


Desert pavements: A hidden key to Earth surface processes

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Abstract

Desert pavements are a global phenomenon in arid environments, representing one of the most extensive geomorphological and geocological features on Earth. To a large extent, they determine the interplay of key processes governing current and past landscape dynamics including landform evolution, surface runoff, soil water dynamics, weathering and soil formation, microbial processes, dust deposition and entrainment into the atmosphere. Hence, desert pavements and their future trajectories of change have a strong local to global impact on coupled Earth system components. However, knowledge of the comprehensive role that desert pavements play in the Earth surface–atmosphere system is still limited, and a profound interdisciplinary understanding of their evolution, spatial extent, microbiological processes, and inherent environmental feedback mechanisms is lacking. This article provides an overview of the current state of knowledge of desert pavements as an important Earth system component and offers an interdisciplinary perspective on the key processes interacting within desert pavements, which improves our understanding of the role and importance of desert pavements within the Earth system.

KEYWORDS

arid environments, desert pavements, earth system, future directions, global relevance

1 | INTRODUCTION

Desert pavements are a global phenomenon in arid environments (Goudie, 2013). They are composed of a monolayer of stones at the surface (Figure 1), albeit the particle dimensions can vary widely, from less than pebble to interspersed boulder sizes. The coarse interlocking fabric can cover almost the entire surface but may also expose significant portions of bare surface underneath (Wood, Graham, & Wells, 2002). That monolayer is associated with an underlying unit of aeolian fines (sandy silt), which exhibits a several centimetre-thick foamy pore structure directly beneath the stones, the vesicular horizon (Anderson, Wells, & Graham, 2002; Dietze et al., 2012; McFadden et al., 1998; Springer, 1958). Depending on the region, these surfaces are known as *serir* (Africa), *gobi*, (Asia), *gibber* (Australia), or *desert pavements* (North America).

With about 50% of arid land surfaces covered by such stone layers (Walker, 1986), desert pavements are probably the most extensive surface feature on Earth, dominating the Earth's surface over any other surface feature (Schultz, 2005). Instead of being predominantly

erosive features, desert pavements together with their underlying fine material need to be interpreted as accretionary phenomena, formed by mineral dust trapping, causing vertical accretionary rise on top of a thickening aeolian mantle (Dietze et al., 2012; Gerson & Amit, 1987; Mabutt, 1977; McFadden, Wells, & Dohrenwendt, 1986). This entire system of stone monolayer and underlying vesicular horizon, which supports a unique microbial ecosystem and set of pedogenic processes, is defined as desert pavement. This perspective goes beyond the simple classic concept of desert pavement as a surface lag deposit (Figures 1 and 2).

Instead of being just a widespread homogeneous surface cover, desert pavements rather show distinct morphological patterns on multiple scales, with a unique set of properties that determine to a significant extent the interplay of processes that govern current and past landscape dynamics: surface runoff, weathering and soil formation, (micro)biological activity, and dust capture and entrainment into the atmosphere (Abrahams & Parsons, 1991; Adelsberger & Smith, 2009; Bullard et al., 2011; Dietze et al., 2012; Genderjahn et al., 2021; McFadden, Wells, & Dohrenwendt, 1986; von Holdt et al., 2019;

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FIGURE 1 Desert pavement landscape. Example from Namibia, south of Bukarros crater, near the town of Berseba (Lat.: -25.981724° ; Lon.: 17.793285°). The inserts show a typical vesicular soil structure sampled beneath the pavement (a) and fine dusty material (b) below the stone surface.

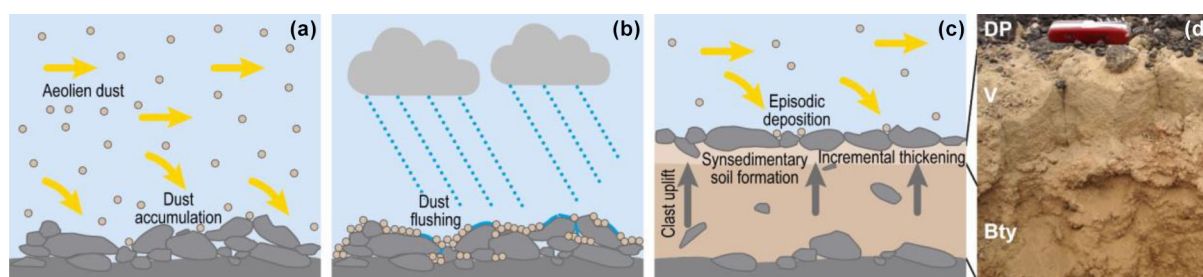


FIGURE 2 Concept of desert pavement formation: (a) The rough stony surface acts as dust trap and (b) episodic rainfall flushes the trapped dust below the stone cover. (c) Rock fragments from the fines migrate upward to the surface by swell–shrink dynamics and by soil air degassing, the latter forming the vesicular horizon. While episodic dust deposition occurs repeatedly leading to incremental thickening, synsedimentary soil formation takes place (Mabutt, 1977; McFadden, Wells, & Dohrenwendt, 1986). (d) The photo shows the typical pedological structure of a desert pavement, with the stones on the surface (DP), and the V and Bty horizons below (knife for scale).

Wells et al., 1985). On a local scale, desert pavements influence, for example, water infiltration, in turn affecting translocation of solids and dissolved substances, soil morphology and texture, vegetation patterns and (microbial) habitats (Hwang et al., 2021; Wood, Graham, & Wells, 2002, 2005). The surface stones protect the underlying fines from wind and water erosion and create at the same time a dust trap (Cooke, Warren, & Goudie, 1993). Acting as both dust source and trap, desert pavements have a direct impact on regional to global atmospheric dust concentrations (Von Holdt, Eckardt, & Wiggs, 2017), modulating the radiation balance, cloud formation and water and nutrient cycles (Schepanski, 2018 and references therein). Therefore, desert pavements represent an important Earth system component, in particular of the Earth's surface.

Although desert pavements presumably have a strong impact on Earth system components via a variety of feedback processes also beyond arid regions (Sweeney, McDonald, & Etyemezian, 2011; Vandenberghe, 2013), their importance for the Earth system has not yet been comprehensively recognised. Discipline-specific and often case-study focussed research on, for instance, topographic, lithologic,

climatic, and hydrologic boundary conditions for the formation and preservation of desert pavements (Abrahams & Parsons, 1991; Cooke, 1970; Dietze & Kleber, 2012; Dunkerley, 1995; McDonald, McFadden, & Wells, 2003) has rarely considered the complexity of interacting Earth system components and their feedback mechanisms (e.g. Adelsberger & Smith, 2009; Al-Farraj, 2008). Thus, despite decades of research on desert pavements, knowledge about this key component of arid landscapes remains fragmented and key questions unresolved.

Desert pavements have been regarded as a static system and until a few decades ago, studies have shown that this model is no longer tenable, as it cannot comprehensively explain the sedimentary structure and genetic evolution of the desert pavement system (Amit & Gerson, 1986; Amit, Gerson, & Yaalon, 1993; Anderson, Wells, & Graham, 2002; McFadden, Wells, & Dohrenwendt, 1986; Wells et al., 1995). Without attributing the additional processes involved in desert pavement formation and preservation, understanding the impact of future landscape change remains challenging and incomplete. Furthermore, systematic information on desert pavement

distribution and the related boundary conditions is still lacking, although rough estimates of the spatial extent of desert pavements have been made (Cooke, 1970; Walker, 1986). Without knowledge of the spatial extent and distribution patterns, upscaling of desert pavement-driven effects remains inaccurate. In addition, the role of desert pavements in the Earth's dust cycle has not been investigated thoroughly so far. This includes the significance of desert pavements as dust sources and sinks, as well as their temporal variability with regard to their source-sink function (Sweeney, McDonald, & Etyemezian, 2011; Von Holdt, Eckardt, & Wiggs, 2017). Simulating interannual variability, whose understanding is the key to climate projections, the presence of desert pavement may reduce or even inhibit dust emissions as long as the surface cover remains intact (Sweeney, McDonald, & Etyemezian, 2011). These open questions are crucial for understanding desert pavements, especially in a world facing drastic environmental change and undergoing systemic transformation. In other words, desert pavements and their crucial role in the Earth system need to be recognised beyond isolated and case study-based investigations. Furthermore, the complexity of interacting system components with their feedback mechanisms has to become the focus of future research initiatives. In this respect, desert pavements need to be considered more vividly across disciplines and beyond the currently oversimplified, static and isolated view.

In this article, we synthesise existing fragmented knowledge on desert pavements, focussing primarily on the stone pavement and the underlying unit of aeolian fines (V horizon), as these represent the soil-atmosphere transition and its interacting processes. We thereby demonstrate the need for an interdisciplinary concept of desert pavement perception to assess its roles as regulator of water distribution, engine for weathering and soil formation, microbiological reactor and host, collector and emitter of climate-relevant dust from and to the atmosphere, as well as recorder and player of landscape evolution. The formation of desert pavements will briefly be reviewed in relation to their boundary conditions, which help to understand the spatial distribution of desert pavements and how an interdisciplinary approach may contribute to shedding light on the processes responsible for the formation, preservation and destruction of desert pavements, as well as on the relevance of desert pavements for the Earth system.

2 | DESERT PAVEMENT FORMATION, BOUNDARY CONDITIONS, DISTRIBUTION AND AGE

2.1 | Desert pavement formation

Although various processes have been suggested to explain desert pavement formation (e.g. Amit & Gerson, 1986), early proposals have always included an erosive component, such as aeolian winnowing of fines from a formerly mixed sediment body, rendering desert pavements a mature lag deposit (e.g. Blake, 1858; Cooke, 1970). That still widely communicated interpretation of desert pavements as a terminal stage of ongoing erosion is challenged by the striking textural, structural and mineralogical difference between the stone cover and the underlying deposit of usually almost stone-free aeolian dust. In essence, such a stark contrast rather implies that

desert pavement formation includes the deposition of aeolian fines (Amit, Gerson, & Yaalon, 1993; Mabutt, 1977; McFadden, Wells, & Dohrenwendt, 1986). While in exceptionally clay-rich soils and under periglacial conditions, exhumation of stones through a fine-grained body of sediment may be an additional mechanism to create a desert pavement (Mabutt, 1977), and the majority of desert pavements in hot deserts can only be explained by the active accretion of aeolian fines and their subsequent integration into the mantle below the coarse surface cover (Figure 2). Once formed, the clasts at the surface experience pronounced mechanical weathering (Amit, Gerson, & Yaalon, 1993; McFadden et al., 2005; Eppes, McFadden, et al., 2003), predominantly driven by insolation trajectories, rock type (and hence mineral composition) and clast geometry. In addition, there are feedbacks of the rock fragments with the fine material below, through vertical element fluxes and pedogenic processes under arid conditions (McFadden et al., 1998), all of which may contribute to the formation of the characteristic dense interlocking clast fabric, emerging clast orientation patterns and the overall effective weathering.

According to the initial concepts for this accretionary formation (Mabutt, 1977; McFadden, Wells, & Dohrenwendt, 1986), the rough stone surface reduces wind shear stress sufficiently to act as a dust trap, and episodic rainfall flushes the trapped dust below the stone cover (Figure 2). Rock fragments engulfed by fines are hypothesised to be pushed upwards because of swell and shrink processes of the substrate, called ped doming (McFadden et al., 1998), which is controlled by water infiltration. Over time, these mechanisms lead to a bisectonal stratigraphic sequence of a continuously exposed stone surface with a thickening virtually stone-free mantle of accretionary fines. The elegance of that concept arises from its uniform applicability to a wide range of desert types and initial sedimentary environments, and delivers a plausible explanation of the stone-free aeolian mantle below the densely packed surface cover.

All the above explanation approaches of strictly vertical desert pavement formation—downward by deflation of fines and upward by accretion of fines—fail to explain the occasional yet systematic existence of sequences of buried desert pavement and vesicular horizons (e.g. Figure 7 in Wells et al., 1985; Figure 6 in Dietze & Kleber, 2012). The deflation concept is unable to accommodate such cases at all. The accretion concept runs into the problem of explaining how dust would further be trapped when the rough stone surface as driver of accretion is buried, and also where a new generation of surface stones may be recruited from. As a consequence, a lateral component needs to be considered that is able to advect fresh coarse material onto previously deposited fines. Throughout different deserts, Dietze and Kleber (2012) have quantified the orientation angle of pavement stone length axes and found an average, symmetric deviation of $40 \pm 14^\circ$ from slope aspect for intact, recovering and buried desert pavements. Such preferred orientation patterns have been explained by water drag force of overland flow events and subsequently tested in laboratory flume experiments and physical modelling (Dietze et al., 2012), yielding a plausible mechanism for sites where the specific catchment is large enough to generate strong episodic overland flow of the required magnitude. Evidence of such sheetflood events has been reported as well (e.g. Wells & Dohrenwendt, 1985). Hence, systematic observations of buried desert pavements and vesicular horizons require the consideration of additional mechanisms. First, surface

transport of fresh pavement stones from local source areas like bedrock outcrops or older desert pavements upslope is vital for the establishment of a new generation of surface cover above a buried one. Second, dust collection independent from the rough stone mantle is needed to explain the burial of an old surface and can be achieved, for example, by climate-controlled vegetation shifts into and out of currently desert pavement covered landscapes (e.g. Quade, 2001).

The described formation and preservation processes represent a system behaviour, defined by external and internal boundary conditions and their interaction. In the following sections, we lay out important aspects of those boundary conditions to develop a framework for the interdisciplinary view on the role of desert pavements for desert hydrology, weathering, soil formation and nutrient cycles, microbiological feedbacks, dust collector and emitter, and recorder and player of landscape evolution.

2.2 | External boundary conditions

External boundary conditions define the formation and preservation of desert pavement through physical and chemical processes that are controlled by climate, hydrology, biology, topography, dust flux and human activity, even though these processes are closely interlinked.

2.2.1 | Climatic and hydrological boundary conditions

Precipitation, temperature and wind are the main climatic elements that define the boundary conditions for desert pavement formation and preservation. Rain that causes surface runoff can directly affect the stone cover of desert pavement systems. Extreme rainfall events with surface runoff exceeding the critical 'bed' shear stress will result in stone transport and subsequent destruction or at least reorganisation of the surface (Wells & Dohrenwendt, 1985). When persisting, even rill and gully erosion will occur within the fine material beneath the surface. Together with temperature, precipitation amount and seasonality have a significant influence on vegetation composition. Vegetation has a negative impact on desert pavements, as root growth destroys the vesicular horizon and fixes the surface rock fragments in place (Dietze et al., 2012; Section 2.3). In combination, this can lead to the burial of a desert pavement as dust may continue to settle at the vegetation-covered surface. Nevertheless, precipitation in limited amounts is needed to form and maintain desert pavements. It ensures that the trapped dust gets washed between and below the surface, and water infiltration is a prerequisite to form the vesicular horizon within the fines directly below the stone cover (Section 2.3). It has been suggested that the current upper limit for desert pavement distribution is around 300 mm average annual precipitation (Dietze & Kleber, 2012), above which vegetation abundance tends to impede vesicular horizon formation and a closed stone cover. A lower limit has not been proposed, and desert pavements have been reported to occur in hyper-arid regions like the Atacama Desert (Cooke, 1970; Warren-Rhodes et al., 2007) or Antarctic landscapes (Bockheim, 2010). In hyper-arid deserts, air moisture and fog are often the dominant water sources, playing a role in desert pavement

formation as well as possibly its inhibition through vegetation growth (Rundel et al., 1991).

Wind is the means of transport for dust from remote sources being deposited on the pavement surface and eventually being incorporated into the desert pavement system. When the stone-protected surface is destroyed, it also becomes the means for the erosion of the fines. Pavement destruction can also be temperature controlled, when temperature enables frost action within the fines as it may become relevant in cold deserts causing cryoturbation.

2.2.2 | Biological boundary conditions

The absence or at least only dispersed occurrence of vegetation is of crucial importance for the conservation and formation of desert pavements (Haff, 2001; Wood, Graham, & Wells, 2005). As soon as vegetation affects not only the surface, but grows into the fines, the process of desert pavement formation will stop because of the destruction of the vesicular horizon. Especially the roots of plants affect the structure of the uppermost soil horizons, but as plants grow bigger, they also destroy the surface cover directly. Animals can both destroy and prevent the formation of desert pavements (Haff, 2001). Burrowing and subterranean animals (e.g. gophers, rabbits and earth worms) reorganise the soil structure, thereby disrupting the processes responsible for pavement formation (Kraus et al., 2022), while larger animals that move on the surface directly destroy the surface by grazing and trampling (e.g. gazelles; Moradi et al., 2023). However, individual animals generally do not cause spatially extensive destruction, but larger numbers, such as animal herds, can cause significant pavement destruction.

Generally speaking, all climatic conditions and soil characteristics that lead to the absence of higher vegetation, or that lead to sparse herbaceous and grassy vegetation, support the formation and preservation of desert pavements. In addition, sparse vegetation patches represent obstacles for the transport of dust and saltating sand on the otherwise smooth surface. Thus, enhanced sedimentation rates at vegetation patches may exceed the possible upward migration rate of the stones (Figure 3). Moreover, the vegetation also provides food and thus attracts burrowing animals, which in turn promote the disturbance or even the destruction of desert pavements.

2.2.3 | Topographic and geomorphic boundary conditions

Topography controls geomorphic, hydrological, biological and soil formation processes that are relevant not only for desert pavements but also for competing Earth surface processes that may inhibit desert pavement formation or preservation. Where slope angles exceed 5°, mass wasting processes such as creep and solifluction (owing to swell-and-shrink processes related to moisture, salt or frost) progressively contribute to surface dynamics and thus inhibit desert pavement-forming processes (Matsuoka, 2001). Rainfall-induced mass wasting processes, such as earth flows may occur even at relatively gentle slope angles > 4° in the absence of vegetation, and soil creep at > 1° (Sidle & Ochiai, 2006), limiting the preservation of desert pavements. Nevertheless, desert pavement may be present at slope angles of



FIGURE 3 Sediment accumulation around plants: In desert regions with high aeolian activity, patches of higher plants lead to enhanced accumulation of aeolian sediment, creating stone-free islands where uplift of clasts cannot keep pace with sediment accumulation. Example from the Gobi Desert, Mongolia (Lat.: 43.600723°; Lon.: 102.938674°).

more than 20° (e.g. Dietze & Kleber, 2012). Furthermore, topographic eminences, such as buttes, are sources of coarse material required for the formation of desert pavement (Dixon, 2009) and exert a control on local wind fields. Conversely, local depressions in landscapes with a poorly developed drainage system as well as lee side topographic positions may be unsuitable for desert pavement formation if the dust deposition rate exceeds the incorporation rate.

Abandoned landform surfaces are particularly suitable for the formation of desert pavement systems. Abandonment means here that the landforms are decoupled from the wider geomorphological process regime, which can be achieved by the incision of alluvial fan surfaces or the erosion of escarpment margins, river terraces or paleo-beach ridges. Abandonment can also be a primary feature, for example, when lava flows modulate the existing drainage system. The predominant effect of abandonment is the prevention of excessive overland flows that tend to remove surface stones.

Among the more common desert pavement-bearing landforms are those that meet the above topographic criteria and provide abundant loose rocks or rubble. These include alluvial fans (Warren-Rhodes et al., 2007; Atacama Desert, Chile; Meadows, Young, & McDonald, 2006; Mojave Desert, California), fluvial terraces (Fuchs & Lomax, 2019; Negev Desert, Israel), table mountains, beach ridges, lava flows (Fuchs et al., 2015; Badia Desert, Jordan; Fuchs & Lomax, 2019; Fuerteventura, Spain) and weathered granite fields (e.g. at the western margin of the Laguna Salada basin, Mexico; Dietze & Kleber, 2012), among others. In the Cima Volcanic Field (Mojave Desert, USA), one of the most intensively studied field sites, desert pavements were described on the erosional remnants of 560 and 270 ka old basalt flows inclined about 2° (Anderson, Wells, & Graham, 2002; Dietze et al., 2016; McFadden, Wells, & Jercinovich, 1987). Here, not only was the presence of desert pavement topographically controlled, but contrasting desert pavement characteristics (fine material thickness, stone size, soil maturity) were also found along a toposequence, for example, near local drainage channels and near local shoulders (Dietze et al., 2016).

2.2.4 | Dust flux boundary conditions

Atmospheric dust flux is a critical boundary condition for both the formation and the preservation of desert pavements. Specifically, a dust deposition flux and the entrainment of mineral particles into the

desert pavement system are mechanisms necessary for the accretionary rise of the stone cover and thickening of the aeolian mantle of fines, and once formed, a desert pavement can be preserved even in the absence of additional dust incorporation. The stone-paved surface inhibits or at least significantly reduces dust emission and hence the loss of fine material via entrainment into the atmosphere. Dust emission flux, dust deposition and the parameters controlling them must therefore be in a dynamic equilibrium for desert pavement to develop, to be maintained, and to not be destroyed by erosion or dust cover.

Dust deposition flux is directly related to the position of the dust source taking distance and prevailing wind direction during dust events into account. This not only determines whether a dust source delivers dust to a geographic location considered; atmospheric residence time and travel pathway may also impact dust particle size distribution and atmospheric dust particle concentration eventually determining the local dust deposition flux. Dust deposition flux is most effective when the source is proximal to the deposition area in an upwind direction. In arid environments, topographic basins with only an internal drainage system (e.g. playas; McFadden et al., 1998) and extensive fluvial fines (Schepanski et al., 2013; Schepanski, Tegen, & Macke, 2012) often represent major dust sources (e.g. Ginoux et al., 2012). After wind erosion of dust from the surface, wind speed is the most important parameter controlling dust transport distance; however, a significant wind speed reduction at surface level is a prerequisite for dust deposition as this reduces the buoyancy of the atmosphere which is needed to keep the dust particles suspended in the air. The surface roughness plays a central role in possible dust deposition, because it controls the wind speed in near-surface air layers (Zhang et al., 2001). Thereby, the surface roughness varies significantly with the spatial scale considered (Menuet et al., 2013; Zhang et al., 2001). At the synoptic scale (10–1000 km), the aerodynamic roughness length is used to take the modulating effect of orography, large vegetation structures like forests or dense built structures like those in urban areas into account (Menuet et al., 2013). The values are in the range of centimetres to metres (Menuet et al., 2013). With regard to dust deposition flux calculations, surface roughness at the synoptic scale impacts the regional and local wind speed distribution, which impacts the local dust deposition flux as it affects the atmospheric dynamics. Complementary to surface roughness at the synoptic scale, surface roughness at the mesoscale (1–10 km), the aeolian roughness, impacts regional and local (at kilometre scale) wind speed distribution (Menuet et al., 2013). Values are generally smaller than at

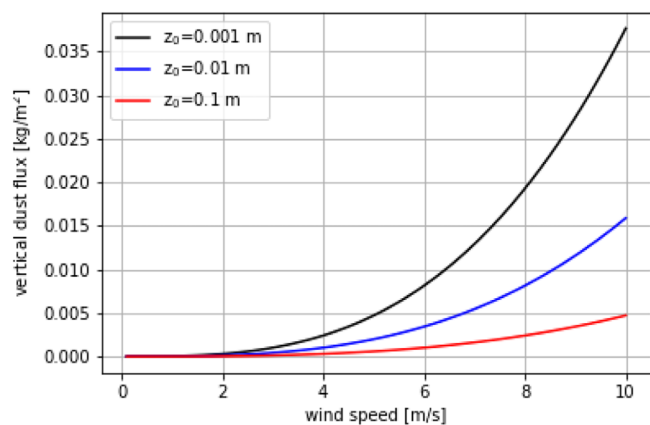


FIGURE 4 Vertical dust emission flux as function of surface wind speed for exemplary smooth and aeolian roughness lengths z_0 . $z_0 = 0.001$ m represents exemplarily smooth playa surfaces (e.g. Darnenova et al., 2009), $z_0 = 0.01$ m represents vegetated surfaces or surfaces covered sparsely by solid obstacles (e.g., Darnenova et al., 2009), and $z_0 = 0.1$ m represents rough surfaces defined by subgrid-orographic elements (Menut et al., 2013), following Marticorena and Bergametti (1995) for medium emitting alluvial fines as defined in Feuerstein and Schepanski (2019).

the synoptic scale and in the range of millimetres to centimetres (Menut et al., 2013). For calculations of the local dust deposition flux, surface roughness at the local scale (1–100 m), the smooth roughness, is of relevance accounting for surface texture and particle sizes (Marticorena et al., 1997). The smooth roughness length is also referred to as aerodynamic roughness length in aeolian research. Here, the surface roughness is used to determine turbulent fluxes ultimately allowing the suspended dust particles to settle onto the surface (Menut et al., 2013; Zhang et al., 2001). Values are calculated as a function of soil particle size diameter (cf. Marticorena et al., 1997).

Whereas the deposition of dust is an essential boundary condition for the formation of desert pavements and describes the gain of particles, dust emission, which describes the loss of particles, balances the input flux of particles. Thereby, dust emission is a function of wind speed, which is modulated by the surface roughness. Depending on the size of roughness elements and hence the roughness length, the surface modulates the near-surface wind speed and hence the momentum available from the atmosphere to ultimately mobilise and inject particles into the atmosphere (Dong, Liu, & Wang, 2002; Marticorena & Bergametti, 1995; Menut et al., 2013; Pye, 1987). The roughness length can be calculated from wind speed measurements under adiabatic conditions via $U(z) = \frac{u_*}{k} \ln\left(\frac{z}{z_0}\right)$ with $U(z)$ the wind speed at height z , k the Von Kármán's constant (-0.4), u_* the wind friction velocity and z_0 the roughness length (Marticorena & Bergametti, 1995). In addition to measurement-based calculations of the roughness length (e.g. Greeley et al., 1997), Marticorena et al. (2004) and Prigent et al. (2005) estimated the roughness length from satellite-based scatterometer measurements for desert surfaces.

Figure 4 illustrates the impact of the aerodynamic surface roughness on the dust emission flux as a function of wind speed for three different roughness lengths. In addition to its impact on near-surface wind speed because of its surface roughness characteristics at local scale, a rough stone covered surface physically reduces dust emission potential.

2.2.5 | Anthropogenic boundary conditions and climate change

Human activities often impact desert pavements directly, for example, through the construction of transport infrastructure or settlements. Off-road driving on desert pavements by motorised sports and military vehicles also causes direct destruction (Webb & Wilshire, 1983), as does the installation of large energy infrastructure like wind or solar farms, or extensive livestock farming (e.g. Namibia, Jordan). Anthropogenic activities outside the desert pavement area can have an indirect influence on desert pavements by affecting dust emission and hence dust deposition fluxes onto the desert pavement. For example, land degradation increases the susceptibility to wind erosion, water management (irrigation, drainage and watersheds) alters the hydrological balance of potential dust source areas such as desert lakes, playas, and floodplains, and mining activities influence the extent and characteristics of exposed fine-grained surface materials through excavation and the deposition of waste rock and tailings (Chen et al., 2018; Sweeney, McDonald, & Etyemezian, 2011; Zucca et al., 2021, 2022). Moreover, anthropogenic climate change has a significant influence on the boundary conditions of desert pavement formation and preservation as it affects the frequency and intensity distributions of factors including rainfall and wind fields directly, and indirectly controls vegetation and land use.

2.3 | Internal boundary conditions

2.3.1 | Pedological boundary conditions

The internal processes that determine the formation and preservation of desert pavements are controlled by boundary conditions within the desert pavement system, such as the formation of the vesicular horizon in the accumulated dust, the weathering of the mainly silt-sized dust particles into clay, and further soil-forming processes like the mobilisation and accumulation of clay, carbonates (Mayer, McFadden, & Harden, 1988), gypsum, and soluble salts (Amit, Gerson, & Yaalon, 1993; Marion et al., 2008). Soil formation over time leads to increasing clay content and soil structure (Young et al., 2004), leading to changes in soil moisture and shrink-swell dynamics. The resulting soil moisture pattern in turn controls soil microbiomes, which cause feedback on desert pavement formation, thus additionally contributing to the pedological boundary conditions.

The vesicular horizon (V) is essential for the preservation of desert pavement and is intrinsically coupled with it (McFadden et al., 1998; Dietze et al., 2012). Its foamy structure originates from abundant round to oval, millimetre-sized vesicles (Figures 1 and 5). In addition, the V horizon is characterised by a coarse prismatic to columnar structure (Figure 6). Thereby, the soil peds exhibit a characteristic internal structure (Anderson, Wells, & Graham, 2002) with respect to the size and shape of vesicles, clay content and soil organic matter content. The polygonal macro cracks between the prismatic or columnar aggregates of the V horizon strongly impact water percolation and particle transport through the V horizon. Moreover, the V horizon shows an internal differentiation with depth. The top part exhibits 0.5–3 mm-sized roundish vesicles. With depth, the vesicles

FIGURE 5 Vesicular horizons (V) formed under natural and laboratory conditions. (a) Naturally formed V from the Tabernacle Hill volcano, Black Rock Desert, Utah, USA (Lat.: 38.90844°; Lon.: -112.53307°). (b) Experimentally formed V produced by repeated wetting and drying of silty material (Dietze et al., 2012).

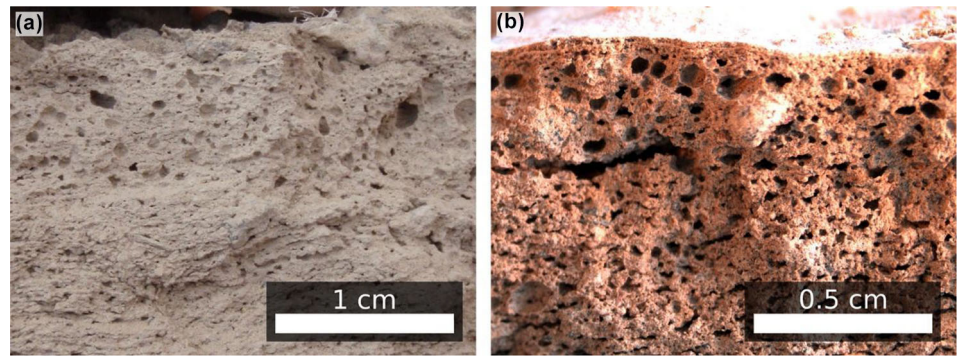


FIGURE 6 V horizon: (a and b) Characteristic polygonal cracks of V horizons in 1×1 m large cleared patches shown from the top. (c) Soil peds obtained from a V horizon below a desert pavement, Cima Volcanic Field, USA (Lat.: 35.16531°; Lon.: -115.80776°).

become increasingly flattened until they give way to a platy soil structure without any vesicles.

The isolated macro pore system of the V horizon has been shown to form because of rapid infiltration of water. As the wetting front advances from the soil surface downwards, it pushes out soil air from the finer pores, but the air cannot escape through the puddled, structureless soil surface (Dietze et al., 2012). As a consequence, gas pressure within the soil increases. This leads to the successive growth of the vesicles, until they eventually collapse (Anderson, Wells, & Graham, 2002). Thus, there is a dynamic equilibrium between vesicle formation and collapse. These dynamics keep the stones at the surface (Figure 2). Under laboratory conditions, a vesicular structure can form in typical dust material by less than 10 wetting and drying cycles (Dietze et al., 2012). As the vesicular structure forms, the infiltration rate decreases exponentially until, under mature natural conditions, hydraulic conductivity is reduced by more than one order of magnitude (Greenbaum et al., 2020; Young et al., 2004). The vesicular horizon thus affects and is affected by soil water distribution via preferential flow along macro cracks at aggregate interfaces and matrix flow into its internal parts (Anderson, Wells, & Graham, 2002; McFadden et al., 1998). Its internal structural differentiation at several different scales corresponds to a multi-scale functional structure. The large prismatic to columnar soil peds (several centimetres in diameter) are responsible for the doming, keeping the covering stones at the surface. In between them, macro-cracks open during sustained dry periods, allowing rapid infiltration of rain water into lower parts of the vesicular horizon as well as into lower soil horizons, if the cracks extend into those. Likewise, the macro cracks allow fine sediments accumulated at the surface to be washed down and incorporated into the soil.

Because the doming caused by the swell-shrink dynamics of the soil peds is a crucial process in keeping the desert pavement at the soil

surface during the ongoing dust accumulation (McFadden, Wells, & Jercinovich, 1987), any factor that enhances the extent of the swell-shrink dynamics contributes to the maintenance of desert pavements. Thus, clay content and clay mineralogy of the soil most likely play a role, too, although to our knowledge their effect has so far not been systematically investigated. McFadden, Wells and Dohrenwendt (1986) reported increased clay contents of V horizons, while their clay-mineralogical composition included no smectites, but mainly illite, kaolinite and illite/smectite mixed-layer clay minerals. In such cases, considerable clay contents are needed to significantly enhance the swell-shrink dynamics.

The stone cover at the surface is exposed to weathering, with thermal cracking being an efficient physical weathering process (McFadden et al., 2005). In addition, salt shattering seems to be a common physical weathering process as described by Amit et al. (1993). Mechanical weathering also takes place subaerial, with moisture as a potential rate-setting factor in the fracturing process (Shaanan et al., 2023).

Because desert pavement formation requires the absence of dense vegetation (cf. Section 2.2), soil characteristics that prevent dense vegetation and shrubs support undisturbed desert pavement formation and long-term persistence. Such properties include, for example, silty texture that tends to form surface crusts, extremely dry soil conditions in the root zone, and salinisation. All of these pedological boundary conditions are interlinked, together supporting the maintenance of desert pavements. In turn, the above pedological boundary conditions may be supported by desert pavements, because desert pavements—acting as dust traps—create the preconditions for extended soil moisture storage, which leads to enhanced chemical weathering and clay mineral formation.

The microbial system is closely linked to the pedological system of desert pavements. As part of the pedosphere, microbial life

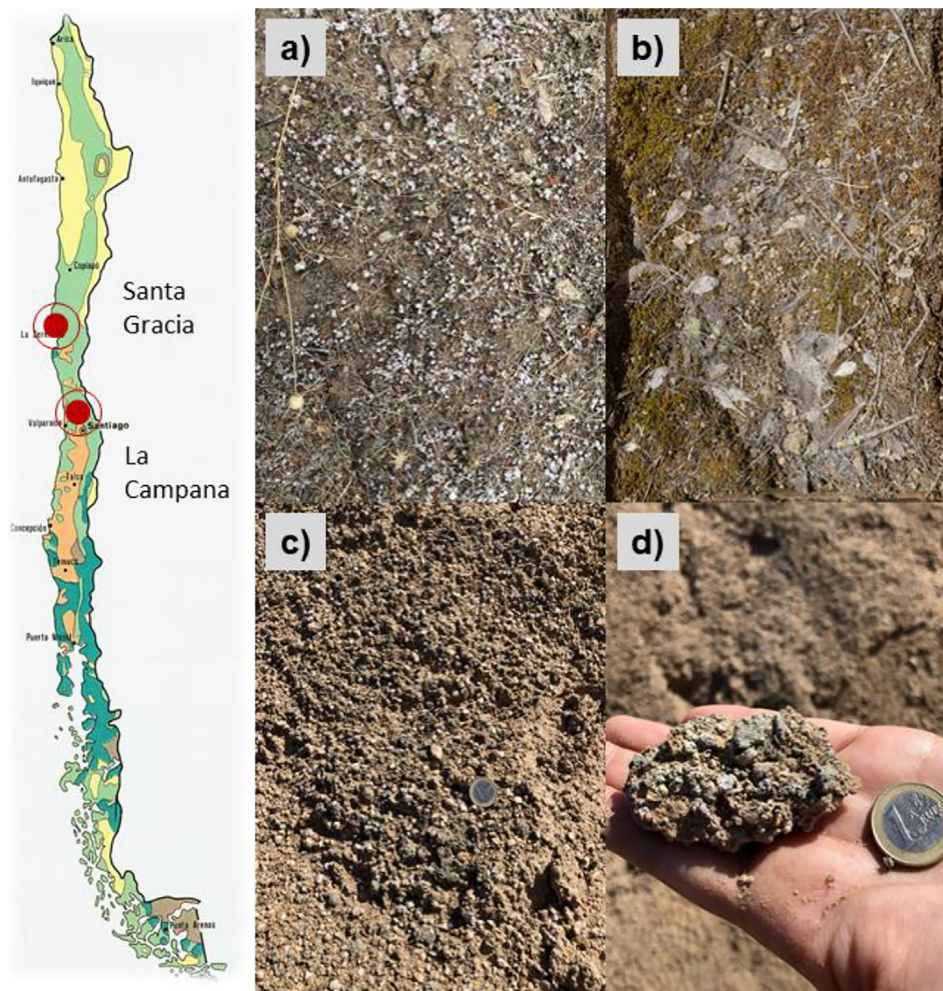


FIGURE 7 Biological soil crusts (BSC) from two different environments in Chile along a climate gradient (left site): (a) BSC from La Campana under Mediterranean climate, (b) BSC from Santa Gracia under semi-arid climate (photo: Nicolás Riveras-Muñoz, University of Tübingen), (c and d) showing the morphology and stability of BSC from Pan de Azúcar (Atacama Desert) under arid climate conditions.

influences pedogenic processes such as weathering and transformation of plant-unavailable nutrients (i.e., nutrients inside primary minerals, and atmospheric carbon and nitrogen) into plant-available nutrients by nutrient uptake during their lifetime and release after their death.

2.3.2 | Microbial life in desert soils and factors influencing microbial communities

Data on microbial communities, their function, and their potential impact on initial soil formation in deserts are still quite rare, in particular with a focus on desert pavements. Nevertheless, during the last two decades, it has become evident that the extreme desert habitats harbour a unique, well-adapted community of microorganisms, and an increasing number of studies have begun to focus on unravelling the structural network, the adaptation mechanisms and the physiological properties of these microbial communities.

Recent studies in the Kalahari region and in the Atacama Desert showed a wide range of gene copy numbers (amount of microorganisms) for bacteria and archaea, from 10^4 to 10^8 and 10^4 to 10^6 g^{-1} soil, respectively (Bernhard et al., 2018; Genderjahn et al., 2018; Schulze-Makuch et al., 2018). The data suggest that these microbial communities have been mainly shaped by geochemical drivers, including water content, salinity and the supply of organic matter. Modern DNA-based (high throughput sequencing) analysis revealed diverse microbial communities characterised by the main microbial phyla such

as Actinobacteria, Acidobacteriota, Bacteroidota, Proteobacteria, Chloroflexota, Firmicutes, Cyanobacteria, Gemmatimonadota and Halobacteria (Bartholomäus et al., 2024; Crits-Christoph et al., 2013; Genderjahn et al., 2018; Vikram et al., 2016). Many of the observed taxa are halophilic and adapted to water-limiting conditions. Another common phenomenon is the so-called biological soil crusts (BSC) which are assemblages of cyanobacteria, green algae, mosses, liverworts, fungi and/or lichens (Figure 7, Belnap & Büdel, 2016; Riveras-Muñoz et al., 2022). BSCs form along with the initial assembly of microbial communities in initial soils; their succession under arid to semi-arid conditions plays a vital role in the susceptibility of the soil surface to erosion (Bowker et al., 2008; Guida et al., 2023).

Another very special habitat for microorganisms in deserts is the desert varnish. Desert varnish is a thin, dark coating found on exposed rock surfaces in arid regions. It is a product of microbial activity and environmental interactions, primarily consisting of manganese and iron oxides, along with clay particles, which are gradually deposited over thousands of years (Goldsmith, Stein, & Enzel, 2014; Watchman, 2000). This surface layer forms a dense, chemically stable crust that protects the underlying rock from wind abrasion, thermal stress and chemical attack, thereby enhancing its long-term weathering resistance. Microorganisms, particularly certain bacteria such as Actinobacteria, Cyanobacteria and manganese-oxidising bacteria, are thought to play a crucial role in concentrating manganese and iron from the environment and facilitating their oxidation, a process that gives desert varnish its distinctive colour and sheen (Krinsley, Dorn, & Tovey, 1995; Lingappa et al., 2021). The microbial

communities involved in this process survive in extreme conditions, relying on minimal water and nutrients, often scavenging trace elements from dust and aerosols. These microorganisms are adapted to UV radiation, desiccation and temperature fluctuations, making desert varnish an extraordinary example of microbial resilience and geochemical activity in extreme ecosystems such as desert pavements (Kuhlman et al., 2008; Lingappa et al., 2021).

Although the majority of studies have focussed on desert soils without or in fragmentary desert pavements, the few studies available to date that have specifically considered desert pavements showed that the soils beneath the clasts harbour a specific microbial community that differs in both composition and abundance from the microorganisms in the adjacent soils. It has been shown that the communities beneath the clasts are highly specialised with cyanobacteria playing an important role in these habitats as primary producers for other microorganisms such as heterotrophic bacteria and archaea (Chan et al., 2012; Gwizdala et al., 2021; Lacap-Bugler et al., 2017; Warren-Rhodes et al., 2006). Another recent study showed that microbial communities beneath boulders in the Atacama Desert were characterised by a high abundance of ammonia-oxidising Thaumarchaeota, which have the potential for nitrogen and carbon cycling (Hwang et al., 2021). In contrast to these findings, these specific organisms are rarely found in desert soils without desert pavement cover. Here the microbial communities are characterised more by UV- and drought-stress-resistant microorganisms such as Actinobacteria, Firmicutes (e.g. spore-forming *Bacillus* species) and Gemmatimonadota (Bartholomäus et al., 2024; Genderjahn et al., 2018; Horstmann et al., 2024; Schulze-Makuch et al., 2018). Another study, which was the first to examine intracellular DNA (DNA from intact, living and potentially active microorganisms) of clasts and soils, was able to show that there are also numerous microorganisms in the soils under the clasts that have the potential to weather rocks (Genderjahn et al., 2021), which is an important process in the course of soil formation.

2.3.3 | Role of microorganisms in the formation of soils and desert pavements

Mineral substrates devoid of organic enrichment, such as saprolite or initial desert soils, are colonised by microbial specialists, including chemoautotrophic organisms such as phototrophic cyanobacteria, or ammonia-oxidising bacteria and archaea, which can make carbon and nitrogen bioavailable, thereby promoting soil life and thus enabling the colonisation by other organisms (Bartholomäus et al., 2024; Cowan et al., 2011; Meier et al., 2019; Niederberger et al., 2015). In addition to the importance of microorganisms in nutrient fluxes, their role in shaping desert environments has been described through the accumulation of organic matter, the acceleration of weathering processes, changes in pH, and structuring the soil (e.g. aggregation: Gadd, 2010; Bajerski & Wagner, 2013; Bernhard et al., 2018).

The main components of aggregate formation and stabilisation are organic materials, including (i) decomposition products of plants, animals and microorganisms; (ii) living microorganisms themselves; and (iii) the products of microbial synthesis (e.g. polysaccharides: Schlecht-Pietsch, Wagner, & Anderson, 1994). The latter two points are particularly important for the formation of initial desert soils. Furthermore, microorganisms can attack mineral surfaces by organic

acids or redox processes and mobilise metals (Al, Fe and Mn: Gadd, 2010). Metal oxides have a positive effect on aggregate formation and the stabilisation of soil structure (Giovannini & Sequi, 1976). Important groups of bacteria involved in the dissolution of soil minerals and their metal mobilisation belong to *Agrobacterium*, *Bacillus* and *Burkholderia* (Kim, Bae, & Choung, 2005; Leyval & Berthelin, 1989). Metal mobilisations followed by metal adsorption to microbial cells play an important role in all microbe-metal-mineral interactions (Burford, Fomina, & Gadd, 2003), taking place over a massive range of timescales from milliseconds to years (Borda & Sparks, 2008), and enhance metal transport, biomineralisation processes and soil stabilisation (Barkay & Schaefer, 2001). However, despite the progress in the field of microbial diversity in extreme desert habitats in recent years, we still know very little about the impact of microbial communities on desert pavement evolution and stabilisation and their interaction with soil formation, particularly under changing environmental conditions.

2.4 | Desert pavement distribution

The distribution of desert pavement systems is limited to arid environments and has been estimated to cover nearly 50% of these regions (Walker, 1986; defining 'arid' as mean annual precipitation < 250 mm). Because this frequently cited figure lacks a traceable empirical foundation and does not highlight specific arid regions as being more likely to present desert pavements, Brenning et al. (2025) presented the first effort towards implementing a model-based global assessment using a GIS-based multicriteria decision analysis (MCDA) approach (Figure 8). Their model combines key limiting factors—climate, topography, vegetation cover, soil texture, anthropogenic disturbance and water bodies—into a weighted favourability index at a 1-km resolution. Thematic layers are reclassified into suitability categories based on thresholds derived from 20 desert pavement field sizes reported in the literature, and these scores are combined in a weighted sum to produce a composite favourability index. Areas with favourability index values ≥ 0.75 , covering 25.7 million km², correspond to 80% of the field evidence and should therefore be prioritised for future refinement using higher-resolution geomorphometric and remote-sensing data (Brenning et al., 2025).

Geomorphic distribution modelling and digital soil mapping using statistical and machine-learning methods are promising conceptual and methodological frameworks for such research (e.g. Dragut & Blaschke, 2006; Hengl et al., 2017; Hjort & Luoto, 2013). Locally and at high, but widely available resolutions, optical and thermal remote sensing can be instrumental in discriminating desert pavements from other desert surfaces by detecting spectral characteristics of the mineralisation of the stone layer or excluding local vegetation occurrences (Beratan & Anderson, 1998; Potter, 2016; Spatz, Taraniik, & Hsu, 1989), or characterising the surface layer thermophysically in terms of its thermal inertia (Brenning et al., 2012).

2.5 | Age and dating of desert pavements

Knowledge about the age of desert pavement systems is still very limited (Arnold, 1971; Seong, Dorn, & Yu, 2016) and only available

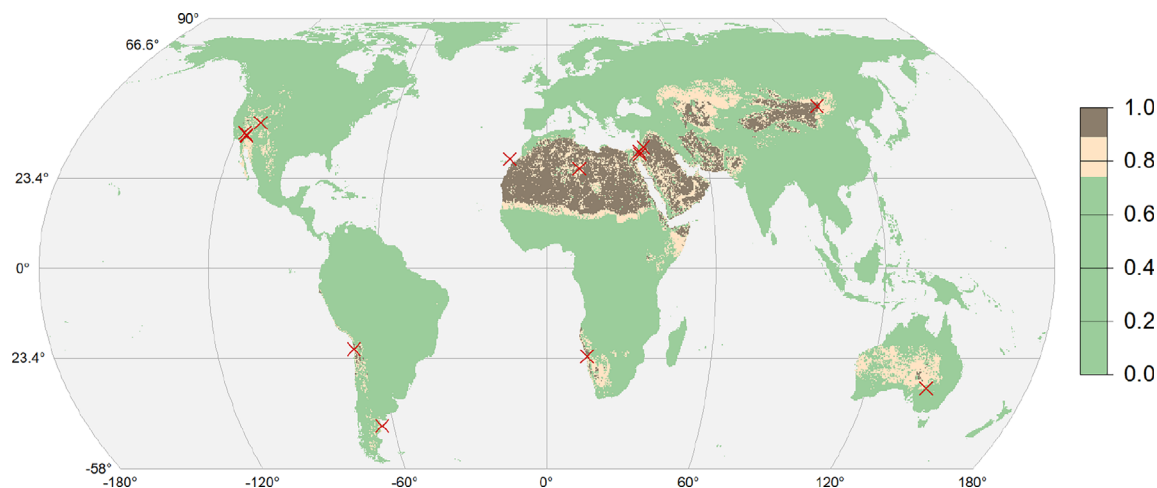


FIGURE 8 Potential global distribution range of desert pavement estimated with GIS-based multicriteria decision analysis considering ecoregions, climate, vegetation, topography, soil texture, anthropogenic disturbance and water bodies. Larger index values indicate a higher suitability for desert pavement formation and preservation. Twenty field sites with coordinates identifiable in the literature are marked with red crosses. Source: Brenning et al. (2025).

for certain regions, although they are significant features of the Earth system and can provide important information about the past and future climates and environmental scenarios (Dietze et al., 2016). Based on different approaches (see succeeding discussion), intact desert pavement surfaces appear to form within decades and may be as old as millions of years (Dietze & Kleber, 2012; Matmon et al., 2009; Wells et al., 1985). To decode the information that desert pavement systems provide as environmental and climate archives, the age–depth relation and temporal evolution of the archive must be known. Therefore, the age determination and the establishment of a chronology of desert pavement system formation are of central importance for analysing desert pavement dynamics in relation to changing internal and external boundary conditions leading to desert pavement formation, preservation and degradation.

Desert pavements can be dated in several ways, and therefore, it is essential to first define the question to be answered and its associated process of pavement formation and evolution. There are two, not necessarily synchronous processes that can be dated: (1) the initial formation of the stone cover and (2) the incorporation of dust below that stone cover (Figure 2). It must therefore first be clarified whether the specific question concerns the beginning of desert pavement formation or the dynamics of dust input, the latter allowing a statement to be made about the environmental conditions during dust deposition. For example, the surface clasts of the stone cover might be millions of years old in terms of persistence at the surface (Fujioka & Chappell, 2011; Matmon et al., 2009), whereas the dust below the stone cover has a much younger and often modern age, as the dust was incorporated after the formation of the stone cover and depends on the temporal availability of dust sources, on-site trapping mechanisms and their efficiency (Dietze et al., 2016; Fuchs et al., 2015; Fuchs & Lomax, 2019; Matmon et al., 2009; Quade, 2001). Hence, ‘the age of desert pavements’ is no straightforward number but requires asking more specific questions. Therefore, it is important to first define (1) the specific question to be answered, (2) then to consider the material to be dated accordingly and (3) to clarify the formation process associated with

the material to be dated, before finally choosing a suitable dating method.

For quantitative dating of desert pavements, only a limited number of suitable methods are available (Wagner, 1998). One source of chronological information is provided by the land surface roughness, with the evolution of roughness as a function of surface age. By correlating dated surfaces with surfaces of unknown age, roughness can be used as a dating tool for quantifying surface ages (Mushkin et al., 2014). A similar approach has been pursued using remotely sensed radiometric properties to interpolate between independently dated alluvial fan surfaces (D’Arcy et al., 2018). However, in both cases the chronologic information is relative and indirect. A more direct method of dating the stone surface is to use desert varnish, which forms on the surface of clasts of the desert pavement and can be dated by, for example, cation ratios, microlamination or potentially radiocarbon dating (Liu & Broecker, 2008; Wagner, 1998), the latter being applicable if the varnish contains organic matter, although the ^{14}C dating approach has so far yielded questionable results. Following the same approach to dating the stone surface of desert pavements, Matmon et al. (2009) and Fujioka and Chappell (2011) applied ^{10}Be surface exposure dating (SED) to clasts on the surface, indicating stable, stone-covered surfaces in the range of million years. While this may be arguably true for the surface exposure aspect, these approaches have not considered the incorporation of dust into the desert pavement system and their subsequent integration into the mantle below the stone surface. To constrain this dynamic process of dust incorporation, which extends over the entire time of existence of the stone cover, the dust and its time of incorporation need to be dated. Luminescence dating methods allow the numerical and direct dating of the process of dust trapping and incorporation into the aeolian mantle, which could be demonstrated on various desert pavements at different locations worldwide (e.g. Fuchs et al., 2015; Fuchs & Lomax, 2019; Matmon et al., 2009). Another innovative approach is OSL exposure dating of rock surfaces, which provides additional information on the bleaching history of rock surfaces and thus on the history of the formation of desert pavement clasts (Sohbati et al., 2015).

3 | ROLE OF DESERT PAVEMENT SYSTEMS IN LANDSCAPE DYNAMICS

3.1 | Role for landscape hydrology and soil formation

Desert pavements directly affect landscape hydrology, as the clasts covering the soil surface represent impervious surfaces (Dunkerley, 1995). Thus, precipitation falling on clasts may directly evaporate without touching the soil matrix (El Boushi & Davis, 1969). This effect is enhanced by the thermal properties of the clasts, which rapidly heat up, especially when coated by dark desert varnish (McFadden et al., 1998). On the other hand, soil moisture persists longer under desert pavements (Kaseke et al., 2012). Interception by desert pavements is even more relevant in deserts where dew deposition is the main source of soil moisture; there, vapour uptake by soils below desert pavements is reduced compared to soils without desert pavement (Kaseke et al., 2012). Another direct effect is caused by the rough surfaces created by larger clasts in desert pavements, potentially slowing down surface runoff (Greenbaum et al., 2020). The extent of this hydrological effect depends rather on the clast sizes and sorting than on the percent surface coverage by clasts (Dunkerley, 1995; Hirmas, Graham, & Kendrick, 2011). Indirect—but even more important—hydrological effects arise from the silty texture of the dust that accumulates below the stone cover (Hirmas & Graham, 2011). This silty material strongly controls the soils' water infiltration rates and water holding capacity, and the resulting spatio-temporal soil-moisture patterns across the landscape (Eppes, McDonald, et al., 2003; Wang et al., 2021; Young et al., 2004). These soil-moisture patterns, in turn, lead to spatially differentiated rates of chemical weathering and soil formation. Soil formation, involving clay mineral formation and potentially calcrete formation, in turn creates a feedback on the landscape hydrology. The underlying causal chains include the following main mechanisms:

1. The silty soils under the desert pavement tend to form surface crusts (McIntyre, 1958). These promote surface runoff and restrict water infiltration mainly to the non-sealed soil surface at the margins of the clasts of the desert pavement (Dunkerley, 1995). The surface crusts, together with the clasts, moreover inhibit the escape of air from the soil, as it is displaced from the pores by the infiltrating water. The resulting vesicular horizon (V horizon; see Section 2.3 for details) further promotes surface runoff during heavy rain (Amit & Gerson, 1986) because of its decreased infiltration rates (Young et al., 2004). Moreover, with progressive evolution of the V horizon, water percolation through the V horizon becomes increasingly dominated by preferential flow along the cracks between the soil peds (Meadows, Young, & McDonald, 2008). Because of the reduced hydraulic conductivity of the V horizon, an increasing proportion of the water is redirected from slopes into topographic depressions and the ephemeral drainage network. Thus, a decreased proportion of the rain water is stored in soils on sloping terrain and at convex topographic positions. Hence, soil conditions in these relief positions become drier, while topographic depressions and valley bottoms may receive additional water from the slopes (Dunkerley & Brown, 1995). The drier soil conditions on upper slopes and in convex relief positions result in decreased weathering

rates in these locations. In contrast, the additional water in topographic depressions and valley bottoms enhances the rates of chemical weathering and soil formation there. Together with the surface runoff, these relief positions also receive soluble salts, which may also accelerate physical weathering and may potentially lead to salinisation and formation of salt crusts.

2. The influence of biological soil crusts on infiltration and surface runoff is more complex than the effects of the vesicular horizon and surface crusts formed by superficial silting during heavy rain as summarised above. Even conflicting results on the influence of biological soil crusts have been found (Guida et al., 2023). Beside their hydrological relevance, another important effect of biological soil crusts is that they protect soil particles from being detached from the soil surface, thus substantially reducing soil erosion and, hence, sediment concentrations in surface runoff, especially as the biological soil crusts progress along their successional series.
3. Silty texture leads to increased soil water holding capacity at shallow depth, potentially supporting annual plants with shallow rooting systems. However, the amount of water that percolates to greater depth is reduced. This does not only impede the growth of shrubs and other deep-rooting vegetation (Hamerlynck et al., 2002) but also decreases the rates of chemical weathering and element leaching at depth (Young et al., 2004). In addition, the increased water holding capacity at shallow depth leads to an increased proportion of soil water that evaporates, because it keeps the water from percolating to greater depth, from where it would not be affected by evaporation anymore (Hamerlynck et al., 2002). This effect counteracts the one of the desert pavement that generally decreases the evaporation rate of the underlying soil (Kaseke et al., 2012). A higher proportion of evaporation, in turn, goes along with enhanced precipitation of salts at or near the soil surface, which may potentially lead to salinisation (McAuliffe, McFadden, & Hoffman, 2018; Wood, Graham, & Wells, 2005).
4. In addition to the formation of a V horizon as the pedogenic process with the greatest impact on landscape hydrology, two other pedogenic processes taking place in the accumulated dust potentially alter the landscape hydrology over time as well, that is, clay formation and calcrete development. Clay formation, which takes place especially in the V horizon, further reduces infiltration rates, thereby enhancing surface runoff and lateral water redistribution across the landscape. Carbonates that are contained in the accumulating dust dissolve and reprecipitate at some depth (Sauer, Schellmann, & Stahr, 2007). Over time, this process leads to the formation of calcretes. In level topographic positions, these may increase the proportion of water that is perched and stored within the root zone, supporting above vegetation growth (Monger, 2006), whereas in sloping terrain, the calcretes may lead to enhanced interflow after rain events, redirecting a higher proportion of the water into depressions.

Beyond the soil-hydrological effects of dust trapped by desert pavements on the rates of chemical weathering and soil formation described earlier, the silt particles that are provided through dust accumulation under the stone cover of desert pavements also directly affect soil formation. They are much more readily weatherable and can be much faster transformed into clay (Chadwick & Davis, 1990) than most autochthonous types of bedrock such as hard rock or



FIGURE 9 Soil profile in a Late Pleistocene alluvial fan in the Providence Mountains piedmont, Mojave Desert, belonging to a soil chronosequence investigated by McDonald et al. (1996) and McDonald, McFadden, and Wells (2003). The profile has the horizon sequence Vk-Btk-Bk-Ck-C, whereby the clay in the Btk horizon and most of the pedogenic carbonate below 75 cm depth accumulated under the moister conditions of the Late Pleistocene (McDonald et al., 1996; McDonald, McFadden, & Wells, 2003).

gravel. Thus, the enhanced rates of soil formation at shallow depth are not only a result of the increased water holding capacity of the silty upper soil horizons but also of the availability of easily weatherable particles. These enhanced weathering rates at shallow depth are, however, not reflected in commonly used chemical weathering indices, because of the steady incorporation of fresh dust into these upper soil horizons, which keeps the common weathering indices at a low level (Sauer, Schellmann, & Stahr, 2007). Moreover, dust accumulation leads to upward growth of the profile (McFadden, Wells, & Jercinovich, 1987; Sauer, 2015). Thus, pedogenic features at greater depth correspond to earlier phases of profile upbuilding and reflect former environmental conditions (Figure 9).

3.2 | Role for soil microbiota

Compared to bare, unvegetated desert soils, desert pavements create a specific microclimate that influences the evolution of microbial communities and their activity. The stone cover acts as a barrier that shields the underlying soil from intense UV radiation and minimises thermal stress for the microorganisms (Pointing & Belnap, 2012). In addition, soil moisture is higher in soils covered by desert pavements because, on the one hand, the clasts cause condensation of water from air and, on the other hand, minimise the evaporation of moisture from the soil. They thus provide a refuge for microbial life in an otherwise quite hostile environment (Cary et al., 2010; Genderjahn et al., 2021; Schulze-Makuch et al., 2021).

The limited studies that have specifically examined desert pavements indicate that the microbial assemblages beneath the clasts differ markedly from those in surrounding exposed soils. In these protected microhabitats, Cyanobacteria often form the phototrophic base of the community, supporting heterotrophic bacteria and archaea (Chan et al., 2012; Gwizdala et al., 2021; Lacap-Bugler et al., 2017; Warren-Rhodes et al., 2006). In the Atacama Desert, ammonia-

oxidizing Thaumarchaeota have been reported as particularly enriched beneath clasts (Hwang et al., 2021), whereas they occur only sporadically in adjacent unvegetated desert soils. Another study, which was the first to examine intracellular DNA of clasts and soils, was able to show that there are also numerous microorganisms in the soils that have the potential to weather rocks (Genderjahn et al., 2021), which is an important process in the course of nutrient cycling and soil formation (Section 2.3).

Another aspect that affects the microbial communities of desert pavements is the accumulation of dust in the pavements, which improves soil water availability (Young et al., 2004), which in general is an important prerequisite for microbiological activity. Moreover, dust influences the geochemical cycles and thus also the availability of nutrients (Neff et al., 2008; Okin et al., 2004), which is also usually a limiting factor for microbial life in desert soils. Desert pavements, therefore, represent a specific habitat in desert environments. The exact effects of desert pavements on microbial communities and their processes with regard to soil formation and stabilisation as well as the associated interactions with the dynamics of desert soils have not yet been sufficiently investigated and understood.

3.3 | Role for atmosphere dust cycle

Desert pavements are located at the interface of land surface and atmosphere and can stimulate the local atmospheric dust concentration in various ways. Considering the atmospheric dust aerosol burden as being balanced by emission (entrainment) and removal (deposition) processes, desert pavements play a role in both balancing processes: Desert pavements may reduce soil erodibility and at the same time act as a sink for suspended dust particles because of their aerodynamic surface roughness and sediment covering nature in case of emission.

Desert pavements act as a regulator for dust emission. The covering and hence protecting nature of desert pavements directly impacts the dust emission potential of bare or sparsely vegetated desert surfaces. Acting as a physical barrier between loose, fine sediment underneath the stone cover and the top surface being the interface between the land surface and the atmosphere, desert pavements protect the potential dust source from atmospheric wind, turbulence, drag and shear forces. Consequently, momentum from the atmosphere otherwise being 'used' to mobilise soil and dust particles will be absorbed by the surface (e.g. Bacon et al., 2011; Dong, Liu, & Wang, 2002; Marticorena & Bergametti, 1995). In the case of dust particles being deposited between stone-free areas of the desert pavement, these dust particles may be entrained into the atmosphere in the case of strong shear and drag forces (Goossens, 1995). Experiments on the dust production potential of different desert soils have shown that soils covered by desert pavements show a significantly reduced dust emission potential despite a reservoir of fine sediments being available underneath the pavement compared to unpaved sediments (Bacon et al., 2011; Sweeney, McDonald, & Etyemezian, 2011).

Desert pavements also control dust deposition. Conceptually, dust deposition and hence removal from the atmosphere is often described by a two-layer model (Zhang & Shao, 2014): an upper transfer layer and a lower collection layer. Whereas dust particle concentration is in steady state and the vertical deposition flux (vertical motion of dust particles) is constant across the so-called transfer layer, the collection layer characterises the layer above the land surface in which surface roughness elements such as pebbles, stones, vegetation, natural or human-made barriers 'collect' dust particles. Thereby, the vertical extent of surface roughness, as well as the spatial heterogeneity of differently sized roughness elements (clasts in the case of desert pavements), will impact the collection efficiency and hence the dust deposition flux onto the surface (e.g. Pelletier, 2007). In the light of surfaces armoured with roughness elements of different sizes such as clasts, desert pavement systems can be assumed to enhance dust deposition compared to smooth surfaces.

The atmospheric dust cycle consists conceptually of the three major elements: 'emission (source)', 'transport' and 'deposition (sink, trap)'. Thereby, dust emission and deposition balance the atmospheric dust concentration, and wind regimes and atmospheric dynamics determine dust transport routes and hence airborne dispersion. The balance at a local scale may differ from the balance at a regional or global scale. For example, the atmospheric dust concentration may increase over a dust source region as the emission flux is stronger than the deposition flux.

Considering those two impacts in concert, the presence of desert pavements may have a reducing effect on the local atmospheric dust concentration. The role of stone-paved surfaces in general and desert pavements in particular has also been examined and illustrated by field studies in various deserts representing a high diversity of soil surface conditions in desert environments. Thereby, the soils' wind erosion potential is estimated by means of portable wind-tunnel experiments and Pi-SWERL (Portable In Situ Wind Erosion Lab) measurements. Sweeney, McDonald and Etyemezian (2011) investigated dust emission fluxes from different soil surfaces in the Mojave Desert by means of Pi-SWERL measurements; Van Pelt et al. (2017) studied dust emission fluxes (vertical sediment fluxes in their study) from desert soils in the Chihuahuan Desert, which include desert

pavements. Their measurements were obtained by means of a portable wind tunnel. Besides these studies investigating the wind erosion potential in North American deserts, Cui et al. (2019) performed Pi-SWERL measurements across different soil surfaces in northern China. The work by Wang et al. (2012) assesses the wind erosion potential from stony surfaces in the Gobi Desert by means of portable wind tunnel measurements. The work by Marticorena et al. (2006) presents measurements of aerodynamic surface roughness for different soil surfaces, including stony surfaces, in Tunisia, Northern Africa. The impact of gravel surfaces on aerodynamic roughness is also discussed in Dong, Liu and Wang (2002). Besides vertical dust emission fluxes, stony surfaces and desert pavements also affect horizontal dust fluxes, saltation layer height and sand transport because of their aerodynamic roughness (e.g. Tan et al., 2020) illustrating the complex web of interactions associated with desert pavements. Findings from field studies have been used to determine wind erosion thresholds and functions describing local, soil type and wind speed-dependent dust emission fluxes as implemented in dust emission models (e.g. Darnenova et al., 2009 and references therein).

4 | DESERT PAVEMENTS AS RECORDER OF LANDSCAPE EVOLUTION

Landscapes and their environments are parts of the four-dimensional and dynamic Earth surface system, which is characterised by a complex interaction of lithosphere, pedosphere, biosphere, hydrosphere and atmosphere. Desert pavements as a widespread element of arid landscapes are an expression of this interplay of spheres, which control the formation, preservation or destruction of desert pavements through their individual boundary conditions. Desert pavements thus bear witness to the prevailing landscape, environmental and climate conditions, but at the same time control landscape, environmental and climate processes through diverse feedback mechanisms. They are thus a 'recorder' and 'player' of landscape evolution.

The 'recorder' role is played by the accretionary fine sediments beneath the stone surface, which constitute a sedimentary archive that thickens over time, preserving information about the environmental and climatic conditions during their deposition as well as subsequent modifications. Turning this archive into a 'recorder' of environmental history requires the analysis of the contained proxy information, transforming the depth scale into an age scale (see Section 2.5). The protective stone cover is an advantage over many other sedimentary archives in arid environments such as dunes, which are much more susceptible to erosion. Desert pavements therefore represent an additional valuable climatic and environmental archive in arid environments that need to be deciphered (Dietze et al., 2016; Quade, 2001; Wells et al., 1985).

Various proxies within the sedimentary archive potentially document the past climate and environmental conditions, such as organic matter and calcite precipitation, which can be used for, for example, pollen, biomarker or stable-isotope analyses. However, the comparably low organic carbon content of mostly < 0.3% (Anderson, Wells, & Graham, 2002; McFadden et al., 1998) could limit the use of that set of proxies. But the sediment itself, with its lithologic, pedogenic, granulometric, mineralogic and geochemical features, can also serve as an indicator of past climate, environments and their dynamics.

However, a general prerequisite for using the desert pavement system as a suitable environmental and climatic archive is a basic understanding of the temporal evolution of desert pavements and their dynamics (see Section 2.5). A robust numerical chronology of the sedimentary archive is therefore a necessity, which can be achieved by precise sediment dating. Luminescence dating is ideally suited for this purpose because, in contrast to most other dating methods, it enables the direct dating of the sediment, that is, the temporal determination of the sedimentation process itself (Bateman, 2019; Fuchs et al., 2015; Fuchs & Lomax, 2019). This dating approach would also provide an opportunity to elucidate the previously unknown role of the vesicular horizon in the mixing and redistribution of particles and solutes until they are finally incorporated into the accretionary sediment section of the desert pavement system. There are concepts about the timing and formation rate of the vesicular horizon (Anderson, Wells, & Graham, 2002; McFadden et al., 1998), but comprehensive sediment dating approaches are required to develop clear concepts for the formation of the vesicular horizon and associated sediment turnover times (Fuchs et al., 2015; Fuchs & Lomax, 2019). This would ultimately allow the desert pavement system to be used as a complementary climatic and environmental archive in arid environments.

5 | CONCLUSION AND PERSPECTIVES

As a central component in the Earth system of arid environments and because of the interaction with the different spheres, desert pavements are an important element in landscape and environmental evolution. Desert pavement systems control the hydrology, pedology and (micro)biology of the accretionary fines, as well as the stone cover at the surface, and therefore have an important role for processes below, at and above the surface. All these processes have direct and indirect effects on the climate, as the characteristics of the land surface, for example, moderate dust deposition and entrainment from the atmosphere. At the same time, these processes shape and modulate the surface topography, especially in arid environments, where only sparse vegetation prevents erosion by wind and water. Desert pavement systems thus not only play an important role in landscape and environmental evolution, but, through their accretionary fines, also serve as important 'recorders' of past environmental and climatic conditions. They can become a useful source of information about the past in arid regions where alternative sedimentary archives are generally scarce.

Even though the importance of desert pavements within the Earth system is of local, regional and global significance, we know relatively little about the functioning of the desert pavement system. In particular, the interacting feedback processes between the individual system components are poorly understood, and some aspects within the desert pavement system are still largely unknown. Addressing the following research questions and research fields will therefore contribute to a significantly improved knowledge of the functioning and feedback mechanisms of desert pavements, which would acknowledge the importance of desert pavements in the Earth system:

The general concept of desert pavement formation as an accretionary system is basically known, but far from conclusive. The phenomenon of buried stone pavements needs to be explained in detail and existing concepts ask for a critical review. The answer to

this question is directly linked to the question of surface transport of individual stones, which has not yet been fully answered. This leads to the question of the region-specific boundary conditions that control the processes involved in desert pavement formation. These geomorphic, lithologic, climatic, pedologic and microbiologic boundary conditions need to be quantified in space and time, and correlated with specific formation stages (Wells et al., 1985) of the desert pavement system. A chronological framework is needed not only to determine the timing and duration of specific desert pavement formation stages but also to better understand the boundary conditions and their influence on the involved formation processes. These above goals have to be enrolled in representative, regional key sites and then required to be synthesised for a more advanced global understanding of how desert pavements operate.

Despite the general notion of accretionary growth, a prime precondition for their terrestrial archive function, there is only sparse, case study based evidence of the modes and the ranges of rates at which desert pavements operate. This means that our understanding of the processes involved in clast production, exhumation, erosion and importantly mobility to form the surficial coarse fabric is very limited, conceptual (Amit & Gerson, 1986) or dominated by case studies (Dietze et al., 2016).

Once desert pavement formation and the general process of accretionary growth with their modes and region-specific rates are known and understood for a given site, the full potential of the archive function inherent in accretionary desert pavement systems can be used (e.g. Dietze et al., 2016; Fuchs et al., 2015; Wells et al., 1985). The general advantage of this understudied terrestrial archive is its widespread occurrence in arid landscapes where other terrestrial sediment archives are rare. Hence, desert pavements bear the potential to fill an important gap of information to better grasp the effects of past environmental change on a particularly sensitive component of the terrestrial ecosystem (Quade, 2001; Wood, Graham, & Wells, 2005).

Although in recent years much progress has been made in microbial community analysis in deserts, almost nothing is known about their role in the formation of desert pavements and their importance for the formation and stabilisation of the underlying soils and sediments. Microbial-driven soil stabilisation, in particular, is of great importance as it controls sediment transport as well as dust generation and incorporation, and thus has a direct influence on matter fluxes and pavement formation. In light of ongoing global climate change, a more comprehensive, interdisciplinary and integrated approach is needed to better understand the impact of microorganisms on the formation of soil architecture across scales, from molecular mechanisms to ecosystem-level dynamics and landscape evolution by combining cutting-edge methods (e.g. new DNA extraction procedures, multi-omics, single-cell analysis and soil μ CT) and examining them from various perspectives. This approach will enable more accurate predictions of the evolution of deserts and its broader environmental impacts.

Soil-forming processes under desert pavements have been studied in various regions around the world. Yet, the interplay of soil formation, changing the spatio-temporal soil-moisture patterns, and the feedback of those altered soil-moisture patterns on spatial patterns of soil formation is not fully understood. It has been proven that the formation of the V horizon leads to decreased water infiltration and

enhanced surface runoff, resulting in lateral redistribution of water across the landscape. This redistribution leads to increased rates of chemical weathering and soil formation at sites gaining water and decreased rates at sites losing water. This relationship is yet only qualitatively known, while quantification is still lacking. Meanwhile, the effect of the desert pavements on infiltration rates is ambiguous. On the one hand, interception by clasts reduces infiltration; on the other hand, a desert pavement consisting of big clasts can increase surface roughness, slowing down surface runoff and thus giving the precipitation more time to infiltrate. It is not yet clear under which boundary conditions—specifically the combination of rain-event intensity, slope, clast size, clast shape and percent clast coverage—one or the other effect dominates. Meanwhile, it is obvious that evaporation of soil moisture is decreased by the clast cover. However, this effect is counteracted by the fines accumulated under the desert pavement, as they increase the water-holding capacity at shallow depth, thus keeping the water from percolating to greater depth, where it would not be prone to evaporation anymore. Again, both effects are only qualitatively known but still lack quantification. The increased water-holding capacity at shallow depth should enhance soil formation at shallow depth, while substantially decreasing the leaching of soluble salts, gypsum and carbonates to greater depth. In contrast, evaporation should partially bring soluble back to the soil surface.

Desert pavements are exposed to the lowest part of the atmosphere, in particular the atmospheric (planetary) boundary layer, and hence are interacting with atmospheric processes determining the nature of this layer, in particular turbulence and near-surface wind. Thereby, the surface roughness affects near-surface wind speed and turbulent fluxes. Besides the impact of paved surfaces on the atmospheric boundary layer dynamics, the surface covering nature of desert pavements controls the soil surface's susceptibility to wind erosion. Furthermore, because of their aerodynamic rough surface, desert pavements act as a sink for mineral dust particles suspended in the lowest layers of the atmosphere as the dust deposition flux is increased. This in return plays a pivotal role for the formation of desert pavements. Although these interactions between desert pavements and the atmosphere are conceptually known and have been demonstrated for individual cases, detailed knowledge of the processes at the desert pavement–lower-atmosphere is still missing. In particular, the impact on local atmospheric dust concentrations and resulting regional to global consequences because of dust aerosol feedbacks on radiation, cloud formation processes, and atmospheric dynamics is not fully understood despite its relevance.

Accurate knowledge of the spatial extent, location and characteristics of desert pavements at continental to global scales is needed to quantitatively assess their role as an important component in the Earth system cycle by upscaling local process understanding. Nevertheless, these characteristics are still very poorly constrained as they have received little attention in the literature until now. While GIS-based multicriteria analyses offer a first quantitative and reproducible glimpse into the distribution of these phenomena, geomorphological distribution modelling and digital soil mapping are state-of-the-art methodological frameworks for more detailed assessments of extent, location and characteristics. Systematically collected desert pavement data are required to calibrate and validate statistical or machine-learning models for this purpose in the future.

The importance of desert pavement systems for the Earth system on local, regional and global scales can only be adequately understood, if the various interacting system components with their feedback mechanisms are comprehensively recognised. This integrative approach would contribute to the understanding of desert pavement formation and their boundary conditions, and thus provide the basis for predicting desert pavement behaviour under future climate and environmental scenarios, a prerequisite for understanding their future role in the Earth system.

AUTHOR CONTRIBUTIONS

All authors were responsible for conceptualisation, writing the original draft, reviewing, editing, and visualisation.

ACKNOWLEDGEMENTS

We would like to thank all our colleagues who discussed the phenomenon of desert pavement systems with us and thus contributed to our ideas and concepts, which are presented in this review article. Open Access funding enabled and organized by Projekt DEAL.

CONFLICT OF INTEREST STATEMENT

The authors are not aware of any conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. Some data may not be publicly available because of privacy or ethical restrictions.

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How to cite this article: Fuchs, M., Dietze, M., Brenning, A., Sauer, D., Schepanski, K. & Wagner, D. (2025) Desert pavements: A hidden key to Earth surface processes. *Earth Surface Processes and Landforms*, 50(15), e70213. Available from: <https://doi.org/10.1002/esp.70213>