produced by a process other than dissolution (Halliday, 2007). Badlands and piping pseudokarst was recognized as one of the nine pseudokarst types that have been differentiated by geomorphologists (Halliday, 2007) although, according to Otvos (1976) only features resulted by piping belong to pseudokarst even there are a great diversity of morphologically karst-like landforms developed on other than limestone by dissolution processes. Furthermore, Eberhard and Sharples (2013) assert that pseudokarst is "not an appropriate umbrella term for describing morphologically karst-like phenomena" (p.111).

Badlands are defined as intensely dissected natural landscapes where vegetation is sparse or absent (Bryan & Yair, 1982) and consist of diversity of landforms usually carved into clay-rich deposits. Because badlands are erosional forms, their morphology progressively changes as they develop (Harvey, 2006). These peculiar landscape features are widespread both in dry and wet regions, although these highly erodible landscapes mainly appear in semi-arid and arid environments (Yair & *alii*, 1980; de Ploey, 1989). Consequently, in the last decades they have been subject of many studies that were reviewed by Gallard & *alii* (2013). Using the climatic criterion, expressed by annual precipitations amount and vegetation factor control, Gallart & *alii* (2002) classified badlands into three major types: arid badlands (annual precipitations < 200 mm), semi-arid badlands and humid badlands (annual precipitations > 700 mm).

The iconic and paradigmatic badland landscapes that were described are those from Mancos Shale, Utah, and Brule Formations (Badlands National Park), South Dakota in USA, Dinosaur Badlands, Canada (Howard, 2009) and Zin Valley Badlands from Negev Desert (Yair & *alii*, 1980).

Within European Mediterranean regions *calanchi* and *biancane* are two distinguishable badland landscapes that differ in morphology primarily due to specific physical and chemical properties of the lithology (Ciccacci & *alii*, 2008). However, their thorough study, apart from the parent material properties (sediment size and clay mineralogy), have taken into account the topography, tectonics,

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rainfall quantity, vegetation, and land use (Canton & *alii*, 2001; Ciccacci & *alii*, 2008; Desir & Marín, 2013; Pulice & *alii*, 2013; Summa & Giannossi, 2013; Torri & *alii*, 2013; Vergari & *alii*, 2013; Nadal-Romero & *alii*, 2014; Cocco & *alii*, 2015). The reference works on badlands from the warm-arid and semiarid regions are those of (Bryan & Yair, 1982; Kuhn & Yair, 2004; Kuhn et *alii*, 2004; Howard, 2009; Yair et *alii*, 2013).

Piping pseudokarst or synonymous tunnel erosion accompanies badlands very often. The piping was defined as the progressive removal of dispersive clays and clastic particles within weakly consolidated sediment by shallow ground water movement (Eberhard & Sharples, 2013; Bartolomé & *alii*, 2015) that leads to the formation of underground channels in natural landscapes (Parker & *alii*, 1990) and it is analyzed as an extension of the badlands systems (Bryan & Yair, 1982; Halliday, 2007). Tunnel erosion and piping is commonly associated with desiccation cracking (Faulkner, 2013).

Due to the presence of subsurface drainage that induces formation of channels, caves, sinkholes, funnel-shaped drains, arid valleys, natural bridges and sinkhole-like slumps, there is a striking similarity with real karst forms, even where the carbonate content of the sediments is at a minimum level. The typical landforms are created by the periodically evolving water flows on bare, moderately steep areas, mainly on slopes consisting of granular rock, rich in silt and clay (Parker, 1963; Jakucs, 1977; Parker & Higgins, 1990; Zhu et *alii*, 2002; Veress, 2004; Waltham, 2004; Móga & Németh, 2005; Halliday, 2006; Kiss & *alii*, 2007).

As the water streams down the slope, it seeks for a path partly on the surface and in small cracks, carrying away and moving the fine particles from the rough ones, which eventually leads to material loss and cavitation. In clay sediments, which are prone to swelling when they absorb water and shrinking when become desiccated, the swelling and shrinking alternates continuously, thus resulting larger and smaller cracks in the rock, which serves the piping.

Within regions with rainfall and temperature seasonality, badland erosional processes are confined to the wet season but microclimate may strongly influences geomorphic development (Bryan & Yair, 1982). In the mid-latitude regions and mountainous areas during the winters fluvial action is limited but instead, due to freeze-thaw cycles, significant amounts of materials are moved frost creep on steep and unstable slopes. However, wetting-drying and freezing-thawing processes are involved in formation of a weathering layer on the bedrock called regolith (Gallart & *alii*, 2002), which also, in turn, is an important control factor of erosional processes. The prevailing role of gelivation in weathering processes over wetting-drying cycle within mountainous regions was tested in laboratory (Pardini & *alii*, 1996).

The aim of this paper is to present the pseudokarst developed on the sediments layers of the Lamayury paleolake from Ladakh, India, within a cold dry climate in the last 1000 years. The semi-carbonate karst phenomena have been surveyed in relationship to geological formations. The identified landforms were classified on genetically criteria. In the end, the evolution of geographical environment in the area is presented, with emphasis on evolution of semi-carbonate karst landscape.

REGIONAL SETTING

Lamayuru paleolake is an area of around 3.5 km^2 (Juyal & *alii*, 2004; Juyal, 2014) that represent a former lake depression filled with lacustrine deposits which nowadays are subaerially exposed. It is situated in the western Ladakh region, Trans-Himalaya (NW India), at an altitude of 3,600 m, on the North-Eastern side of the Zanskar Range (fig. 1, 2) that belongs to the Indus Suture Zone (Fuchs, 1979), one of the most active tectonic zones of the Globe (Kotlia & *alii*, 1998). During the Quaternary period, the area of Himalaya were reactivated, major faults that have led to slopes failures and further these have caused the impoundment of rivers and formation of lake basins along the Indus basin (Kotlia & *alii*, 1998; Blothe & *alii*, 2014. One of them was Lake Lamayuru.

Earlier geomorphological works on the area reported that the lacustrine conditions on the Lamayuru River were set up around 35,000 ± 600 years BP (Fort & *alii*, 1989) due to a massive landslide triggered by tectonic activity that induced damming of the Lamayu drainage (Kotlia & *alii*, 1998). Based on charcoal dating, initiation of the lacustrine sedimentation in the basin started around 40,000 years BP (Bagati & *alii*, 1996), a moment which coincides with a regional tectonic event in the Trans-Himalaya. Recently, Valdiya and Sanwal (2017) advocate that Lake Lamayuru is a result of strong movements on a fault pair trending NW-SE, which are perpendicular to the valley that was ponded.

However, the tectonic activity that leads to the occurrence of the Lake Lamayuru and other lakes along Indus valley (Phartiyal & *alii*, 2005) is evidenced by the various geomorphic features within Trans Himalaya area (Kotlia & *alii*, 1998; Blöthe & *alii*, 2014; Nag & Phartyal, 2015) and the sedimentation model for Lake Lamayuru proposed by (Shulkla & *alii*, 2002) reveals basin evolution both under neotectonics influences and changing climatic conditions of the area.

The Lake Lamayuru survived until around 400-1000 years BP, when it was drained, either due to a substantially debris flow from adjacent mountain slopes that was poured into the valley and breached the lake (Fort & *alii*, 1989), or possibly because of the structural disruption of the lake floor that was tectonically induced, earlier to debris flow event (Kotlia & *alii*, 1998).

At the moment there is no data available nd unambiguous date for the depletion of lake although the disappearance of Lake Lamayuru about 1000 years ago (Fort & *alii*, 1989) is geomythologically supported by the legend of the establishment of the Lamayuru monastery (Keilhauer & Keilhauer, 1982; http://lamayuru.com/our-monastery/history/), which was reported by researchers of the area since were published first studies in XIXth century (Fort & *alii*, 1989). Moreover, it is reported that Lamas of the XVI th-century monastery state that in that time the monastery was situated on the shore of a big lake (Valdiya & Sanwal, 2017).

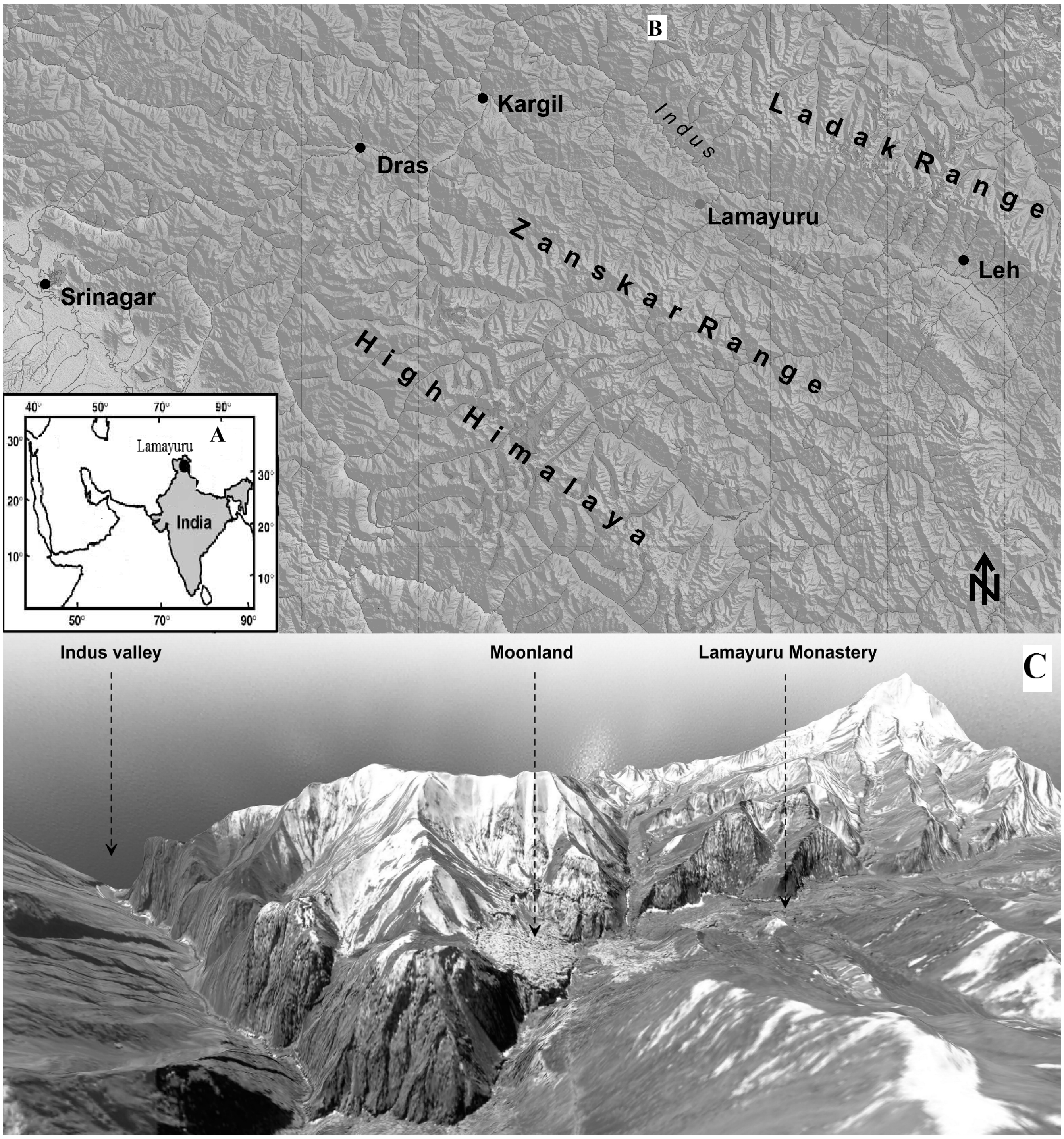

FIG. 1 - Location map of Lamayuru paleolake (A). Shaded topography of the Indus Suture Zone with location of Lamayuru peleolake (B). Position of Lamayuru paleolake deposits/Moonland (Lamayuru badland terrain) related to Indus Valley (C).

The remained paleo-lacustrine and associated sedimentary deposits have a considerable vertical thickness, up to 200 m (Fort & *alii*, 1989), according to the original topography of the floor developed in the first phase, and are partially coped by debris from its adjacent drainage basin (Nag & Phartyal, 2015). The basement rocks of lacustrine depression are composed of argillaceous and calcareous Lamayuru flysch (Fuchs, 1979) and Tethyan carbonates (Bagati & *alii*, 1996).

The Lamayuru palaeolake deposits were lithological described, dated with different dating methods, and paleontologically investigated (Kothlia & *alii*, 1997; Kothlia & *alii*, 1998; Blöthe & *alii*, 2014; Nag & Phartyal, 2015). The results indicate that Lake Lamayuru was formed during a cold and humid climate, which according to dating of the lacustrine sediments, this kind of environment have persisted until 25,000 years BP (Nag & Phartiyal, 2015). Previously asssessement, based on plant impressions and charcoal fragments from the basal part of sediment, indicate in the region a warm temperate climate up to around 30,000 years BP (Bagati & Takur, 1993).

After a sequence of 105 m thick lacustrine deposits was investigated using palaeomagnetic, paleontological and sedimentological methods, five lithological units were identified that shows an increase in grain size from lake mud at the base to cobble-size clasts at the top (Kotlia & *alii*, 1997). The sedimentation in the paleolake took place in form of lacustrine muds, deltas, fluvial sands and colluvial debris flow (Kotlia & *alii*, 1997; Kotlia & *alii*, 1998). Of the five lithological units, four are clastic in nature and one is biogenic and comprises carbonate layers interbedded with clayey/silty horizons that contain oncoliths, shells and charophytes. The lacustrine sedimentation that took place in a shallow water environment is proved by the carbonate-rich strata containing abundant organisms, high organic content and *Chara* algal concretions (Fort & *alii*, 1989; Kotlia & *alii*, 1997).

The late quaternary remnant lacustrine deposits comprises mudstone, siltstone and sandy shale facies that have been sculpted into dramatic badlands landscape and paleokarst features, locally called "Moonland rocks". However, the lake sediments, if are not hidden by debris and rock slides resulted from post-lacustrine mass wasting processes, can be observed only in excavations, under the regolith, a few cm thick clay and carbonate polygonal-cracked crust that covers the surface.

The geographical location and topography of the area explains its cold arid climate. The region lies in the rain shadow of the Himalayas and the mean elevation of landforms exceeds 3500 m. As a result winters are long and piercing cold and summers are short and mild. Based on the climatological records at Leh, the nearest meteorological station to Lamayuru Moonland, which is located at 3506 m above sea level, the mean annual precipitations is around 100 mm (Flohn, 1958, quoted by Fort & *alii*, 1989; Archer & Fowler, 2004; Blöthe & *alii*, 2014; Gupta & Arora, 2017; India Meteorological Department 2017). During the winter, from December to March, the entire Ladakh region is under the influence of Westerly winds which brings precipitation in the form of snow (Blöthe & *alii*, 2014). The summer rainfalls are caused by the Indian summer monsoon (Demske & *alii*, 2009) and sometimes cloudburst and associated flash floods events occur and may have exacerbate impacts in a cold desert with very sparse vegetation as happened in 2010 (Thayyen & *alii*, 2013). The relative humidity is low throughout the year, ranging between 50 percent in January and 33 percent in June.

The mean annual air temperature is 5.7 °C. January is the coldest month and August is the warmest. Due to the high altitude, the area receives considerable solar radiation and is characterized by large diurnal temperature range. From September to May the night temperature remains below the freezing point and even during the summer months, when the mean daily air temperature varies between 22 and 25 °C, the mean minimum temperature of the nights remains below 8 °C.

A recent study revealed that the climate over Leh shows a warming trend with reduced precipitation in the current decade (Chevuturi & *alii*, 2016) but increasing the frequency of cloudbursts as dramatic rainy events in the last years (Thayyen & *alii*, 2013).

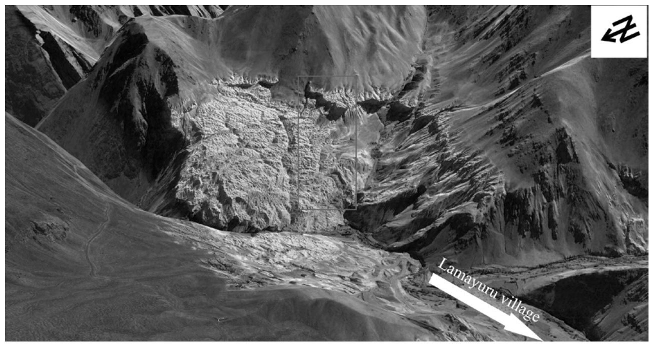

FIG. 2 -The close view of the Lamayuru Moonland. The sampled plot that was surveyed is outlined by red polygon. The southern half of the lacustrine floor sediments was removed almost entirely by erosional activity of the Lamayuru River. The extension of the former lake floor is marked by scarps in the remnant sediments on the mountains slopes.

MATERIAL AND METHODS

The field work was carried out in August 2007 and 2012. During the field survey we made observations over geomorphic diversity related to the lithological structure of the area and pesudokarst processes. Detailed investigations were performed over the site that is located eastward to the Lamayuru village (fig. 3), next to the pathway which starts from 'Moonland view' parking lot and leads to the Lamayuru Badland terrain.

In order to determine the carbonate content of the sediments that support development of pseudokarst processes we collected five sample of material from the area where semi-carbonate karst landforms occur within the study site (fig. 3). Samples 1, 2 and 4 were taken from the area of a big pit that emerged by the fusion of many sinkholes, but for each one was chosen a different sedimentary strata. The first sample was taken from a sloping lacustrine succession, yellowish-grey, and easy crumbling. The sample 2 was taken from the polygonal-cracked crust that covers the ground surface around the previously mentioned sinkholes, while the sample 4 derives from the layered lake sediment beneath the previous crust.

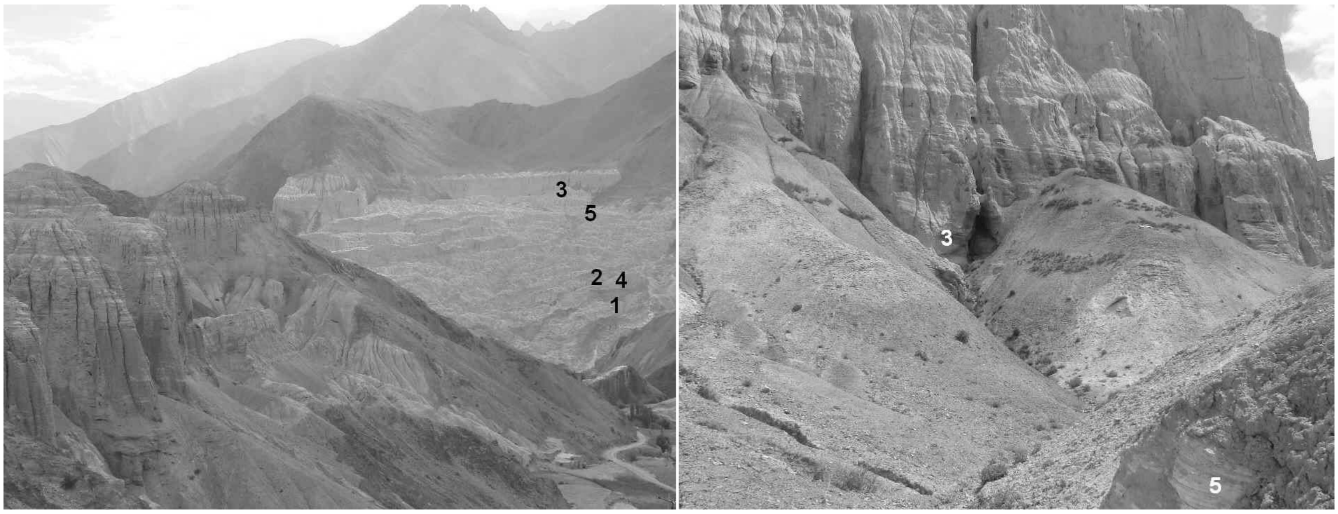

FIG. 3 - The sampling profile on the west east direction (left picture). The numbers indicate the sampling sites. Close view of sampling sites 3 and 5 (right picture).

Sample 3 was taken from the upper layer of the lake succession formations, from the wall of a spring cave that was formed at the base of a nearly 30-50 m high scarp edge, which surrounds the former lake depression. Sample 5 derives from the white marl layer within was created a deep wadi with steep slopes that proceeds from the abovementioned cave.

Apart from macroscopic examination, for all sediment samples were performed laboratory analyses: particle-size distribution test, determination of carbonate content which was measured by Scheibler calcimeter method, and determination of the hygroscopic moisture content (hygroscopicity, *hy*) following Kuron method (Mados, 1938). Laboratory determinations have taken place in the laboratory of the Department of the Physical Geography of the Eötvös Loránd University according to the appropriate methodology MSZ 12749: 1993 (http://www.mszt.hu).

For the map (fig. 1) and images of geographical location of Lamayuru palaeolake (fig. 2 and 3) were used Google images that were drawn using the program Aster GDEM v2 Worldwide Elevation Data (1 arc-second Resolution) downloaded from Global Mapper 17.

The description and classification of the badland features and paleokarst processes that have been developed on lacustrine deposits is based on the published classical taxonomy (Parker, 1963; Parker & Higgins, 1990; Jakucs, 1977; Bryan & Yair, 1982; Zhu & *alii*, 2002; Waltham & *alii*, 2004; Halliday, 2006; Ford & Williams 2007; Kiss & *alii*, 2007).

RESULTS AND DISCUSSIONS

Grain size analysis

After the analyse of particle-size distribution of all five sediment samples, the results showed that there are similarities between them. However, samples 1, 2, 4 make a cluster on the one hand, and samples 3 and 5 are another cluster, on the other hand.

The grain-size distribution for the textural classification of sampled sediments 1, 2 and 4 is shown in fig. 4. It has been found that the dominant particles have size diameter that ranges between 0.05 and 0.02 mm, which means they belong to the silt fraction, followed by particles lower than 0.01 mm that represents clay. These silt and clay particle have presumably fluvial origin. The fine gravels, with various colours, size and origin as well as the sand grains fractions, which were removed after sifting with 0.2 mm sieve, are an additional proof. On the whole, the silt and fine sand fractions are dominant in these sediment samples.

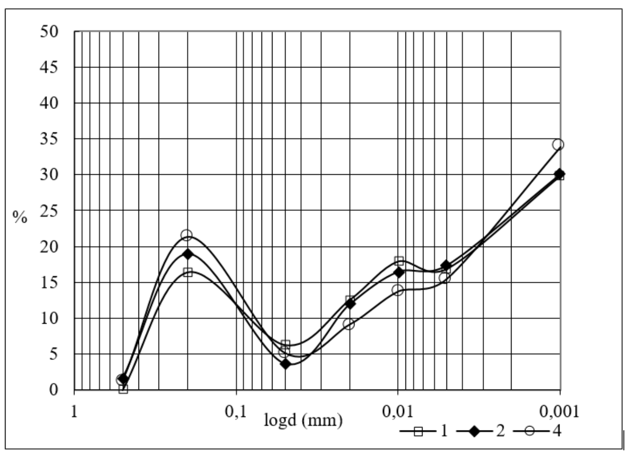

FIG. 4 - The grain-size distribution of sediment samples 1, 2 and 4 collected from the top of Lamayuru lacustrine formations. The number indicates the site sample number.

Sample 3, which derived from the rock layer of the spring cave, was a white-yellowish white sediment with a very high contain of lime that has contributed to agglutination of component particles. As a result it was dificult to establish the real distribution of fractions size, despite the fact that the sediment material was crumbly. The sample, also, had contained organic particles, consisting of fragments of shells with size between 0.2 and 0.6 mm.

Sample 5 originates from a lacustrine sedimentation environment. It is a extremelly white succesion, beneath the rock layer of the spring cave, and consists of mud with a high content of biogenic lime that shows as a white, visibly stratified, easily fragmented sediment alongside the laminar layers, without any fossils. The clay content is low and similarly to sample 3, it may crumble relatively easily. Both type sediments, 3 and 5, described as chalk marls, are calcareous and accumulated limestone.

Carbonate content and hygroscopicity

With respect to the carbonate contain, as expected, considering the sampling sites and the results of particle size assessment presented above, the highest values were measured in sample 3 and 5, which means over 80% and 60%, respectively.

The carbonate content of the other three samples is much lower than of the two above, as follows: 24.6% in sample 1, 13.2% in sample 2, and only 7.2% in sample 4. In the latter case it may be assumed that the carbonate content is higher in the surface-covering crust than in the sediment layer below it.

The hygroscopicity of sampled sediments (fig. 5) ranges between 1.25% and 1.75% for sample 1, 2 and 4, with the lowest value in case of sample 3 and highest value in case of sample 5, respectively, despite of its low clay content.

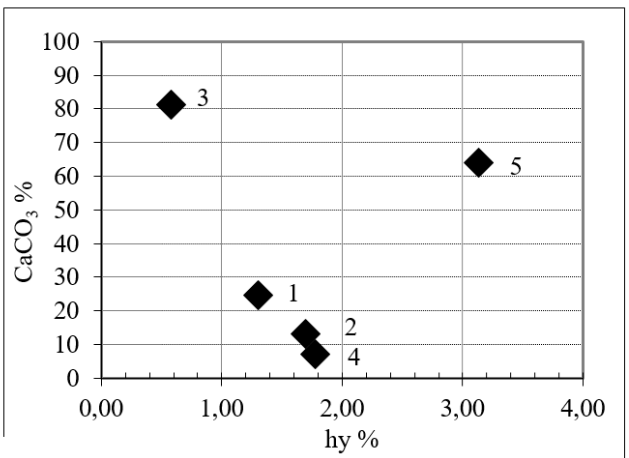

FIG. 5 - The carbonate content and hygroscopicity of the sampled sediments from Lamayuru paleolake. The numbers indicate the collected samples.

Comparing the results of calcium content and hygroscopicity in combination with fieldwork observations allowed us to conclude that the conditions for the development of the karstification processes are met in the case of the area from where collected sample 3 and 5, although in the area of site sample 5, the sediment material is less presumable for karstification because it has tendency to fall apart easily. The less suitable for karstification is the sediment from where originate the sample 4.

Based on the carbonate content examination it is obvious that sediments with various carbonate content have played a major role in the setting up of the landforms diversity over time since Lamayuru paleo lake sediment surface became subaerially exposed. Therefore, in the area of the bottom sediments of the former lake Lamayuru, the geomorphological landscape could be described as a badland where a semi-carbonate karst has evolved on the surface of the sediment layers due to various carbonate-contain.

Peculiar landforms of the semi-carbonate terrain

Due to the lithological proprieties of the lacustrine sediments and the cold dry desert environment, in the area of the former Lake Lamayuru has developed a badland landscape with a highly dissected topography and a great diversity of typical features. The density of ephemeral water courses is extremely high. The rills and trenches are usually shallow, with few decimetres wide in the upper part and begin larger as they converge to the Lamayuru River, when they merge into tens of meter deep and look like canyons.

The above ground and underground waters vary frequently – considering the characteristics of the rocks – on small areas as well. Because of the alternation of sediment layers with larger and smaller lime content (sandwich structure), thousands of sinkholes and funnels have evolved (fig. 6). They have usually small water catchment area, considering their diameter range between 10-40 m. The majority of funnels are open, usually continuing in pipes, and during rainfall events lead the runoff water to the near (10-50 m) spring entrance (fig. 7, 8). The sinkholes from the study area were grouped based on their age/stage of evolution and morphological position.

According to stage of evolution, three types of sinkholes were differentiated: 1) the insulated sinkholes; these are the youngest sinkholes, usually attached to undeveloped passage, but are not part of any sinkholes network. 2) The mature stage is indicated by the joint of the sinkholes into a system, the formation between them of a conduit-like passage, and occurrence of a spout (fig. 7). 3) The old stage is revealed by the breaking of the edges of sinkholes, their merger and the collapse of the passage ceilings.

According to their morphological position, the sinkholes are referred to the autogenic and allogenic terrains (Jakucs 1971; Ford & Williams, 2007).

The sinkholes developed on the autogenic terrains, meaning lacustrine sediments, are those on the flat terrains of larger calcareous lake sediment layers. They are usually small but are numerous, of the order of several hundred in the study site (fig. 6).

Compared to the large number of sinkholes there are significantly less typical sinkholes or sinkhole-like forms on the lake sediments. Those pits and closed cavities that have a diameter of several tens and hundreds m and are without surface runoff are separated from the sinkhole terrains regionally as well. A remarkably small amount of sinkholes can be found at the bottom of these pits, furthermore at the bottom of the sinkholes without sinkhole there are often traces of longer and shorter water level and traces of salt that deposited in the height of the periodic water level and water suffusion.

FIG. 6 - The high density sinkholes gives an eggs crate look like apearence of the landscape.

FIG. 7 - Sinkholes along a tectonic line (left picture). The mature stage is indicated by the joint of the sinkholes into a system (right picture. On the radial slopes the rill network merge into sinkholes.

The sinkholes on the allogenic terrains are those that evolve at the border zone, when the bedrock (Lamayuru flysch) that reaches the surface and the calcareous sediment layers, and also at the border of the lake sediment layers with bigger and smaller lime content and distinct resistivity (fig. 8). Pervious passages and caves are another features developed on the semi-carbonate terrains of Lamayuru paleolake due to subsurface erosion.

In most of the cases the underground pervious pipes and rill tunnels that proceed from the sinkholes and funnels do not reach the size of a cave. They are short, tight tubular passages with small cross-section. Their formation is associated with the tectonic lines and dislocation planes that evolved from larger cave-like corridors or young tectonic movements. Another explication could be that they developed due to the increased periodic water drop at the morphological stairs/scale. In the first case, the traces of tectonic activity are distinctive. In the latter genesis circumstances, the passages formed are narrow-tall corridors with canyon-like incision. The existence of an underground water flow is revealed by the occurrence of numerous funnels and cave-like holes. Over time, the funnels may evolve into sinkholes, but they do not necessarily have large water catchment area.

The spring outlets of the periodically underground streams emerge at the edge of the aquitard layer (flysch, clay sediment, marl) and under the morphological stairs. In addition to sinkholes, natural bridges with piped discharge tunnels occur.

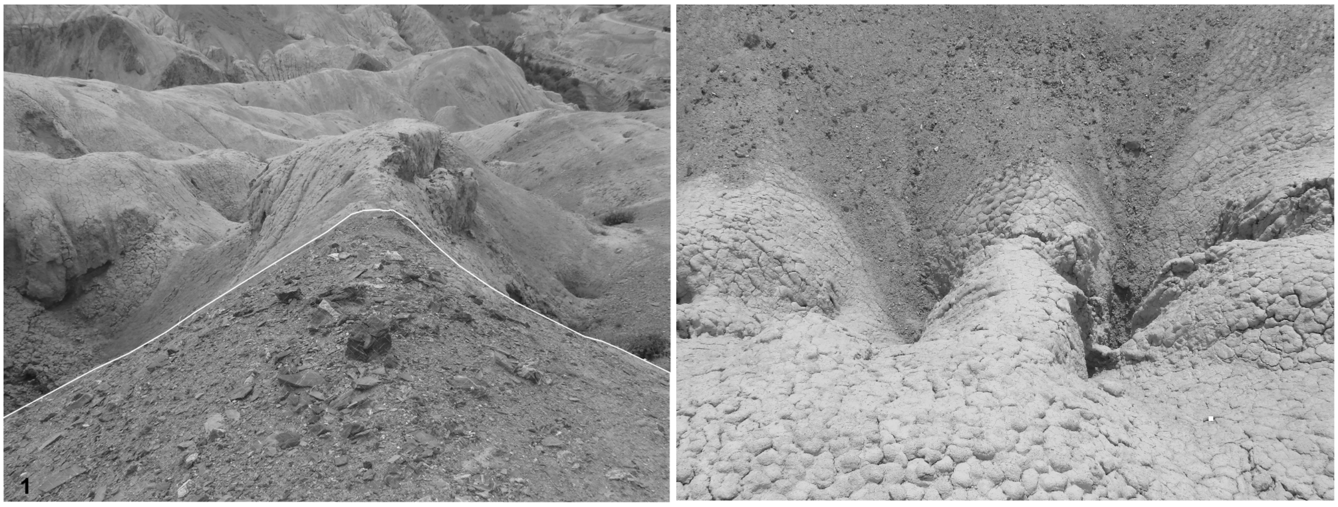

FIG. 8 - Sinkholes developed on the allogenic terrain, at the contact zone of flysch bedrock with lake sediments, 1. flish badrock (left picture). Colluvial material provided by weathering of flysch is collected into sinkholes (right picture).

The surface of the semi-carbonate terrains from the Lamayuru study site is covered with brownish-yellow crust with polygonal cracks which in some areas leads to "pop-corn" surfaces. The crust (regolith) has a higher clay content and hygroscopicity rate than the lacustrine sediments beneath it. Carbonate precipitations and crusts similar to the cave speleothem coatings cover the steep scarps and leaned walls of the larger cavities (fig. 9).

The evolution stages of the Lamayuru paleolake area

Based on the literature review, our field survey and laboratory analyses, we distinguish the following main stages of the Lamayuru semi-carbonate karst area's development:

Phase 1: The incision of the Lamayuru valley. This happened on the flysch formations in the area of the Zanskar mountain range that belongs to the Indus Suture zone, on the left side of the Indus Valley.

Phase 2: The formation of Lake Lamayuru due to a catastrophic landslide caused by neotectonic movements that dammed Lamayuru River about 40,000-35,000 years BP.

Phase 3: Sedimentation. The fill sequence, over 110 m thick, reveals an interplay of lacustrine to fluvio-deltaic to colluvial processes operating in response to changing climate and tectonic conditions within the area during the Late Pleistocene.

Phase 4: Disappearance of Lake Lamayuru. After the lake was drained about 1000 years ago, the Lamayuru River reshaped a new valley into the loose sediments.

Phase 5: Development of the badland landscape and semi-carbonate karst formations (fig. 10). The lithology of exposed sediments from the former lake with suitable texture and cementation degree and the arid climate that avoided existence of vegetation cover were favourable conditions for water erosion and development of an intensely dissected natural landscape called badlands. However, typical landforms associated to badland-like geomorphology such as rills, gullies, ravines, canyons, hoodoos, have been developed in the area of the Lamayuru paleolake sediments. In addition, piping, tunnel erosion and mass-wasting processes enhance the features diversity of the topographic surface.

Due to high erosion rates the interfluve high ridges of the flysch bedrock were exhumed in some places as a hard bedrock spots or as a detritus. In the areas of former valleys that were filled with lacustrine deposits, due to the great thickness of sediments, fluvial erosion, runoff and piping have worked only on the top of stratified sediments.

In certain areas, the flysch bedrock outcrops above the current topographic surface of paleolake sediments that settled on it, therefore the runoff water washes away the loose regolith produced by weathering of flysch rock over the lighter-coloured crust developed on the lacustrine sediments surface (fig.8).

The periodic water flows – swallowed in the soft and calcareous layers – have created semi-carbonate karst formations in the last 1000 years.

We believe that the badland landscape was created soon after depletion of the lake when, most probably, the denudation rate reached the maximum. Then, the denudation rate, taking into account the rainfall amount during the summer and the frequency of rainstorms events from the area, has decreased fallowing the formation of coating crust. The formation of crust fosters an "autostabilisation" of the slopes, which increase their resilience to runoff erosion, but favor support the piping and pseudokarst processes.

Anyway, in order to estimate the current rate of erosion and the future evolution of the Moonland Lamayuru landscape it requires organization of erosion tests on the field as well as replicate of freeze-thaw cycles.

To conclude, the Lamayuru Moonland may be the representative badlands of weak sedimentary rocks in a mountainous cold-dry region, where the average annual precipitation is about below 100 mm/year (Demske & *alii*, 2009), which is very similar with precipitation amount from the area of Zin Valley Badlands that is located in the northern Negev desert (Yair & *alii*, 2013).

Fig. 9 - Runoff and crusts similar to the cave speleothems coatings cover the steep scarps and leaning walls of larger cavities.

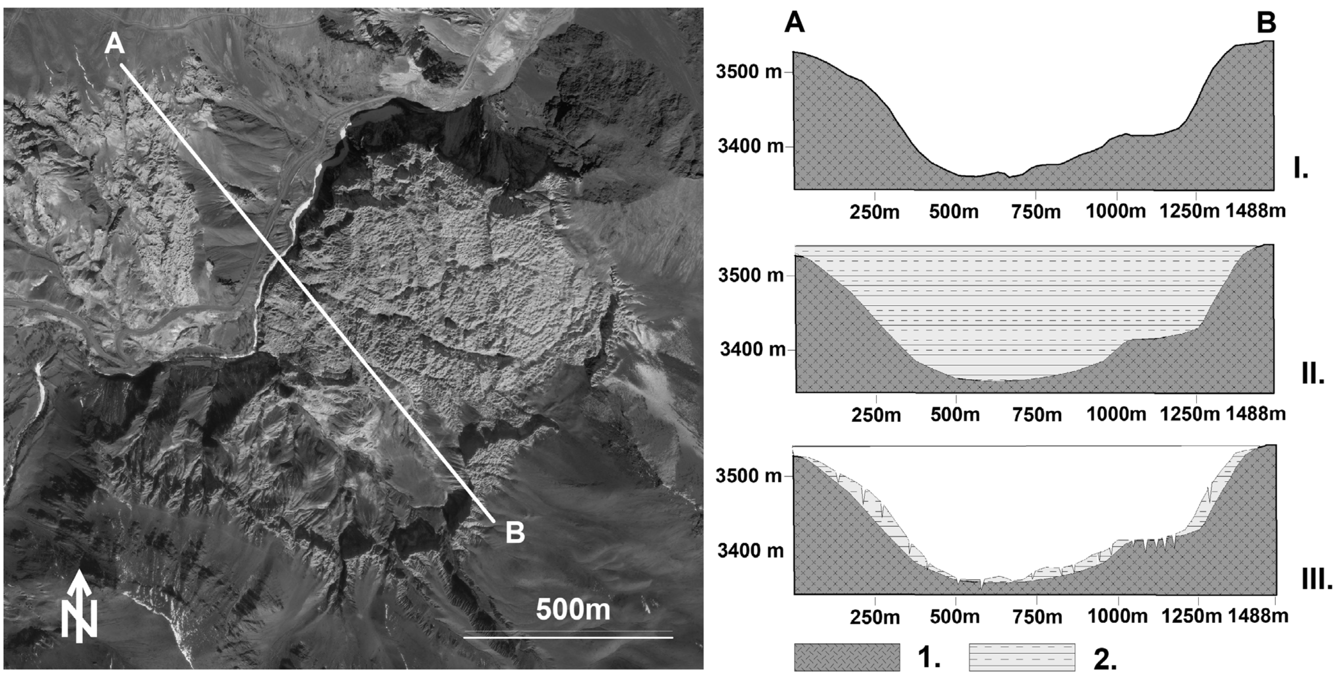

Fig. 10 – The main stages of the Lamayuru semi-carbonate karst area's development: I. Incision of the Lamayuru valley. II. The formation of Lake Lamayuru due to a catastrophic landslide caused by neotectonic movements that dammed Lamayuru River and sedimentation. III. After the lake was drained the Lamayuru River reshaped a new valley into the loose sediments. Development of the badland landscape and semi-carbonate karst formations. 1. flish bedrock, 2. lake sediments.

CONCLUSIONS

The geomorphological investigations of the Lamayuru paleolake revealed that the exposed Lamayuru paleolake sediments have experienced dramatic fluvial erosion during the late 1000 years, after the lake depleted due a tectonic event, that induced a higher erosion rate in the first period after fluvial sediments have become subaerial exposed.

The high clay content of the bedrock and cold arid climate played a key role in developing a peculiar badland landscape, called Moonland, within the area of northern half of the lake floor sediments.

Due to alternation of soft and resistant sediment layers, alternation of permeable and impermeable layers, alternation of layers with larger and smaller carbonate content, and development of a cracks network, pseudokarst processes and features have occurred. The main landforms are sinkholes, which given their high density, overall, have leaded to an eggs crater topographic surface.

REFERENCES

ARCHER D.R. & FOWLER H.J. (2004) - *Spatial and temporal variations in precipitation in the Upper Indus basin, global teleconnections and hydrological implications*. Hydrology and Earth System Sciences, 8 (1), 47-61.

BAGATI T.N. & THAKUR V.C. (1993) - *Quaternary basins of Ladakh and Lahaul-Spiti in northwestern Himalaya*. Current Science 64 (11-12 Special Issue), 898-903.

BAGATI T.N., MAZARI R.K. & RAJAGOPALAN G. (1996) - *Palaeotectonic implication of Lamayuru lake (Ladakh)*. Current Science,71 (6), 479-482.

BARTOLOMÉ M., SANCHO C., MORENO A., OLIVA-URCIA B., BELMONTE Á., BASTIDA J., CHENG J. & EDWARDS R.L. (2015) - *Upper Pleistocene interstratal piping-cave speleogenesis: The Seso Cave System (Central Pyrenees, Northern Spain)*. Geomorphology, 228, 335-344. doi: 10.1016/j.geomorph.2014.09.007.

BLÖTHE J.H., MUNACK H., KORUP O., FÜLLING A., GARZANTI E., RESENTINI A. & KUBIK P.W. (2014) - *Late Quaternary valley infill and dissection in the Indus River, western Tibetan Plateau margin*. Quaternary Science Reviews, 94, 102-119. doi: 10.1016/j.quascirev.2014.04.011.

BRYAN R. & YAIR A. (1982) - *Perspectives on studies of badland geomorphology.* In: BRYAN R. & YAIR A. (Eds.), Badland Geomorphology and Piping. Norwich: Geo Books. Regency House, 1-14.

CANTON Y., DOMINGO F., SOLE-BENET A. & PUIGDEFABREGAS J. (2001) - *Hydrological and erosion response of a badlands system in semiarid SE Spain*. Journal of Hydrology, 252, 65-84.

CHEVUTURI A., DIMRI A.P. & THAYYEN R.J. (2016) - *Climate change over Leh (Ladakh), India*. Theoretical and Applied Climatology, 1-15. doi: 10.1007/s00704-016-1989-1.

CICCACCI S., GALIANO M., ROMA M.A. & SALVATORE M.C. (2008) - *Morphological analysis and erosion rate evaluation in badlands of Radicofani area (Southern Tuscany - Italy)*. Catena, *74*, 87-97. doi: 10.1016/j.catena.2008.03.012.

COCCO S., BRECCIAROLI G., AGNELLI A., WEINDORF D. & CORTI G. (2015) - *Soil genesis and evolution on calanchi (badland-like landform) of central Italy*. Geomorphology, 248, 33-46. doi: 10.1016/j.geomorph.2015.07.031.

DE PLOEY J. (1989) - *Erosional systems and perspectives for erosion control in European loess areas*. Soil Technology Series, 1, 93-102.

DESIR G. & MARÍN C. (2013) - *Role of erosion processes on the morphogenesis of a semiarid badland area.Bardenas Reales (NE Spain)*. Catena, 106, 83-92. doi: 10.1016/j.catena.2013.02.011.

DEMSKE D., TARASOV P.E., WÜNNEMANN B. & RIEDEL F. (2009) - *Late glacial and Holocene vegetation, Indian monsoon and westerly circulation in the Trans-Himalaya recorded in the lacustrine pollen sequences from Tso Kar, Ladakh, NW India*. Palaeogeography, Palaeoclimatology, Palaeocology, 279, 172-185. doi: 10.1016/j.palaeo.2009.05.008.

EBERHARD R. & SHARPLES C. (2013) - *Appropriate terminology for karst-like phenomena: the problem with 'pseudokarst'*. International Journal of Speleology, 42 (2), 109-113. doi: 10.5038/1827-806X.42.2.2

FAULKNER H. (2013) - *Badlands in marl lithologies: A field guide to soil dispersion, subsurface erosion and piping-origin gullies*. Catena, 106, 42-53. doi: 10.1016/j.catena.2012.04.005.

FORD D. & WILLIAMS P. (2007) - *Karst hydrogeology and geomorphology.* John Wiley & Sons Ltd., 576 pp.

FORT M., BURBANK D.W. & FREYTET P. (1989) - *Lacustrine Sedimentation in a Semiarid alpine Setting: An example from Ladakh, Northwestern Himalaya*. Quaternary Research, 31, 332-350.

FUCHS, G. (1979) - *On the Geology of Western Ladakh*. Jahrbuch Geologische Bundesanstalt, 122 (2), 513-540.

GALLART F., SOLE A., PUIGDEFABREGAS J. & LAZARO R. (2002) - *Badland Systems in the Mediterranean*. In: BULL L.J. & KIRKBY M. (Eds.). Dryland Rivers: Hydrology and Geomorphology of Semi-Arid Channels. John Wiley & Sons Ltd., 299-326.

GALLART F., MARIGNANI M., PÉREZ-GALLEGO N., SANTI E. & MACCHERINI S. (2013) - *Thirty years of studies on badlands, from physical to vegetational approaches. A succinct review*. Catena, 106, 4-11. doi: 10.1016/j.catena.2012.02.008.

HALLIDAY W. (2006) - *Piping caves and badlands pseudokarst*. In: GUNN J. (Ed.) Encyclopedia of caves and karst science, Taylor & Francis e-Library, 1260-1968. https://sudartomas.files.wordpress.com/2012/11/encyclopediaof_cavesandkarstscience.pdf.

HALLIDAY, W.R. (2007) - *Pseudokarts in the 21st century*. Journal of Cave and Karst Studies, 6 (1), 103-113.

HARVEY, A (2006) - *Badland dynamics*. In: GOUDIE A. (Ed.) Encyclopedia of Geomorphology (Vol. I). Routledge, London, 47-48.

HOWARD A.D. (2009) - *Badlands and Gullying*. In: PARSONS A.J. & ABRAHAMS A.D. (Eds.) Geomorphology of Desert Environments, 2nd edition, Springer, 265-299. doi: 10.1007/978-1-4020-5719-9.

JAKUCS L. (1977) - *Morphogenetics of Karst Regions.* John Wiley & Sons, New York. 284 pp.

JUYAL N., PANT R.K., BASAVAIAH N., YADAVA M.G., SAINI N.K. & SINGHVI A.K. (2004) *Climate and seismicity in the Higher Central Himalaya during the last 20 ka*. Paleogeography, Paleoclimatology, Paleoecology, 213 (3-4), 315-330. doi: 10.1016/j.palaeo.2004.07.017.

JUYAL N. (2014) - *Ladakh: The High-Altitude Indian Cold Desert*. In: VISHWAS KALE (Ed.) Landscapes and Landforms of India. Springer, Dordrecht,115-124.

KEILHAUER A. & KEILHAUER P. (1982) - *Ladakh und Zanskar. Lamaistische Klosterkultur im Land zwischen Indien und Tibet, DuMont Kunst-Reiseführer*. DuMont Buchverlag, Köln, 414 pp.

KISS K., ZÁMBÓ L., FEHÉR K. & MÓGA J. (2007) - *A lösztakaró karsztosodásban játszott szerepének vizsgálata a Tési-fennsíkon. Karsztfejlődés XII. Szombathely*, 193-205.

KOTLIA B.S., SHUKLA U.K., BHALLA M.S., MATHUR P.D. & PANT C.C. (1997) - *Quaternary fluvio-lacustrine deposits of the Lamayuru Basin, Ladakh Himalaya: preliminary multidisciplinary investigations*. Geological Magasine, 134 (6), 807-812.

KOTLIA, B.S., HINZ-SCHALLREUTER I., SCHALLREUTER, R. & SCHWARZ, J. (1998) - *Evolution of Lamayuru palaeolake in the Trans Himalaya: Palaeoecological implications*. Eiszeitalteru Gegenwart, 48, 177-191.

KUHN N.J. & YAIR A. (2004) - *Spatial distribution of surface conditions and runoff generation in small arid watersheds, Zin Valley Badlands, Israel*. Geomorphology, 57(3-4), 183-200. doi: 10.1016/S0169-555X(03)00102-8.

KUHN N.J., YAIR A. & GRUBIN M.K. (2004) - *Spatial distribution of surface properties, runoff generation and landscape development in the Zin Valley Badlands, norther Negev, Israel*. Earth Surface Processes and Landforms, 29 (11), 1417-1430. doi: 10.1002/esp.1115.

MADOS (KOTZMANN), L. (1938) - *Hygroscopic moisture, as characteristic of soil texture* (In Hungarian). Mezőgazdasági Kutatások, 11, 217-229.

MÓGA J. & NÉMETH R. (2005) - *The Morphological Research of the basalt and loess covered plateaus int he Bakony mountains (Transdanubian Middle mountains – Hungary)*. Acta Carsologica, 34 (2), 397-414.

Nadal-Romero E., Petrlic K., Verachtert E., Bochet E. & Poesen J. (2014) - *Effects of slope angle and aspect on plant cover and species richness in a humid Mediterranean badland*. Earth Surface Processes and Landforms, 39 (13), 1705-1716. doi: 10.1002/esp.3549.

Nag D. & Phartiyal B. (2015) - *Climatic variations and geomorphology of the Indus River valley, between Nimo and Batalik, Ladakh (NW Trans Himalayas) during Late Quaternary.* Quaternary International, 371, 87-101. doi: 10.1016/j.quaint.2014.08.045.

Otvos, E.G. (1976) - *Pseudokarst" and "pseudokarst terrains": Problems of terminology.* Geological Society of America, 87(7), 1021-1027. doi: 10.1130/0016-7606(1960)71[467:ABFMTS]2.0.CO;2

Pardini G., Vigna Guidi G., Pini R., Regues D. & Gallard F. (1996) - *Structural changes of smectite-rich mudrocks experimentally induced by freeze-thawing and wetting-drying cycles*. Catena, 27, 149-165.

Parker G.C. (1963) - *Piping, a geomorphic agent in landform development of the drylands.* International Association of Scientific Hydrology Publication, 65, 103-113.

Parker G.G., Higgins C.G. & Wood W.W. (1990) - *Piping and pseudokarst in drylands.* In: Higgins C.G. & Coates D.R. (Eds.) Groundwater Geomorphology: The role of Subsurface Water in Earth-Surface Processes and Landforms, 252, 77-110. Geological Society of America. doi: 10.1130/SPE252-p77.

Phartiyal B., Sharma A., Upadhyay R., Ram-Awatar, Sinha & A.K. (2005) - *Quaternary geology, tectonics and distribution of palaeo- and present fluvio/glacio lacustrine deposits in Ladakh, NW Indian Himalaya - a study based on field observations*. Geomorphology, 65, 241-256. doi: 10.1016/j.geomorph.2004.09.004.

Pulice I., di Leo P., Robustelli G., Scarciglia F., Covalcante F. & Belviso C. (2013) - *Control of climate and local topography on dynamic evolution of badland from southern Italy (Calabria*). Catena, 109, 83-95. doi: 10.1016/j.catena.2013.05.001.

Shulkla, U.K., Kotlia B.S. & Mathur P.D. (2002) - *Sedimentation pattern in a trans-Himalayan Quaternary lake at Lamayuru (Ladakh), India*. Sedimentary Geology, 148 (3-4), 405-424. doi: 10.1016/S0037-0738(01)00160-9.

Summa V. & Giannossi M.L. (2013) - *The Role of Soil Mineralogy, Geochemistry and Grain Size in the Development of Mediterranean Badlands: A Review.* In: Hernandez Soriano M.C. (Ed.) Soil Processes and Current Trends in Quality Assessment. Intech, 3-32. doi: 10.5772/53050.

Thayyen R.J., Dimri A.P., Kumar P. & Agnihotri G. (2013) - *Study of cloudburst and flash floods around Leh, India, during August 4-6, 2010*. Natural Hazards, 65 (3), 2175-2204. doi: 10.1007/s11069-012-0464-2.

Torri D., Santi E., Marignani M., Rossi M., Borselli L. & Maccherini, S. (2013) - *The recurring cycles of biancana badlands: Erosion, vegetation and human impact*. Catena, 106, 22-30. doi: 10.1016/j.catena.2012.07.001.

Valdiya K.S. & Sanwal J. (2017) - *Himalayan Mobile Belt: The Main Arc.* In: Shroder Jr. (Ed.), Developments in Earth Surface Processes. Neotectonism in the Indian Subcontinent. Landscape Evolution, 22, 31-108.

Veress M. (2004) - *A karszt.* Szombathely. 382 pp.

Vergari F., Della Seta M., Del Monte M. & Barbieri M. (2013) - *Badlands denudation "hot spots": The role of parent material properties on geomorphic processes in 20-years monitored sites of Southern Tuscany (Italy).* Catena, 106, 31-41. doi: 10.1016/j.catena.2012.02.007.

Waltham T., Bell F. & Culshaw M. (2004) - Sinkholes and subsidence. Springer, 381 pp.

Yair A., Lavee H., Bryan, R.B. & Adar E. (1980) - *Runoff and erosion processes and rates in the Zin Valley Badlands, Northern Negev, Israel*. Earth surface Processes, *5* (3), 205-225. doi: 10.1002/esp.3760050301.

Yair A., Bryan R.B., Lavee H., Schwanghart W. & Kuhn N.J. (2013) - *The resilience of a badland area to climate change in an arid environment*. Catena, 106, 12-21. doi: 10.1016/j.catena.2012.04.006.

Zhu T.X., Luk S.H. & Cai Q.G. (2002) - *Tunnel erosion and sediment production in the hilly loess region, north China*. Journal of Hydrology, 257, 78-90.

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