2 Sandstone Landforms of the Karoo Basin: Naturally Sculpted Rock

Stefan Grab

Abstract
South Africa boasts some of the most impressive sandstone landscapes and landforms in the world, and although these are widely distributed across South Africa, some of the most spectacular examples are associated with the Molteno, Elliot and Clarens Formations in the central region of South Africa. The prominence of sandstone in this region is primarily owing to palaeo-basin infilling during the late Carboniferous and a climate dominated by seasonal precipitation patterns, both now and in the past. Consequently, a range of weathering and erosion processes have operated at wide-ranging spatial scales upon the sandstone outcrops. The chapter describes prominent sandstone landscapes (plateaus, mesa-butte topography, scarplands, slopes) and landforms (e.g. ichnofossil structures, honeycombs, rock arches, rock doughnuts) of central South Africa and reflects on their associated cultural heritage and geoheritage linkages. For instance, almost all known San rock art sites are associated with sandstone, yet rapid weathering of such rock is jeopardizing the longevity of this cultural legacy.

Keywords
Sandstone • Karoo basin • Weathering • Cultural heritage/geoheritage

2.1 Introduction

A considerable portion of South Africa's landscape is characterized by sedimentary rocks which represent infilled basins such as the Main Karoo basin, which is now the primary host to the subcontinent's sandstone landscapes and landforms (Fig. 2.1). Importantly, this basin contains rich palaeontological and hominid fossil records (e.g. Sterkfontein), and world-renowned rock art sites (e.g. Kamberg, Main Caves at Giant's Castle), which therefore has considerable geotourism appeal. It is likely that the spectacular sandstone landscape and landforms also fascinated early settlers, as attested by place names such as 'Kamieskroon' (kroon = 'crown', to describe the prominent sandstone rock formation upon a hill) in the Western Cape, and 'Maanhaarrand' (meaning 'mane of a horse' which describes a sandstone ridge outcrop) in the Magaliesberg (Fig. 2.1).

Early sandstone work in South Africa was primarily concerned with describing the macroscale landscape of slope forms (e.g. King 1953, 1957; Le Roux 1978; Moon and Munro-Perry 1988). In contrast, more recent work has described the rich variety of sandstone landforms in areas such as the eastern Free State Province (Grab et al. 2011), suggested process mechanisms for rock doughnut formation (Grab and Svensen 2011), and undertaken experimental work on sandstone weathering (e.g. Mol 2014). This chapter provides the geological context to sandstone landscapes in the central Karoo Basin region of South Africa including areas in the Free State and Eastern Cape and illustrates examples of some of the more intriguing landforms found within them. Finally, the strong connectivity between sandstone geomorphology and cultural (stone) heritage

S. Grab (✉)
University of the Witwatersrand, Johannesburg, South Africa
e-mail: stefan.grab@wits.ac.za

S. Grab and J. Knight (eds.), *Landscapes and Landforms of South Africa*,
World Geomorphological Landscapes, DOI 10.1007/978-3-319-03560-4_2,

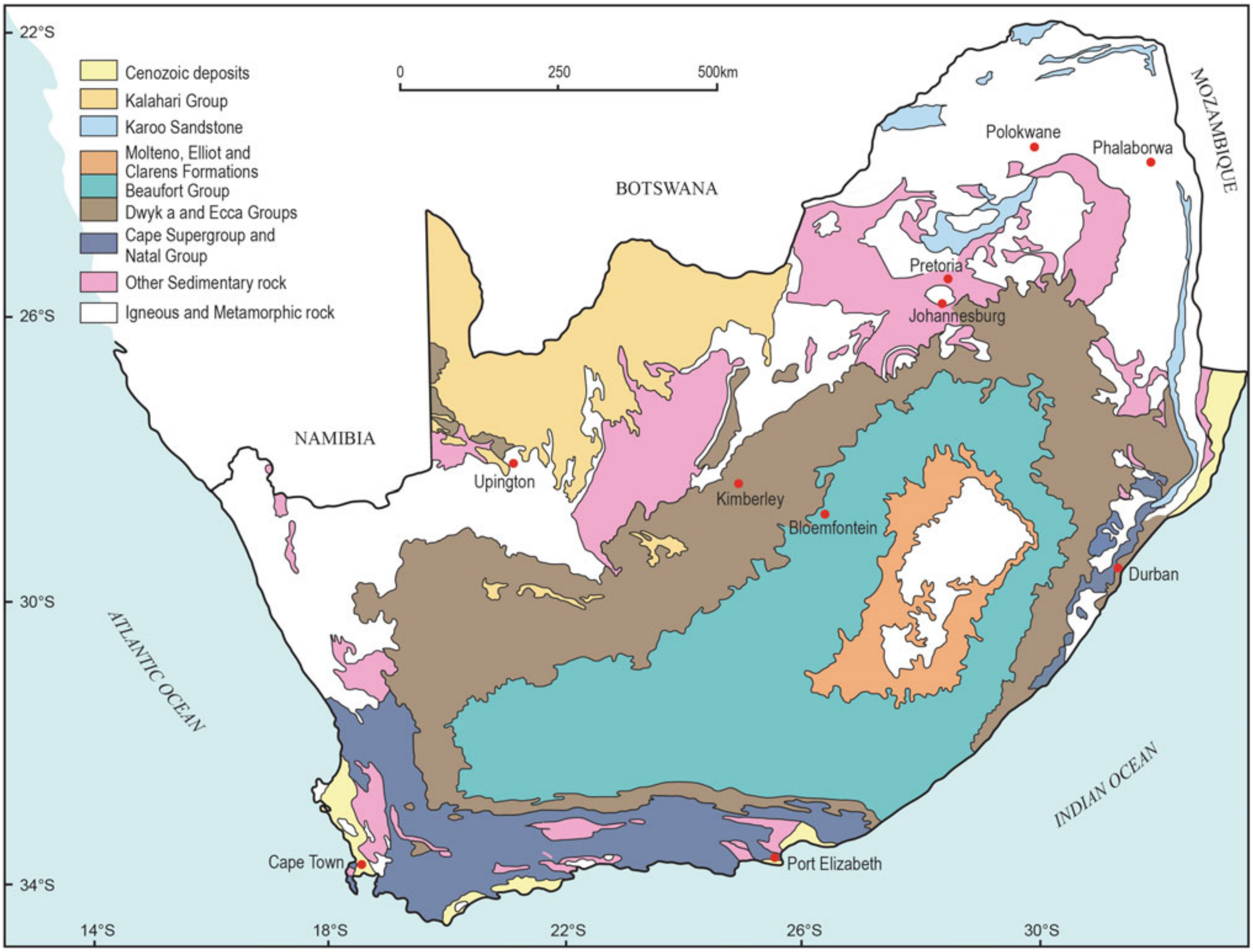

Fig. 2.1 Sandstone/sedimentary outcrops in South Africa, Lesotho and Swaziland (redrafted after Council for Geoscience, 1997; Stefan Grab and Wendy Phillips)

provides for mixed (i.e. natural and cultural) heritage tourist attractions, for which these regions are already well known. Places referred to in the text are represented in Fig. 2.2.

2.2 Geological Setting

Most sedimentary rocks in South Africa are a product of basin infills, of which there are several including the Main Karoo Basin, which existed over much of the central interior of South Africa (Fig. 2.1). This chapter will focus on this region specifically.

The sandstone succession in the Karoo Basin accumulated over a period spanning from the late Carboniferous (~300 Ma) to the early Jurassic (~190 Ma). Climate change over this time period influenced sediment type, depositional environments and geological structures (e.g. bedding planes) of the various sandstone formations. In turn, these have influenced the spatially variable weathering and erosion processes over time. Subsequent infilling of the basin yielded a total stratigraphic thickness of ~12 km, and the Karoo Supergroup currently crops out over more than half of South Africa (~600,000 km^2). However, the most striking sandstone landscapes/landforms are those associated with the Molteno, Elliot and Clarens Formations of the Karoo Supergroup. The late Triassic Molteno Formation outcrops over ~25,000 km^2, consists of rock types ranging from mudstones to coarse sandstones, and attains a maximum thickness of ~460 m (Turner 1983). The Elliot Formation (formerly known as the 'red beds') represents a transition from predominantly fluvial and lacustrine during the late Triassic to increasingly aeolian during the early Jurassic (Lucas and Hancox 2001) (Fig. 2.2). The 'Lower Elliot Formation' consists of thick mudstones and isolated

Fig. 2.2 Locations of sandstone phenomena and places mentioned in the text of this chapter

channel sandstones, while the fine- to medium-grained and interbedded mudstones of the 'Upper Elliot Formation' are thought to be the product of an ephemeral flash flood-dominated fluvial system (Bordy et al. 2004a).

The final phase of basin infill was associated with shallowing-upward lake infill with alluvial fan propagation on the northern basin margin (Eriksson 1986; Holzförster 2007). The resulting Clarens Formation (Fig. 2.3) was previously known as 'cave sandstone formation' owing to the prominent concavities/overhangs at the base of near-vertical cliffs. Although the Clarens Formation is represented by the finest textured sandstones within the sandstone stratigraphic sequence, a variety of sedimentary rock types ranging from mudstones and shale to coarse conglomeratic sandstones has been identified within it.

2.3 Sandstone Landscapes

The sandstone landscapes of central South Africa have an important place in global geomorphology, as this is where Lester King (1953, 1957) developed his ideas of parallel slope retreat. More recently, Moon and Munro-Perry (1988) tested the concept of parallel slope retreat in the sandstone landscapes of the north-eastern Free State province; they found a variety of sandstone slope forms and concluded that many site-specific conditions determine hillslope development. In most instances, valley side slopes develop by cliff retreat and subsequent replacement by rectilinear bedrock slopes, which may at first be mantled by weathered debris. The sandstone slope forms are well preserved over geological

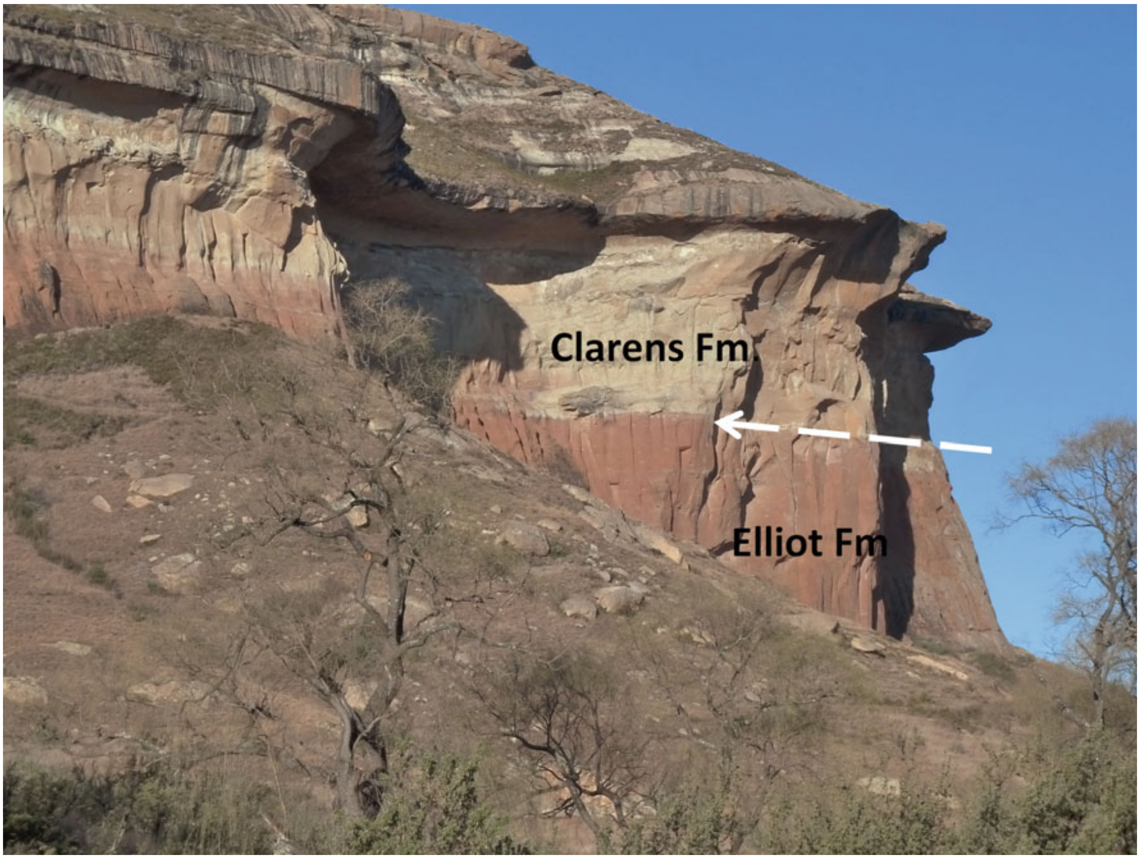

Fig. 2.3 The Elliot Formation ('red bed') underlying the aeolian Clarens Formation, eastern Free State (the *arrow* indicates the distinct boundary between the two formations) (*Photograph* S. Grab)

time scales owing to the relatively resistant nature of the sandstone bedrock (Moon and Munro-Perry 1988).

The western plateau regions, especially in the eastern Free State, are the product of long periods of landscape denudation associated with predominantly parallel scarp retreat through large drainage meander systems undercutting slopes and causing cliffline failure and colluviation. Consequently, this is a landscape of mesas and buttes (Fig. 2.4); here, the cliff faces are relatively smooth and uniform, suggesting little contemporary spatial variation in rates of cliffline retreat. The typical succession of convex interfluves—near-vertical cliffs—linear colluvial mid-slopes—and concave foot slopes is notable in this landscape. In the wetter north-eastern Free State, the lower slopes are relatively stable and vegetated, but as one travels towards the south-western Karoo Basin, the drier climate exposes lower slope elements to more visible contemporary denudation (active gullies and colluvial fans). The mesa-butte sandstone landscape is primarily controlled by a more resistant upper basalt or Clarens sandstone outcrop, which in places provides a distinct lateral protrusion or capping over the underlying light yellowish Clarens and reddish Elliot sandstones (Fig. 2.3). The stratigraphic positioning of more highly jointed lower Clarens and Elliot sandstones (often represented as mudstones) regularly coincides with areas of groundwater seepage (sapping), hence creating the conspicuous overhangs that contour slopes for hundreds of metres. Such undercutting also causes widespread block/toppling failure, which is still currently active and contributes to rock fall debris mantles.

By contrast, the sandstone landscape to the east of the Great Escarpment is a product of rapid incision enhanced by a dense drainage network and wet climate. Upper catchments are within the Drakensberg basalts and are largely controlled by major basaltic lineaments and dolerite intrusions. The drainage network produced relatively deeply incised sandstone valleys (with narrow gorges, waterfalls and cascades) in the upper reaches (Fig. 2.5a), yet elsewhere ridges and valleys are uniformly spaced and asymmetric in cross-profile. Valley-side drainage off sandstone interfluves in several places has also initiated very regular patterns of bedrock 'ribs' and adjacent eroded channels, likely controlled by bedrock mechanical strength and climate.

On interfluves, landforms include 'tors' or 'domes' and 'pillars' (Fig. 2.5b), which in some instances have become tourist attractions named after the rock formation, such as the 'Policeman's helmet' at Royal Natal National Park or

Fig. 2.4 A butte in the eastern Free State, west of the Great Escarpment (*Photograph* S. Grab)

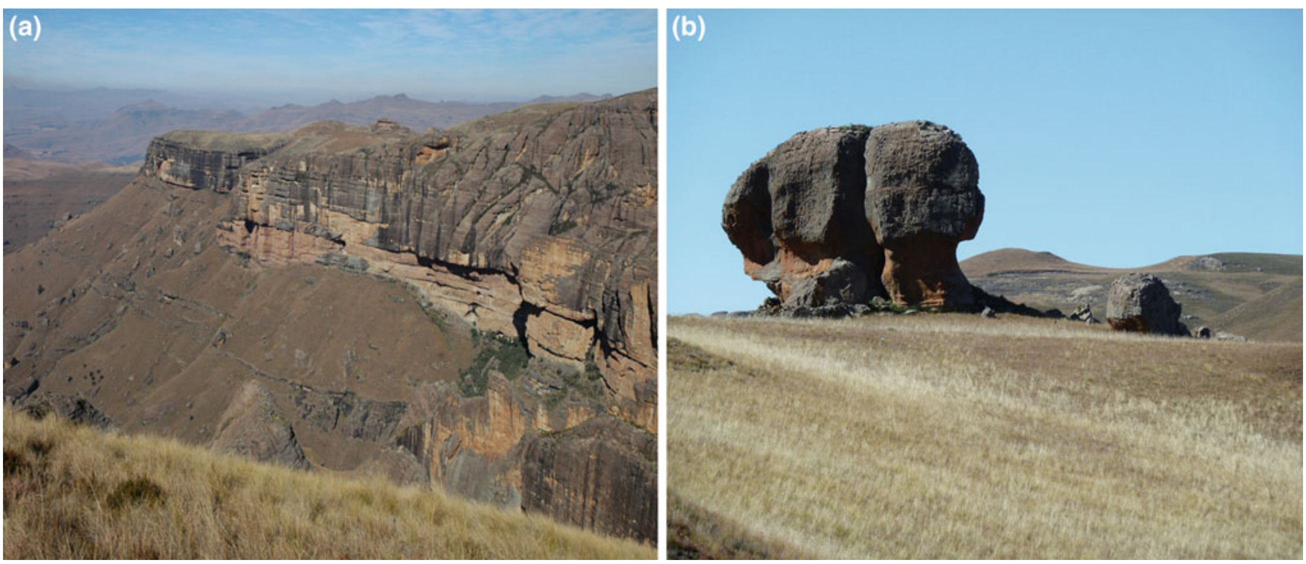

Fig. 2.5 **a** Steep, incised sandstone valley to the east of the Great Escarpment, Drakensberg foothills; **b** mushroom shaped 'tor'/'pillar'/'dome', Sehlabathebe National Park, Drakensberg ($\sim$17 m in height) (*Photographs* S. Grab)

'Mushroom rock' outside the town of Clarens. These are thought to be a product of initial subsurface etching, and once exposed are subject to enhanced weathering and erosion associated with joints and areas of lower rock strength at the base of these phenomena (Ollier 1978).

2.4 Sandstone Landforms

More striking than sandstone landscapes is the diversity of specific sandstone landforms within them, which vary from micro-scale (mm) to tens of metres in size. These are primarily a product of site-specific weathering and erosion over geological and shorter timescales. Several conspicuous contemporary sandstone landforms are also a product of geohydrological or biological activity of the past. Here, a few of the most striking landforms are described.

Pentagonally or hexagonally *fractured sandstone surfaces* (crack diameters = $\sim$2–5 cm; surface diameters = $\sim$5 to >50 cm) are particularly common in case-hardened sandstone outcrops (Fig. 2.6a). Suggested mechanisms include shrinkage of silica gel due to changing rock thermal and/or moisture conditions (Robinson and Williams 1992) and thermal surface stress (Croll 2009), although it remains

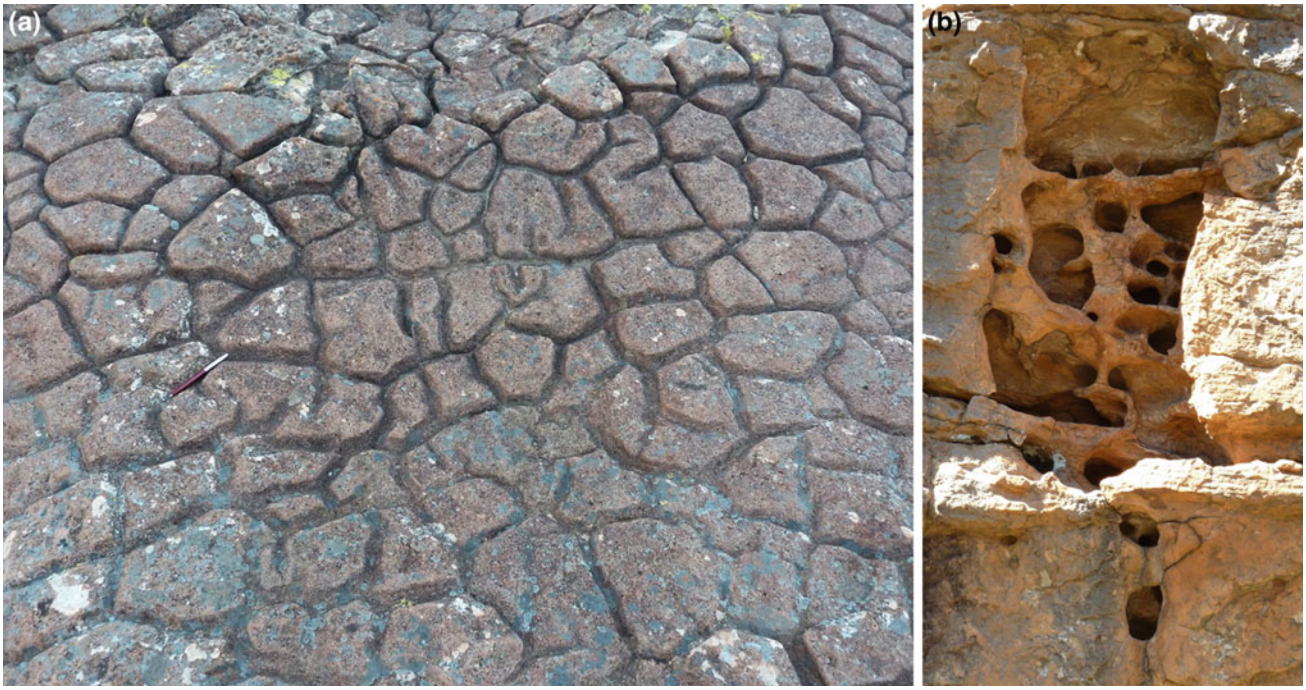

Fig. 2.6 **a** Fractured sandstone surface on case-hardened rock, eastern Free State (pen for scale); **b** honeycombs, in which both birds and rodents build their nests, Eastern Cape (total height = ~220 cm) (*Photographs* S. Grab)

unclear whether these are syndepositional or postdepositional phenomena. In many instances, such fractures direct surface run-off producing rinnenkarren (rundkarren) or rillenkarren ('solution flutes'), which are likely strongly associated with dissolution and biokarstic processes. In some instances, long micro-drainage channels connect a succession of shallow rock basins.

Honeycombs, consisting of closely spaced pits bounded by thin raised lips or walls (McBride and Picard 2004), are widespread in sandstone outcrops throughout South Africa (Fig. 2.6b). Such micro-weathering forms (few tens of cm across), also known as 'alveoli', are commonly ascribed to salt solutional and salt recrystallization processes. In contrast, case-hardening by iron oxide or calcium carbonate provides greater resistance to weathering between the pits (McBride and Picard 2004). Somewhat larger *tafoni* (several metres across) cavernous weathering/erosion forms also occur, albeit less frequently. These typically have overhanging lips/hoods/visors, arch-shaped entrances, concave inner walls, overhanging margins and relatively smooth, gently sloping, debris-covered floors (Grab et al. 2011).

The largest cavernous sandstone forms are those commonly referred to as *amphitheatres* or *alcoves* (e.g. Laity and Malin 1985), which overhang below the cliffline. These may be up to several hundred metres in diameter and over 100 m in height. Several mechanisms may be responsible; these include groundwater sapping and perched water tables locally weakening rock, granular disintegration, wind erosion, rock falls and plunge pool scour at the base of waterfalls, all of which produce caverns below vertical cliffs. These processes are most enhanced where weaker, less permeable sedimentary strata underlie stronger or case-hardened cap rock (Ryan et al. 2012).

Apart from coastal *rock arches* (see Chap. 7), sandstone arches are best known from the Cederberg ('Wolfberg Arch': see Chap. 10) and southern Drakensberg/Lesotho regions of South Africa, with smaller examples also occurring across the Karoo, Eastern Cape, Magaliesberg and Mpumalanga escarpment regions. Natural bridges, which are rock arches that span across valleys, have been documented during historical times from the Golden Gate Highlands National Park (Fig. 2.7), two in the Mpumalanga Province (see Chap. 19) and one in the remote Lesobeng Valley in central Lesotho—which is also likely the largest rock arch in southern Africa at ~70 m across, ~9 m in height and ~4 m in bedrock thickness at the centre of the arch. Arches, in contrast to natural bridges, do not span valleys but are typically found in canyon lands (Dixon 2010) and denuded sandstone-dominated plateaus and interfluves, such as is the case at Sehlabathebe National Park (SNP) (Fig. 2.8). Here is found the highest concentration of rock arches in southern Africa (~10–12); these are typically 5–12 m in diameter and ~4–5 m in height. Most sandstone rock arches are thought to be the product of enhanced weathering and erosion along joint/fracture zones,

Fig. 2.7 A natural rock bridge (now collapsed) in the Golden Gate Highlands National Park, as depicted in a photograph by Johan Van Reenen, dating to ca 1930–1940 (*Source* South African National Parks)

Fig. 2.8 Rock arch in Clarens Fm. sandstone, Sehlabathebe National Park, Drakensberg (~7 m in width; ~5 m in height) (*Photograph* S. Grab)

often associated with rockfalls along horizontal or vertical discontinuities, eventually leading to material collapse and production of the 'window area' (Leasure et al. 2007).

A variety of raised conical- or cone-shaped structures, often with a central pothole (rock basin), have been described from several Clarens Formation sandstone outcrops in

South Africa, including the Eastern Cape, KwaZulu-Natal, Free State and Limpopo provinces. These are typically known as *rock doughnuts*, which are circular/oval in plan, and many are bowl shaped in cross section with a pothole in the centre. Potholes develop singly or in clusters, are flat floored and contain weathered detritus. Rock basins may contain standing water for short periods after rainfall events, or for several weeks to months during wet periods/seasons, and induce both chemical weathering associated with dissolution (Domínguez-Villar et al. 2009), and mechanical (Goudie and Migoń 1997) weathering.

The hypotheses for rock doughnut formation range from differential water-level weathering/erosion due to water/moisture contrasts near the surface (e.g. Twidale and Vidal Romaní 2005) to lithological variations, liquefaction and fluidization, which produce clastic pipes (Netoff and Shroba 2001; Grab and Svensen 2011). In places, small and circular pipe structures filled with calcite-cemented sand are present and suggest conduits for fluidized sand. This may suggest that some of these features are Jurassic remnants cemented with superimposed and secondary silica (Grab and Svensen 2011).

2.5 Biological Influences on Sandstone Formations

Biota such as lichens, fungi and cyanobacteria are known to shape sandstone surfaces, causing relatively small-scale (mm–cm) etching, pitting and flaking (see Viles et al. 2008). Larger-scale (cm–m) fossilized sandstone phenomena (ichnofossils) in the form of insectivorous nests (*calie*) have also been reported from central South Africa.

Most sandstone surfaces in central South Africa are at least partially lichen covered and are thus weathered through processes including cation chelation, dissolution, swelling and hyphal penetration (see Grab et al. 2011). In addition, the larvae of a bagworm moth species (*Lepidoptera*) associated with endolithic lichen further contribute to weathering by dissolving the sandstone-cementing agents (Wessels and Wessels 1991). Cryptoendolithic cyanobacteria (blue-green algae) are also widespread, and typically so along sandstone fractures where weathering is induced by substrate alkalization during photosynthesis (Büdel et al. 2004). These processes are responsible for micro-weathering forms such as circular or crescentic-shaped depressions bounded by micro-scarps (Fig. 2.9a). The sandstone rock basins or potholes mentioned in Sect. 2.4 are not only a product of mechanical geomorphic processes, but also closely connected to cyanobacteria and other micro-organisms found in the microbial mats within sandstone depressions. Complex biofilms may accumulate at the base of rock basins, dissolving cementing agents between sandstone grains, but also act as biological sealants to water infiltration (see Chan et al. 2005).

Unique *sandstone pillars* (Fig. 2.9b) up to 3.3 m in height, possibly representing fossil termite (or other social soil-dwelling organism) nests, are prominent in the eastern Free State/western Lesotho and Tuli Basin regions (Bordy et al. 2004b, 2009). These ichnofossils occur in groups, typically spaced between 0.5 and 10 m. The true height of the features is difficult to determine owing to denudation at the top of the pillars and extension into the parent bedrock at the base, but may typically stand 1–3 m above ground. The basal circumference commonly exceeds 1 m, but

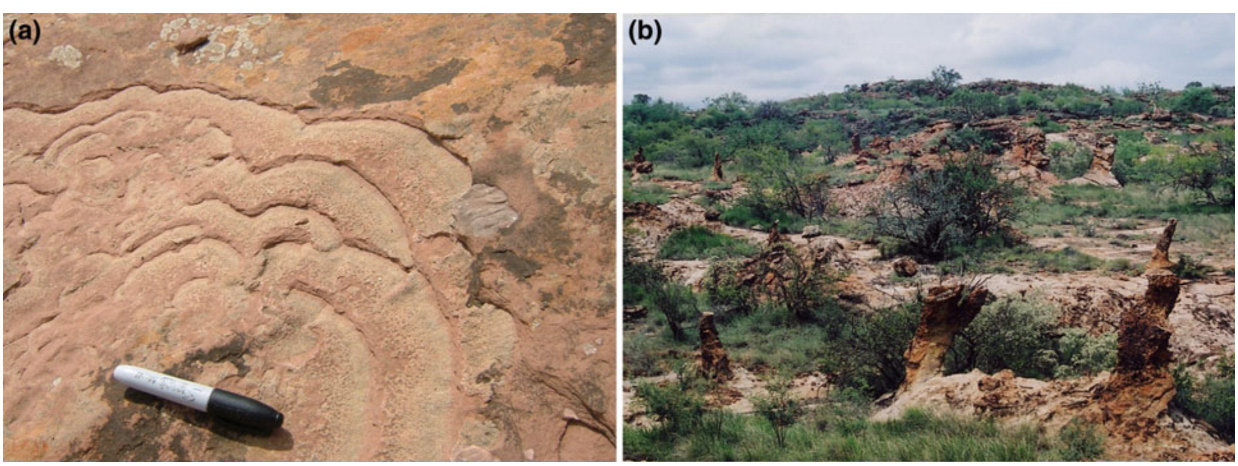

Fig. 2.9 **a** A lichen-weathered sandstone surface: note the crescentic-shaped depressions bounded by micro-scarps (*Photograph* S. Grab); **b** sandstone ichnofossils of likely termite origin, Limpopo Province (*Photograph* E. Bordy)

pillars narrow towards their apices. Although the outer walls are relatively smooth, the internal bioturbated structure consists of interconnected burrows, channels, ducts and tubes averaging 0.5–2 cm in diameter. The pillars are exposed due to differential rates of weathering and erosion between the nest sites and surrounding sandstone, even though both are of aeolian origin. The elongated north–south-orientated nests are thought to be a bioengineered midday heat deflection construction in what would have been an arid hot environment (Bordy et al. 2004b). The biochemical process involved produces a hydrophobic film, which, together with the general absence of swelling clays but abundance of quartz minerals in Clarens Formation sandstones, lowers shrinkage but increases the bonding mechanism. Consequently, surrounding sandstone would have weathered and eroded more rapidly, thus exposing and preserving the ichno-fossiliferous sandstone pillars.

2.6 Sandstone Geomorphology and Cultural Heritage

There are exceptionally strong associations between southern African sandstone and cultural heritage/geoheritage. For instance, the SNP was added to the World Heritage Site List (mixed cultural/natural category) in 2013, in part given its sandstone landscape appeal. Sandstone overhangs (*alcoves*) were important occupation sites by the San ('Bushman') for at least the last two thousand years. In addition, ancient rock dwellings from former hunter-gatherer and early farmers still occur in some sandstone overhangs (Fig. 2.10a). There were even accounts of missionary workers during the nineteenth century taking refuge in such rock shelters during times of war. Elsewhere, sandstone potholes have been used in former times for fire making, and surfaces used for engraving outlines for the Morabaraba

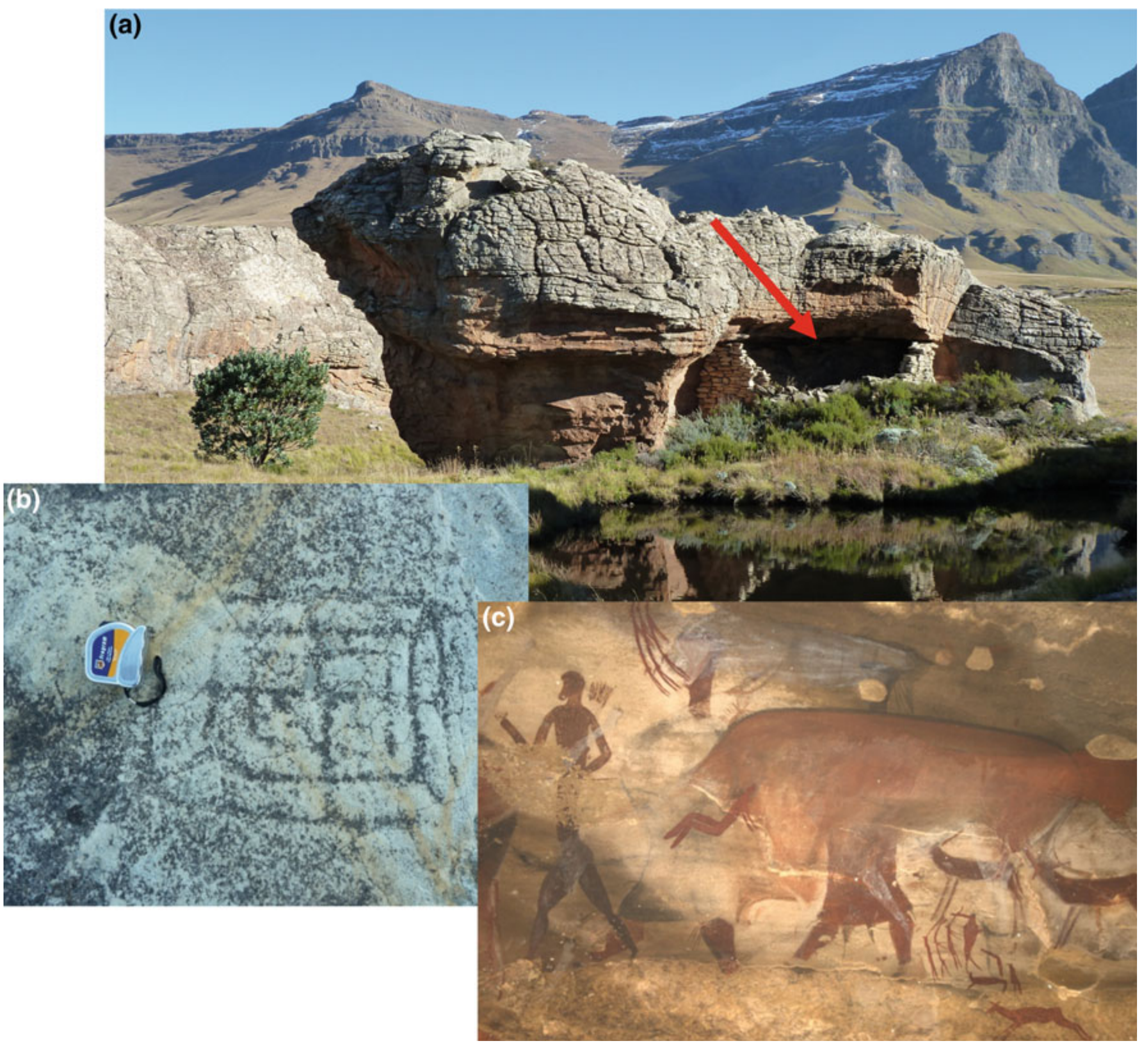

Fig. 2.10 Sandstone cultural heritage: **a** rock dwelling within a sandstone cavity (indicated by *red arrow*), **b** the morabaraba board game (note the lichen growth along the engraved sections, indicating pronounced micro-spatial bioweathering) and **c** weathered San rock art (*Photographs* S. Grab)

board game (Lesotho variant of Nine Men's Morris board game) (Fig. 2.10b).

Arguably the best example of mixed cultural/sandstone heritage is that through the preservation of San rock art on sandstone surfaces (Fig. 2.10c). Several thousand rock art sites are known, almost all of which are located within finer-grained sandstone outcrops (particularly Clarens Formation), owing to their smooth and light-coloured surfaces. Rock art sites frequently occur within overhangs where active weathering makes the paintings fragile. Water seepage and thermal stress at such sites have been identified as contributing factors in their disintegration (e.g. Hoerlé 2006). Thus, considerable attention has been given to understanding rock weathering and art deterioration at key field sites (e.g. Mol and Viles 2010). However, protecting such art in the natural environment is exceptionally difficult. One option is to identify the most critical rock art panels likely to detach in the near future, through techniques such as GPR profiling (e.g. Denis et al. 2009), and possibly to retrieve these panels from such sites—although this action is controversial.

2.7 Concluding Remarks

Sandstone weathering and erosion has produced remarkable landscapes, landforms and niches for cultural preservation in the central Karoo Basin of South Africa; arguably one of the best examples globally. It was through the observation and theorization of South African sandstone landscapes by the likes of King that brought attention to southern Africa's rich geomorphological heritage. In contrast, more recent micro-scale approaches towards understanding sandstone geomorphic processes, particularly in the context of weathering associated with rock art deterioration/preservation, have highlighted the global value of this natural geomorphic laboratory. The longevity and preservation of some sandstone landforms and associated cultural artefacts are now threatened through climate change, inappropriate management, land transformation and tourism, and thus require better attention in future.

Acknowledgments I thank Lisa Mol, Piotr Migoń, John Dixon and Jasper Knight who provided constructive comments on an earlier draft—their input has surely improved the quality of this chapter.

References

Bordy EM, Hancox PJ, Rubidge BS (2004a) A description of the sedimentology and palaeontology of the late Triassic-early Jurassic Elliot Formation in Lesotho. Palaeontologia Africana 40:43–58

Bordy EM, Hancox PJ, Rubidge BS (2004b) Fluvial style variations in the late triassic-early Jurassic Elliot Formation, main Karoo Basin, South Africa. J Afr Earth Sci 38:383–400

Bordy EM, Bumby AJ, Catuneanu O (2009) Possible trace fossils of putative Jurassic (Karoo supergroup) of South Africa and Lesotho. S Afr J Sci 105:356–362

Büdel B, Weber B, Kühl M, Pfanz H, Sültemeyer D, Wessels D (2004) Reshaping of sandstone surfaces by cryptoendolithic cyanobacteria: bioalkalization causes chemical weathering in arid landscapes. Geobiology 2:261–268

Chan MA, Moser K, Davis JM, Southam G, Hughes K, Graham T (2005) Desert potholes: ephemeral aquatic microsystems. Aquat Geochem 11:279–302

Croll JGA (2009) Possible role of thermal ratcheting in alligator cracking of asphalt pavements. Int J Pavement Eng 10:447–453

Denis A, Huneau F, Hoerlé S, Salomon A (2009) GPR data processing for fractures and flakes detection in sandstone. J Appl Geophys 68:282–288

Dixon JC (2010) Canyonlands and arches: windows on landscapes in the American southwest. In: Migoń P (ed) Geomorphological landscapes of the world. Springer, Dordrecht. 39–47

Domínguez-Villar D, Razola L, Carrasco RM, Jennings CE, Pedraza J (2009) Weathering phases recorded by gnammas developed since last glaciation at Serra da Estrela, Portugal. Quatern Res 72:218–228

Eriksson PG (1986) Aeolian dune and alluvial fan deposits in the Clarens Formation of the Natal Drakensberg. Trans Geol Soc S Afr 89:389–394

Goudie AS, Migoń P (1997) Weathering pits in the Spitzkoppe area, central Namib desert. Z Geomorphol 41:417–444

Grab SW, Svensen H (2011) Rock doughnut and pothole structures of the Clarens Fm. Sandstone in the Karoo Basin, South Africa: possible links to Lower Jurassic fluid seepage. Geomorphology 131:14–27

Grab SW, Goudie AS, Viles HA, Webb N (2011) Sandstone geomorphology of the Golden Gate Highlands National Park, South Africa, in a global context. Koedoe 53: Art. #985, 14 p. doi:10.4102/koedoe

Hoerlé S (2006) Rock temperatures as an indicator of weathering processes affecting rock-art. Earth Surf Proc Land 31:383–389

Holzförster F (2007) Lithology and depositional environments of Lower Jurassic Clarens Formation in the Eastern Cape, South Africa. S Afr J Geol 110:543–560

King LC (1953) Canons of landscape evolution. Bull Geol Soc Am 64:721–751

King LC (1957) The uniformitarian nature of hillslopes. Trans Edinb Geol Soc 17:81–102

Laity JE, Malin MC (1985) Sapping processes and the development of theater-headed valley networks on the Colorado plateau. Geol Soc Am Bull 96:203–217

Le Roux JS (1978) Die ontstaan van grotte en holtes in die kranse van die Clarenssandsteenformasie in die Golden Gate-gebied [Formation of caves and hollows in the cliffs of the Clarens Sandstone Formation in the Golden Gate area]. S Afr Geogr 17:129–131

Leasure VL, Kind TC, Busby MR (2007) Formation of Apex natural arch, Kentucky. J Ky Acad Sci 68:96–101

Lucas SG, Hancox PJ (2001) Tetrapod-based correlation of the nonmarine Upper Triassic of Southern Africa. Albertiana 25:5–9

McBride EF, Picard MD (2004) Origin of honeycombs and related weathering forms in Oligocene Macigno Sandstone, Tuscan coast near Livorno, Italy. Earth Surf Proc Land 29:713–735

Mol L (2014) Investigations into the relationship between changes in internal moisture regimes and rock surface deterioration in cavernous sandstone features. Earth Surf Proc Land 39:914–927

Mol L, Viles HA (2010) Geoelectric investigations into sandstone moisture regimes: implications for rock weathering and the deterioration of San rock art in the Golden Gate Reserve, South Africa. Geomorphology 118:280–287

Moon BP, Munro-Perry PM (1988) Slope development on the Clarens Sandstone Formation in the northeastern Orange Free State. S Afr Geogr J 70:57–68

Netoff DI, Shroba RR (2001) Conical sandstone landforms cored with clastic pipes in Glen Canyon National Recreation Area, southeastern Utah. Geomorphology 39:99–110

Ollier CD (1978) Induced fracture and granite landforms. Zeitschrift für Geomorphologie 22:249–257

Robinson DA, Williams RBG (1992) Sandstone weathering in the High Atlas, Morocco. Z Geomorphol 36:413–429

Ryan AJ, Whipple KX, Johnson JP (2012) Are amphitheatre headed canyons indicative of a particular formative process? American Geophysical Union, abstract #EP51A-0969

Turner BR (1983) Braidplain deposition of the Upper Triassic Molteno Formation in the main Karoo (Gondwana) Basin, South Africa. Sedimentology 30:77–89

Twidale CR, Vidal Romani JR (2005) Landforms and geology of Granite Terrains. Balkema, Leiden. 351 pp

Viles HA, Naylor LA, Carter NEA (2008) Biogeomorphological disturbance regimes: progress in linking ecological and geomorphological systems. Earth Surf Proc Land 33:1419–1435

Wessels D, Wessels L (1991) Erosion of biogenically weathered Clarens sandstone by lichenophageous bagworm larvae (Lepidoptera: Psychidae). Lichenologist 23:283–291

http://www.springer.com/978-3-319-03559-8

Landscapes and Landforms of South Africa
Grab, S.; Knight, J. (Eds.)
2015, XIII, 187 p. 119 illus., 106 illus. in color.,
Hardcover
ISBN: 978-3-319-03559-8