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THE SURFACE GEOLOGY AND GEOMORPHOLOGY AROUND GOBABEB, NAMIB DESERT, NAMIBIA

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ABSTRACT. This paper serves as a brief review and overview of the surface geology and geomorphology around Gobabeb in the Central Namib Desert. It introduces the major lithologies associated with the Damara Orogen of Precambrian and Cambrian age, followed by Tertiary sandstones and conglomerates and Quaternary Kuiseb valley conglomerates, silts and gravels. To celebrate the 50th anniversary of the Gobabeb research station and the recent designation of the Namib Sand Sea as a world heritage site, we are presenting a map to inform and guide future research and educational activities around Gobabeb. The contrast between an ancient gravel plain to the north, a dynamic aeolian sand sea to the south and ephemeral river environments in between become apparent. These natural laboratories have attracted investigations of contemporary sand dune movement, hyper saline waters, evaporites and duricrusts and ephemeral flooding and recharge processes as well as environmental change and human impacts.

Key words: surface geology, geomorphology, Gobabeb, Namib Desert, Kuiseb, Namib Sand Sea

Introduction

The research and training centre at Gobabeb (15.0415° East, 23.5618° South, approx 400 m a.s.l.), which celebrated its 50th anniversary in 2012 (Henschel and Lancaster 2013), has provided a focus for a considerable volume of geological and geomorphological research. Its location provides access to a range of contrasting environments that include the ancient stable surfaces of the gravel plains to the north, the massive active dunes of the sand sea to the south and the ephemeral channel of the Kuiseb River between them (Figs 1 and 2). Geomorphological processes in the area around Gobabeb are driven by the persistent and long-lived aridity of the area, a steep environmental gradient and by rare, extreme climatic events (Eckardt *et al*. 2013). This paper describes the geological and geomorphological surface features and processes around the Gobabeb research station and is intended as an introduction for newcomers to the area. It aims to provide a broad, integrated but by no means definitive overview highlighting key papers from the past decades, as well as more recent publications. Central to this is the map of the Gobabeb area (Fig. 2) which was modified from the digital Geological Survey of Namibia map (Geological Survey of Namibia 1994) and features Damaran geology from Sawyer (1981) and Kuiseb geomorphology mapped by Ward (1987a, 1987b), who also provides a full break down of all geomorphological type locations presented here. Table 1 lists the sites most accessible from Gobabeb but we strongly urge interested visitors to consult Ward (1987a), Ward and Corbett (1990) and Miller (2008, in particular Volume 3) for an in-depth description. Locations of saline springs and salts were added from Eckardt *et al*. (2013) and Khommabes Carbonate Member from Ward (1987b).The Namib Sand Sea (Sossus Formation) is rendered using a Landsat 8 image from 4 May 2013.

Surface geology

Cambrian and Precambrian

A visitor approaching Gobabeb on the roads from the north across the gravel plains will see geological outcrops free of sand cover, dominated by Precambrian rocks of the Damara Orogen (±880–460 Ma). These outcrops include the extensive schist exposures (Kuiseb Formation – NKs), which extend from the Gamsberg Pass in the Great Escarpment to the station perimeter (Fig. 2., location 1), as well as the gneissic feldspathic quartzites (Khan Formation) and dolomitic marbles (Karibib Formation)

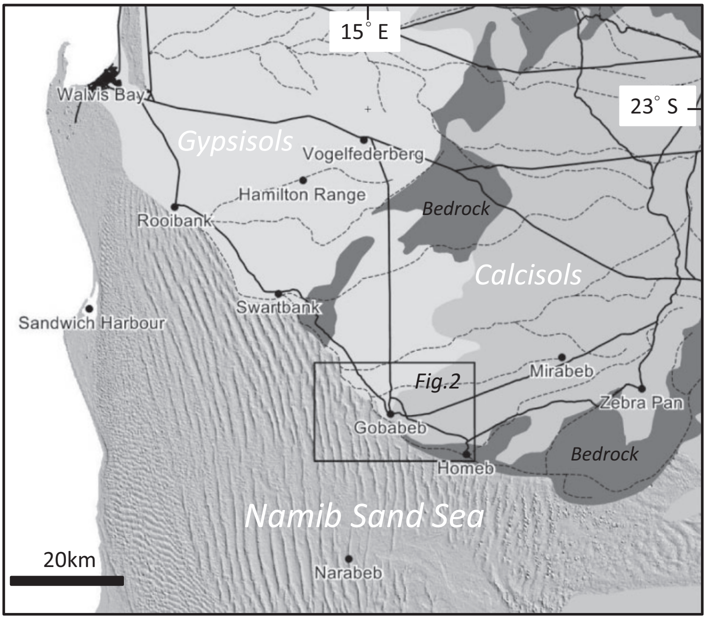

Fig. 1. Regional overview of central Namib. Namib Sand Sea south of Gobabeb depicted using shaded ASTER GDEM data. Plains to the north feature isolated outcrops but are otherwise home to soils rich in gypsum to the west or calcrete to the east (data: Digital Atlas of Namibia, Mendelsohn *et al*. 2003). For map with focus on Gobabeb area consult Fig. 2.

along the coastal approaches from Walvis Bay and Rooibank (Sawyer 1981; Geological Survey of Namibia 1994; Miller 2008). These Nosib and Swakop Group sediments were laid down in the Khomas Ocean triple junction, flanked by the Cratons of South America, the Congo and Kalahari during the break up of Rodinia. Metamorphism was accompanied by post- to syn-tectonic granite intrusions (Salem-type (NgSa), Donkerhuk (EgDh), and Aussinanis (EgAu), ±575-523 Ma) and associated quartz veins and dykes (N/Epe) which now form the most distinct surface lithologies. Notable granite outcrops include the Mirabeb and Vogelfederberg inselbergs (Ollier 1978); and major and dominating Salem-type occurrences in and around the immediate vicinity of Gobabeb (Fig. 2, locations 2, 3 and 4). A few Etendeka dolerite dykes (130 Ma) are present. The post-Gondwana erosion phase in the Cretaceous, represents a major unconformity in the geological record of this area.

Tertiary

The present-day record suggests, that a number of Tertiary deposits (Namib Group Sediments) were deposited prior to the early incision of the Kuiseb River. Today these largely appear south of the modern day river (Ward 1987a) and include the Tsondab Sandstone (TTs), an aeolian analogue of the present-day sand sea which is indicative of a proto Namib Desert some 20-5 million years ago (Ward and Corbett 1990; Pickford and Senut 2000). The sandstone occurs as far east as the escarpment and as far south as Lűderitz (Kocurek and Lancaster 1999) and is most accessible in interdune outcrops south of Gobabeb (Figs 2 and 3, location 5), including small pockets on the south bank of the Kuiseb near Gobabeb (Fig. 2, location 6).

The Tsondab Sandstone was incised due to epeirogenic uplift at the end of the Tertiary (King 1951), which was followed by the accumulation of alluvial fan and braided channel deposits from the proto Kuiseb and Tsondab Rivers. This deposit is now calcified and referred to as the Karpfenkliff Conglomerate Formation (TKk), which is of Neogene age (15–14 Ma). Remnants of this conglomerate are found to the east of Gobabeb on modern elevated Kuiseb canyon terraces and also south of Gobabeb in the form of interdune deposits on top of the Tsondab Sandstone (Ward 1987a; Figs 2 and 3, location 7). Other deposits of associated ages are found further afield from Gobabeb and include the Kammberg Conglomerates, the Rooikop Gravels, the Awa-gamteb muds and Zebra

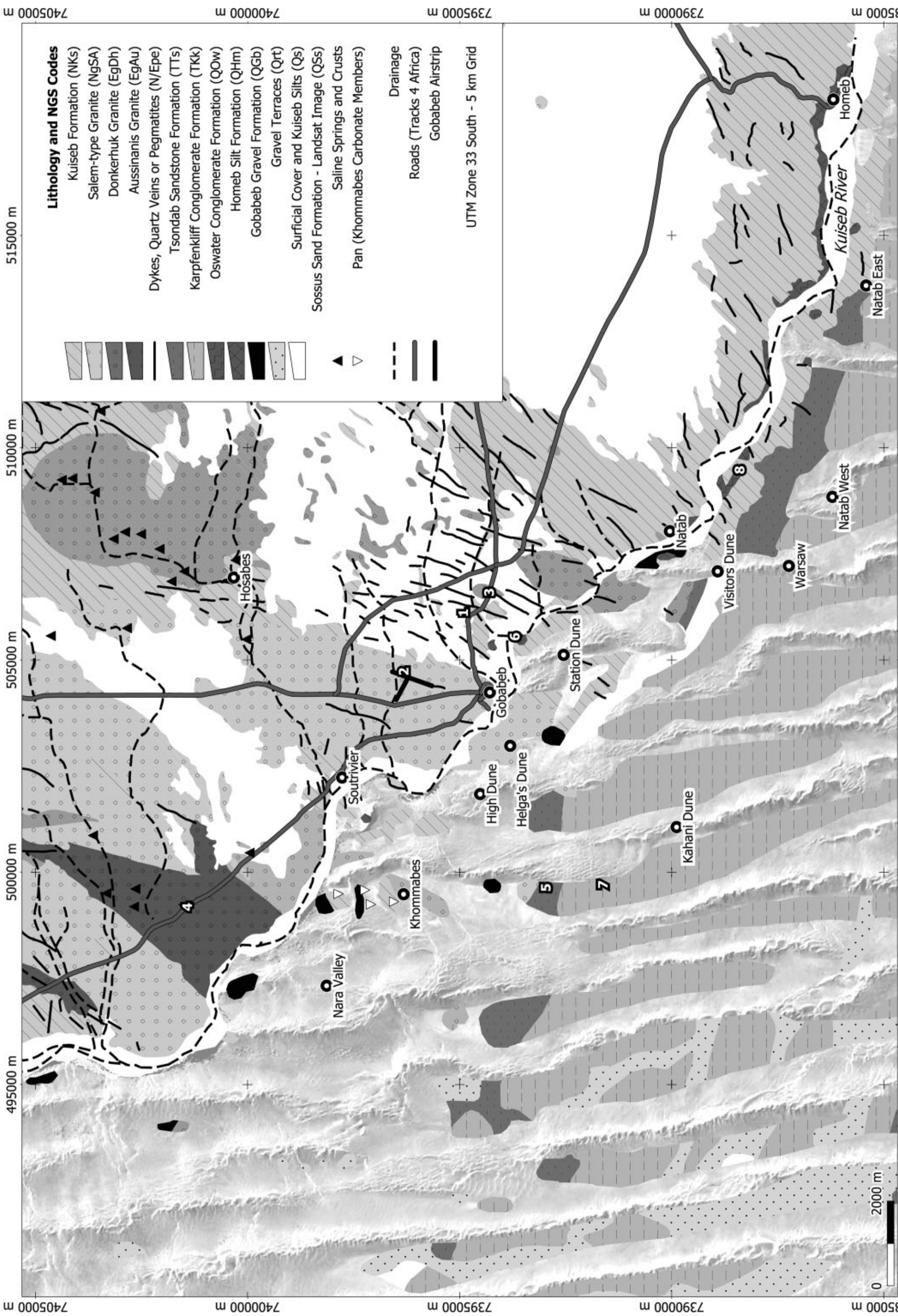

Fig. 2. Map of surface geology of Gobabeb and surroundings, depicting older Precambrian and Cambrian granite and schist geology on the plains to the north of the station, Tertiary sandstones and conglomerates in the Namib Sand Sea interdune corridors to the south, as well as younger Quaternary deposits in the Kuiseb Valley. Recent to active pan deposits occur at Khommabes and Hosabes. Specific dunes subject to long-term monitoring are also presented. Map modified from NGS Kuiseb Sheet 2314, based on Sawyer (1981) and Ward (1987a, 1987b).

Table 1. Locations and coordinates of surface features and sites around Gobabeb as depicted in Fig. 2.

Feature with NGS codes	Location and approximate direct distance from Gobabeb station	Coordinates Lon, Lat
Kuiseb Formation (NKs) Precambrian Damara Supergroup Khomas Subgroup	Widespread micacious schist on eastern approach roads from Gamsberg and Mirabeb. Occurs in pockets north and east of the station (1) (1.9 km)	15.0599° E 23.5587° S
Salem-type Granite (NgSa) Precambrian	These granites form outcrops in and around the station including the south bank below station dune and the airstrip (2) (2.1 km)	15.0463° E 23.5435° S
Donkerhuk Granite (EgDh) Cambrian	Are found on the gravel plains just east of station (3) (2.4 km)	15.0646° E 23.5617° S
Aussinanis Granite (EgAu) Cambrian	Are found north west and north of the station (4) (8.7 km)	14.9920° E 23.4974° S
Tsondab Sandstone Formation (TTs) Tertiary Namib Group	Red brown sandstone, forms interdune outcrops south west and south east of the station including Khommabes valley (5) (4.7 km) (Fig. 3b). A small isolated pocket occurs 1.5 km from the station on the Kuiseb south bank (6)	(5) 14.9973° E 23.572° S (6) 15.0543° E 23.5671° S
Karpfenkliff Conglomerate Formation (TKk) Tertiary Namib Group	Calcified gravels form extensive interdune exposure south of the station including south of Khommabes (7) (5.1 km) (Fig. 3a)	14.9971° E 23.5804° S
Oswater Conglomerate Formation (QOw) Quaternary	Small pockets occur near the station but well developed capped terraces can be found near Natab (8) (7.9 km) (Fig. 3C)	15.0944° E 23.612° S
Homeb Silt (QHm) Quaternary Namib Group	Occur east of the station at Natab but are best viewed at Homeb (16 km)	15.1773° E 23.6336° S
Gobabeb Gravel Formation (QGb) Quaternary Namib Group	Gravels line both sides of the river, small terraces can be found just 320 m to the south east of station perimeter	15.0431° E 23.5647° S
Sossus Sand Formation(Qs) Recent feature	Any dune south of the station including Visitor's Dune	15.0694° E 23.6102° S
Other dune locations	Helga's Dune	15.0291° E 23.5661° S
	Station Dune	15.0501° E 23.5775° S
	Natab West	15.0866° E 23.6347° S
	Natab East	15.1352° E 23.6461° S
	High Dune	15.0180° E 23.5597° S
	Warsaw	15.0707° E 23.6254° S
Saline spring Recent feature	The closest of numerous saline springs north of station is called Hosabes (Fig. 3e), 7 km from station	15.0701° E 23.5069° S
Khommabes Carbonate Member Recent feature	Interdune lacustrine sediments and fossils, 5.1 km from station (Fig. 3d)	14.9979° E 23.5385° S

Pan Carbonates which are not discussed here but are covered in detail by Ward (1987a) and Miller (2008) among others.

Quaternary

The Quaternary then saw a renewed period of Namib Group deposition limited to the immediate Kuiseb channel. The modern deposits which attest to this, include post-Kuiseb-incision conglomerates and silts, which occur mostly upstream of Gobabeb (Fig. 2). The first, Oswater Conglomerate (QOw), was deposited in an ephemeral braided river system steeper than the present day Kuiseb talweg (Ward 1987a, b) and now forms terraces set against the Precambrian lithology of the Kuiseb

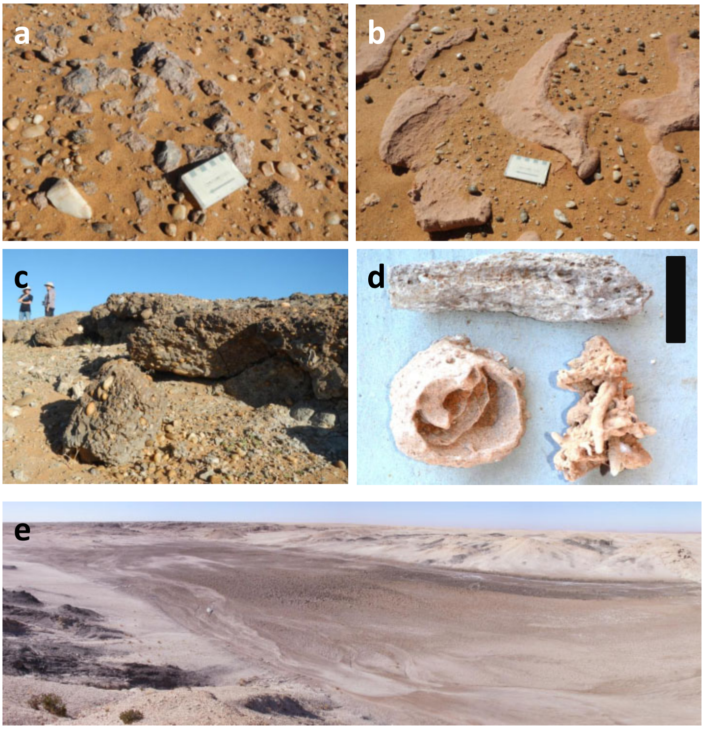

Fig. 3. Examples of major surface features around Gobabeb. Interdune (a) Tertiary Karpfenkliff Conglomerate (TKk) and (b) Tertiary Tsondab Sandstone (TTs) south of Khommabes, location 5 and 7 in Fig. 2. (c) Oswater Conglomerate (QOw) terrace in Kuiseb valley, location 8 in Fig. 2. (d) Fossils of the Khommabes Carbonate Member, including calcified Phragmites reed stem (top) and termite nests (bottom) against 5 cm scale (refer to Smith and Mason 1998) and view of gravel plain depression hosting (e) Hosabes Spring.

Canyon some 30–70 m above the current river bed (Figs 2 and 3c, location 8). Ordinary cut and fill events in the evolution of the Kuiseb fan and valley can account for all units introduced so far. The more recent and second deposit are the silts at the Homeb (QHm) type location, 16 km east of Gobabeb. These have been subject to much debate. According to Miyamoto (2010), the silts have been interpreted as a result of dune dams indicative of an arid environment (Goudie 1972; Rust and Wieneke 1980); river endpoint deposits (Marker and Müller 1978); flood plain sediments of an aggrading river during semi-arid conditions (Ward 1987a; Smith *et al*. 1993); and river flood slack water sediments indicating a wet environment as well as intense precipitation events in the headwaters (Heine and Heine, 2002). The age of the Homeb Silts is equally disputed. Vogel (1982) (19–23 ka) and Miyamoto (2010) (19–26 ka) propose an older age than Bourke *et al*. (2003) (6.3–9.8 ka). The so-called Gobabeb Gravels (QGb), the youngest deposit, occur up and downstream of Gobabeb some 5–30 m above the present river and have their origin in the incised conglomerates described above. Additional gravel terraces, presumably related, occur in the interdune corridors (Qrt). Just 320 m to the south east of the station perimeter, Yamagata and Mizuno (2005) dated these gravel terraces using radiocarbon from calcretes along with dendrochronological data of riparian forests. This produced ages of 300–600 years, 5–6.5 ka and *c*. 22 ka for various gravel beds, the origin of which is not known. The Kuiseb undoubtedly has become the most studied ephemeral river in Namibia since many of the type settings were first identified here. It is now widely recognized that related units occur in most of Namibia's other west coast ephemeral drainage systems (Miller 2008).

The youngest features around Gobabeb include the active dunes of the Sossus Sand Formation (QSs), to be discussed later but which include isolated pockets of interdune pan carbonates and fossils of Late Pliocene age (Fig. 3d; Smith and

Mason 1998). Their type locality at Khommabes is 6 km north west of Gobabeb (Fig. 2). These may be related to lacustrine calcareous mudstone deposits, at Narabeb, a former Tsondab terminus, 30 km south of Gobabeb (Teller and Lancaster 1986).

The Kuiseb River

Gobabeb is not only in close proximity to many of the units outlined above, it is also some 4 km west from Natab where the river exits the deep lower Kuiseb Canyon, a transition which is attributed to a change in lithologies from schistose Damara metasediments to more resistant granites. Natab is also at the apex of several palaeochannels which fan out between the modern day Kuiseb Delta near Walvis Bay and the mouth of Sandwich Harbour (Klaus *et al.* 2008). These channels, now buried, have incised into the Precambrian basement rocks and the Namib Group sediments during Oswater times. At the same time, the lower course of the Kuiseb gradually shifted northward by some 30 km, presumably under the influence of moving sand dunes, trapping and channeling fresh water resources below the present day dune sands.

Around Gobabeb the main channel is around 50–80 m wide, with a riparian flood plain of 20–200 m on either side. The narrow neck at Gobabeb is constrained by Salem-type granite outcrops on both sides of the river. The surficial river sands consist mainly of angular to sub-rounded quartz grains, with minor mica flakes derived from Damara schist and larger grains similar in composition to the arenaceous beds in the Oswater Conglomerate (Ward 1987a). A typical profile suggests that most of the flood-plain deposits are sandy and alternating with fine silt-rich layers. Sediments near Gobabeb revealed a recent environmental shift manifested by a coarse-grained upper sandy part and a lower massive silt boundary consistently at approximately 0.8 m depth. Yamagata (2010) attributes the observed coarsening of river sediments at Gobabeb to a possible decline in riparian vegetation cover and an increase in dune sand as well as the building of upstream dams in the 1960s and 1970s.

The modern channel environment around Gobabeb may be subject to flooding between October and May which can last anything from a day to half a year. The morphological transition zone from bedrock canyon to a wider alluvial channel with flood plains and deeper and less confined aquifer is accompanied by a transition from peak discharge to an increase in infiltration with a maximum of 8.5 mm h^{-1} (Morin *et al.* 2009) as well as deposition of particulate matter including organics and sediments. Dahan *et al.* (2008) noted that floods covering elevated stream channel terraces promote larger transmission losses. However, since these floods are short lived, flood duration and magnitude of active streambed floods are more important in the recharge process. Lateral losses to the above-mentioned palaeochannels can also not be discounted. Seeps at the bottom of coastal beach dunes have been reported (Hellwig 1968), almost certainly attributable to deep groundwater flow through porous Tsondab Sandstone. Both total suspended sediments and particulate organic matter are at a maximum around Gobabeb while conductivity increases significantly between Gobabeb and Rooibank, probably due to saline inputs from gravel plain runoff (Jacobson *et al.* 2000). Downstream, towards the delta the Kuiseb becomes one of the dustiest river environments in southern Africa (Vickery and Eckardt 2013) the exact causes of which are still to be determined.

Drainage on the gravel plains

The Kuiseb is one of the driest and most variable rivers described anywhere (Jacobson and Jacobson 2012). Because its headwaters have their origin in the highlands, its riparian and relatively fresh hydrological environment is in stark contrast to the even drier conditions on the adjacent Namib gravel environment. The southern central Namib north of the Kuiseb has its own drainage network which is perhaps a better reflection of environmental surface conditions north of Gobabeb. These rivers originate in the foothills of the escarpment and traverse an ancient plain, stripped of much of its Cretaceous history with a thin Tertiary cover and little evidence of Quaternary features. None of these rivers seems to reach the sea: they either drain into the Kuiseb or terminate in small coastal pans north of Walvis Bay. Groundwater flow, however, seems remarkably persistent on the 1% gradient of the gravel plains, feeding dozens of perennial springs and small saline pans (Eckardt *et al.* 2001; Eckardt and Drake 2011). The closest and one of the most saline of these (approximately five times ocean salinity) is Hosabes spring (Figs 2 and 3e), a 3 km walk from the Vogelfederberg approach road (Day and Seely 1988). The saline springs on the gravel plain are amongst the most saline waters in sub-

Saharan Africa (Day 1993) but are still important water points, since they facilitate north–south wildlife migration between the fresh water springs found within the east–west oasis of the ephemeral high land drainage (Jacobson and Jacobson 2012). The saline springs occur where shallow groundwater is ponded upstream of NE–SW trending lineaments and structures associated with the Precambrian granites, schists and dykes (Eckardt *et al.* 2001). Persistent seepage points tend to produce a thick crust of halite (NaCl) and gypsum ($CaSO_4{\cdot}2H_2O$) that can occupy drainage depressions of a few hectares in size with other salts such as sylvite (KCl) as well as rare nitrates including humberstonite ($Na_7K_3Mg_2(SO_4)_6(NO_3){\cdot}6H_2O$) (Eckardt *et al.* 2001) having been noted. The latter around Hosabes is also known to host perchlorate (ClO_4^-) (Rao *et al.* 2010), generally regarded an anthropogenic pollutant with natural occurrences being considered rare and still largely unexplained.

These salts are indicative of long-term hyperaridity, but are also a driver of an aggressive salt weathering regime rich in denudation landforms that include inselbergs (Goudie and Eckardt 1999) and associated weathering forms and processes (Viles and Goudie 2013). The resulting plains are remarkably flat and, with the exception of erosional wind streaks (Wilkinson 1988) and nebkha formation around perennial shrubs, have no aeolian landforms. The resulting landsurface is remarkably old in places, with denudation rates for a quartz vein near Mirabeb of 0.1 m myr^{-1} and minimum surface ages of 5.18 Ma (van der Wateren and Dunai 2001). This stability has given rise to thin Tertiary interfluve caps and cover (Qs), rich in pedogenic gypcrete west of the Vogelfederberg road (Besler 1972; Watson 1985; Eckardt and Spiro 1999) and rich in calcrete to the east of that road (Fig. 2). These surfaces are the result of runoff, deflation, entrapment, sorting, salt weathering, cementing by evaporation products with moisture inputs from fog, dew and shallow groundwater. The stable surfaces also hold shallow secondary uranium lenses (Carlisle 1978; Wilkinson 1990) currently subject to ongoing prospecting and mining.

The Namib Sand Sea

The present-day Kuiseb separates two landscapes of the starkest contrast. The geomorphology south of the river is dominated by the dunes of the Namib Sand Sea, a significant aeolian landscape of some antiquity recently designated as a UNESCO World Heritage Site. The dunes of the Sossus Sand Formation (QSs) are frequently large (height 80–120 m), linear and complex, although other dune types are present, in particular in proximity of the Kuiseb River valley. Near Gobabeb dunes rest on a sloping valley calcrete and a breakdown of distinct dune pattern can be observed. Many of the publications cited here are included in the bibliography of aeolian geomorphology of the sand sea by Livingstone (2013). Furthermore a digital atlas of the Namib Sand Sea was produced by Livingstone *et al.* (2010; www.sheffield.ac.uk/sandsea), which includes a bibliography linked to mapped locations.

Dune dynamics

The study of dunes at field sites near Gobabeb has contributed much to our understanding of the movement of desert sand dunes. For example, the movement of a single complex linear dune in the northern part of the sand sea has been monitored for over 30 years. Initially a grid of 58 steel posts was established in 1980 at the site known as 'Visitors' Dune' (Fig. 3) and a second site approximately 500 m south on the same dune and known as 'Warsaw' (Fig. 3) was established in 1982. The position of the posts was ascertained using an optical theodolite. The steel posts at these sites were measured weekly until 1984 to provide a record of surface change presented by Livingstone (1989). Subsequently, these sites have been the subject of repeat surveys at irregular intervals using a variety of surveying techniques (Livingstone 1993, 2003). Lancaster (1989, pp. 96–110) also reported a one-year study of dune movement using measurements every two weeks of steel posts on three cross-profiles on complex linear dunes close to Gobabeb.

Both Lancaster and Livingstone reported that there was a clear pattern of dynamism across the dunes, such that there was very little activity on the lower slopes of the dunes but much greater activity at the crest (Fig. 4). Further, Livingstone has been able to provide a record of change at Visitors' Dune and Warsaw covering more than three decades: Fig. 5 includes previously unpublished data from surveys in 2008 and 2012. This record confirms that the base of the dune is largely static but that there are considerable changes to the crest of the dune, apparently driven, at least in part, by variability in the wind climate (Livingstone 2003).

Surveys have also been carried out on some of the smaller dunes that extend from the large linear

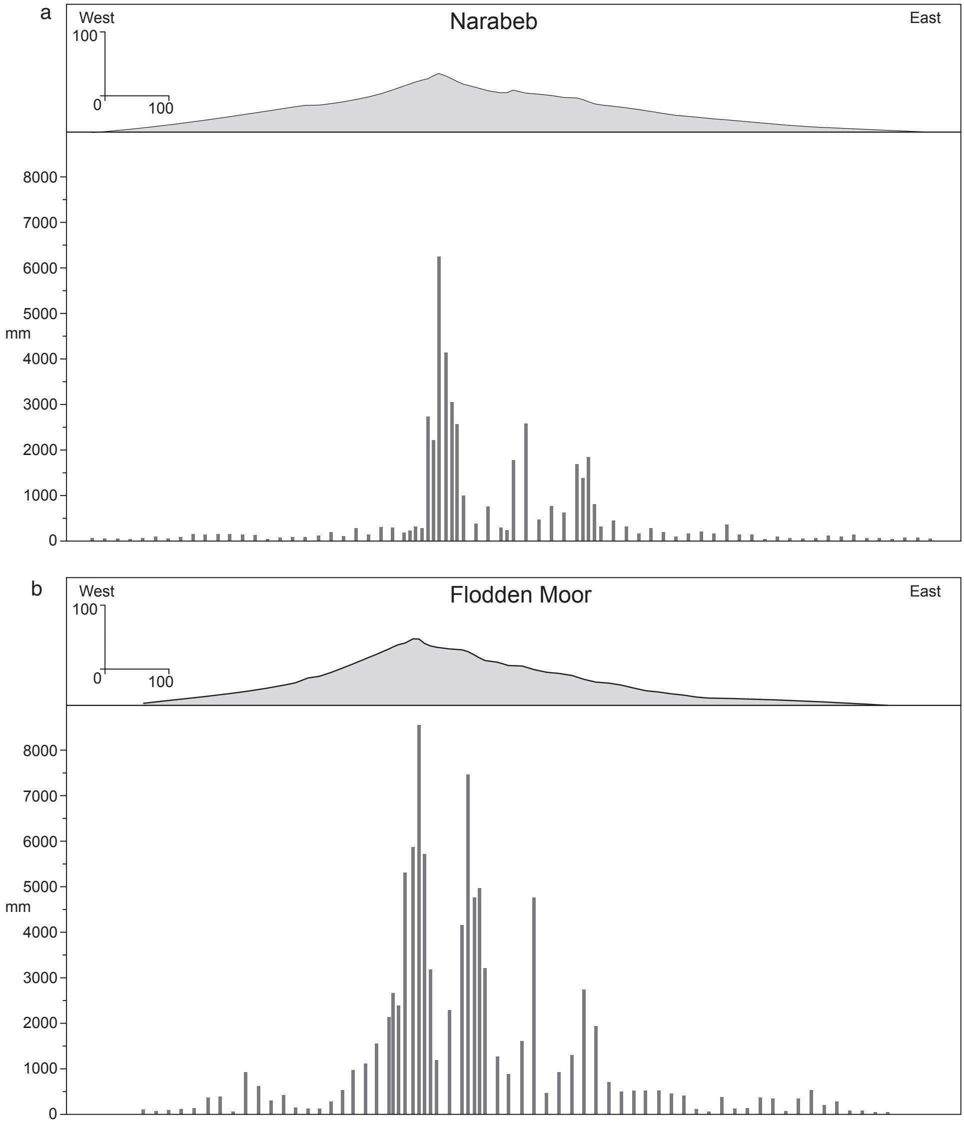

Fig. 4. Surface activity on four linear dune cross-profiles near Gobabeb. Profiles for (a) Narabeb, (b) Flodden Moor and (c) Rooibank are redrawn from data provided by Nick Lancaster, originally plotted in Lancaster (1989, Fig. 59). Profile for (d) Visitors' Dune is redrawn from data originally plotted in Livingstone (1989, Fig. 6). Ordinate scale is the modulus of change (value regardless of whether it is positive (deposition) or negative (erosion)). For Lancaster's data, values are the sum of changes measured every two weeks for a year. For Livingstone's data, values are average change over a four-week period based on four years' data.

dunes across the southern terraces of the river. In 1969, Besler started a survey on an extending tip of a small, simple linear dune close to Gobabeb, which is now known as 'Helga's Dune' (Fig. 2). She reported (Besler 1975) that extension of this dune was roughly 2–3 m yr^{-1}. Subsequent, intermittent surveys up to 2012 have confirmed this extension rate (Besler *et al*. 2013, this issue).

In 1976 McKee used steel posts to mark the 'footprint' of a small dune immediately north of the large linear dune known as 'Natab West' (Fig. 2) dune. The small dune appeared to have been 'spawned' from the large dune and to be migrating away from it. The small dune was re-surveyed using a total station by Bristow and Lancaster in 1999 and they were able to calculate dune move-

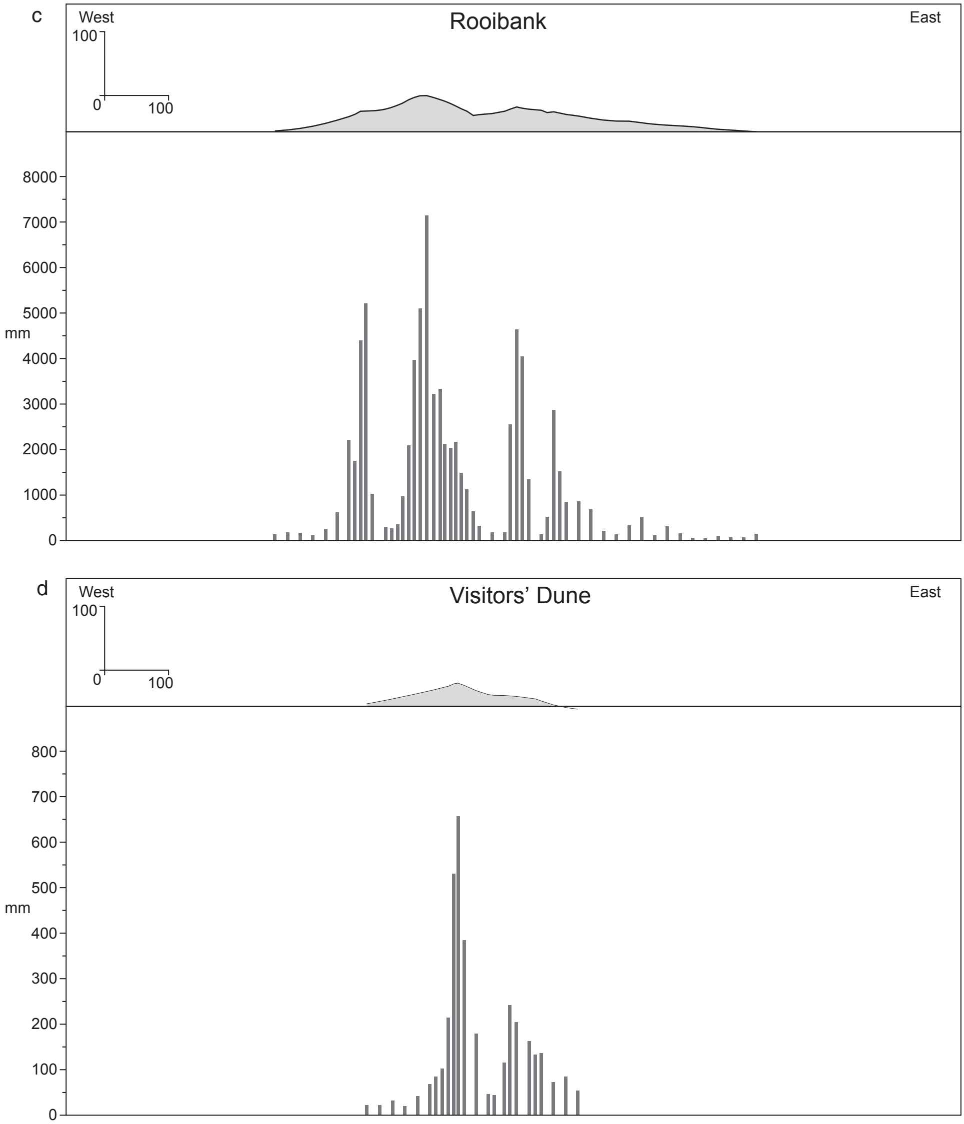

Fig. 4. Continued

ment using McKee's posts which were still present (Bristow and Lancaster 2004). The dune, which they described as a small, slipfaceless dome dune 45 m wide and 1 m high, had moved roughly 90 m, giving an average migration rate of around 4 m yr^{-1}.

Numerous causes for the lack of dunes on the northern banks of the Kuiseb have been put forward by Goudie (1972), including slow movement of dunes and frequent river flooding as well as high-magnitude north easterly winds which keep the dunes from crossing the river. Between 1977 and 1981, Ward monitored the extension of the linear dunes into the bed of the Kuiseb River by using repeated theodolite surveys tied to fixed survey points. Two zones were recognized: one west of Gobabeb between Swartbank and Rooibank (Fig. 1) where dune advance was negligible, often less than 0.04 m yr^{-1}; and a second zone between Swartbank and Natab, where rates of advance were more rapid, peaking at 1.85 m yr^{-1} close to Gobabeb (Ward and Von Brunn 1985). Nevertheless west of

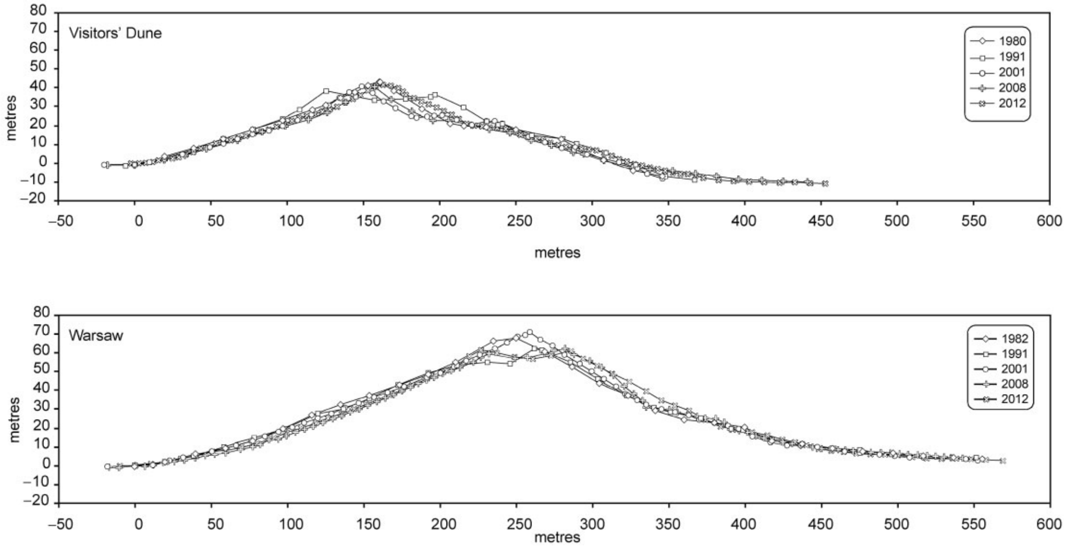

Fig. 5. Cross-profiles for two transects on one linear dune near Gobabeb for surveys between 1980 and 2012. Surveys in 2008 and 2012 are previously unpublished. Some surveys have been omitted to improve the clarity of the diagram. See Livingstone (2003) for these omitted data.

Swartbank dunes cross the Kuiseb River and delta and are amongst the fastest dunes in the Namib Sand Sea system, infringing on Walvis Bay and its associated infrastructure such as approach roads and railway (Barnes 2001).

Field investigations near Gobabeb have also contributed to the study of wind flow over dunes. Lancaster (1985, 1989) reported measurements of the changes of wind speed over linear dunes close to Gobabeb (along with measurements on transverse dunes on the Skeleton Coast). Livingstone (1986, 1988) used the Visitors' Dune site for measurements of wind speed and employed smoke flares for flow visualization. Both of these studies provided early empirical measurements of the geomorphological dynamics of dunes. However, later work showed the shortcomings of measurements of wind speed for ascertaining shear stresses on dune slopes, and field observations are now often used in models of aeolian processes at a dune-field scale rather than at the scale of a single dune (Wiggs 2001; Livingstone *et al.* 2007).

Dune sediments

A considerable body of information has been generated about the sediments in dunes near Gobabeb. Watson (1986) used particle-size data from a linear dune close to Gobabeb to compare with a transverse dune in Saudi Arabia while Fenwick (1991) presented particle-size data from the cross-profile of a single linear dune at Natab. Livingstone (1987) provided particle-size data from the Visitors' Dune site along with data from eight transects on the two dunes on either side of Visitors' Dune. All of these have demonstrated a general pattern of finer crests sitting on coarser plinths which has commonly been attributed to a coarse creep population blown onto the dunes from the interdunes. Lancaster (1981, 1989), who included transects close to Gobabeb, confirmed this observation for the wider Namib.

McKee's study (1982) involved digging pits to examine sediments just below the dune surface in an attempt to consider the shallow internal structures of a variety of dunes. However, only the development of ground penetrating radar (*GPR*) has provided the opportunity to examine sedimentary structures tens of meters below the surface. Bristow and co-workers have made considerable use of dunes in our area for GPR studies (Bristow *et al.* 2000, 2005, 2007). At the Warsaw site, they combined GPR information about the dip of foreset beds with OSL dates and have suggested that the dune here has migrated its full width towards the east in the past 5000 years (Fig. 6). Work on Natab East and Station Dune also indicated lateral migration, although not always

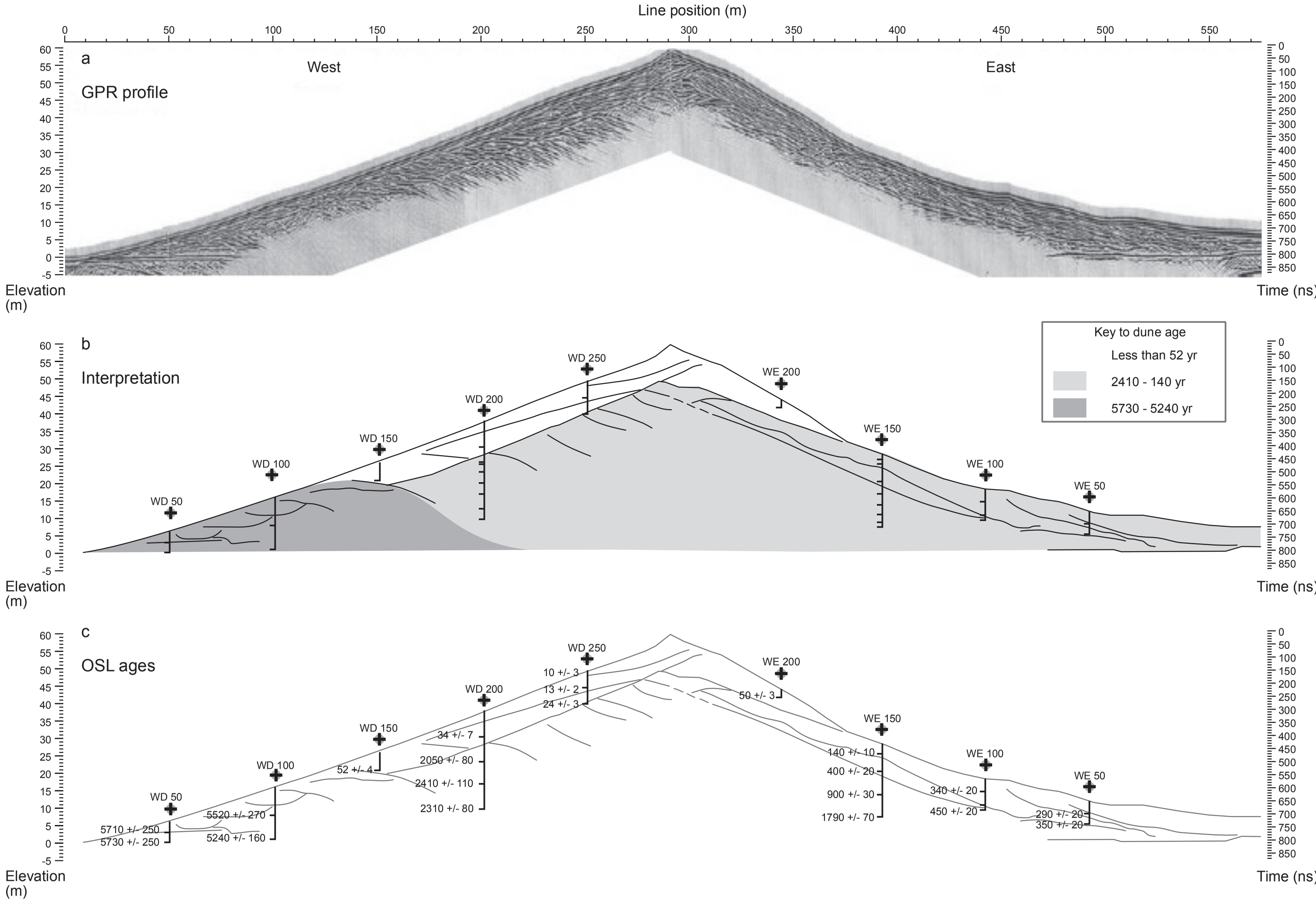

Fig. 6. Survey of the 'Warsaw' transect showing (a) internal structure elucidated by ground penetrating radar; (b) an interpretation of the age of the dune sands; (c) OSL dates. From Bristow *et al.* (2007).

towards the east. Livingstone's 30-year record from repeated surveys shows no evidence for this lateral migration but the combination of GPR with dating techniques will further our understanding about the development of the dunes.

No dunes exist on the gravel plain. However, high-magnitude north-easterly berg winds have produced wind streaks several kilometers in length around numerous outcrops (Wilkinson 1988), in particular the marbles of the Karibib Formation which form part of the Hamilton Range. While the sand sea manifests the frequent south-westerly winds, the gravel plain, due to its lag cover, only responds to the most severe easterly low-frequency winds. These winds are also responsible for silt entrainment and dust transport in the lower Kuiseb River and delta along with other fines generated by gravel plain floods and playas as well as mining operations on the plains.

Conclusion

The surface geology and geomorphology of the three environments surrounding the Gobabeb Research and Training Centre have provided insight into the long-term evolution of the coastal, central Namib Desert. Studying individually the gravel plains north of the Kuiseb River, the Kuiseb River itself and the ancient and contemporary dune deserts south of the Kuiseb has contributed extensively to our understanding of such systems locally as well as beyond the horizons of the Namib. The three systems each provide a graphic laboratory of materials and processes extensively studied by individual researches as well as being used for teaching at all levels.

Based on the landscape around Gobabeb, researchers have been inspired to develop extensive, long-term datasets that enhance description and understanding of the evolution of these systems. Although the plains have been least studied, they are, nevertheless, indicative of erosion and weathering since the break-up of Gondwana. They host numerous salt spring and extensive uranium deposits of several different origins all currently under further investigation.

The Kuiseb River has provided wide-ranging information about past and current excavation and infill of the well defined valley, of current and past floods, infiltration rates in arid environments as well as the interrelationship between the sand sea on the southern bank and the position of the river itself. Other studies include the dynamics and interrelationships of the riparian vegetation with the geomorphology and geology of the linear oasis.

The ancient and contemporary sand deserts south of the Kuiseb have geomorphological characteristics that provide much information about aeolian dynamics. Moreover, the far-reaching research around the Gobabeb Research and Training Centre into the Namib Sand Sea in particular has provided the basis for 30 000 km^2 of this landscape to be designated as a World Heritage Site with one of the criteria being ' viii: an outstanding example representing major stages of earth's history, significant on-going geological processes in the development of land forms, and significant geomorphic and physiographic features'. As a consequence, geomorphological and geological research opportunities been broadly increased and the potential for dissemination of relevant information and interpretations has been enhanced.

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