Andrew Goudie

Desert Landscapes of the World with Google Earth

Springer

Desert Landscapes of the World with Google Earth

Andrew Goudie

Desert Landscapes of the World with Google Earth

Springer

Andrew Goudie
School of Geography and Environment
University of Oxford
Oxford, UK

ISBN 978-3-031-15178-1 ISBN 978-3-031-15179-8 (eBook)
https://doi.org/10.1007/978-3-031-15179-8

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

Since I was a boy, I have been fascinated by landforms and landscapes, and this is why I became a Geomorphologist. One component of this fascination was a delight in the beauty and diversity of geomorphological features. In the last few decades, this delight has become heightened by the new view of the Earth that one gets from space. Google Earth, in particular, provides remarkable images of landforms and landscapes, not least in the world's deserts. I have been able to relate my own desert travels, explorations, and research since 1967 to what can be seen from space. This is the basis for this book. I also feel that in addition to its aesthetic value, Google Earth is not only valuable in research but also, through presenting surface features in such a dramatic way, it is a very useful educational tool.

Over the years I have been in the field with various colleagues. I am grateful to them all for exposing me to so many of the landscapes discussed in this book: Aaron Yair, Adrian Parker, Alice Goudie, Amy Goudie, Andrew Warren, Andrew Watson, Ash Parton, Asher Schick, Asma Al-Farraj, A. A. Nikonov, Bimal Ghose, Bob Allison, Bridget Allchin, Cameron Petrie, Charles Koch, Charles Sperling, Christian Velde, Dan Yaalon, David Jones, David Price Williams, David Thomas, Denys Brunsden, Derek Kennett, Dick Grove, Elaine Heslop, Ewan Masson, Frank Eckardt, Gareth Preston, Gerard Dekker, Gordon Wells, Graham Evans, Harald Schnepfleitner, Heather Viles, Ian Livingstone, Jacques Bonvallot, Jacques Viellefon, Jennifer Lalley, John Doornkamp, John Pugh, Joseph Ballard, Karunakara Hegde, Ken Pye, Kevin White, Helen Rendell, Hong Zhang, Kevin White, Lew Watts, Mahmoud Ashour, Martin Sands, Mary Bourke, Mick Day, Mike Meadows, Mike Summerfield, Nabil Embabi, Nick Rosser, Nigel Winser, Oliver Sass, Olly Atkinson, Owais A. El-Rashidi, Paul Temple, Peter Arbuthnot, Peter Bush, Peter Fookes, Piotr Migoń, Qinglin Guo, Ran Gerson, Ravindra Singh, Raymond Allchin, Robert Knox, Ron Cooke, Sanjeev Gupta, Shane Winser, Sharad Narhar Rajaguru, Statira Guzder, Stefanie Fruhmann, Stephen Stokes, Surendra Singh, Susan Conway, Tesfaye Haile Selassie, Tex Reeves, Vadim Ranov, and Wenwu Chen.

A huge debt of gratitude is owed to Google Earth for all the satellite images used in this book. All other images are either by the author or have been heavily modified from acknowledged sources.

Oxford, UK
September 2022

Andrew Goudie

Contents

About the Author

Andrew Goudie, D.Sc. Emeritus Professor of Geography at the University of Oxford, a former Pro-Vice-Chancellor, Honorary Fellow of Hertford College, and the former Master of St. Cross College, is a geomorphologist who led the Kimberley Research Project in 1988. He is a recipient of a Royal Medal from the Royal Geographical Society, the Mungo Park Medal of the Royal Scottish Geographical Society, and the Farouk El-Baz Award of the Geological Society of America. He is a Fellow of the British Society of Geomorphologists. He has been Chair of the British Geomorphological Research Group, President of the Geographical Association, and President of the International Association of Geomorphologists. He has written extensively on arid lands, producing over 120 scientific papers on deserts, and is the author of *Great Warm Deserts of the World* (2002), *Arid and Semi-arid Geomorphology* (2012), *Great Desert Explorers* (2016), *The Human Impact* (2018), and *Camel Tracks* (2021).

1 Introduction

Abstract

This chapter comprises two parts. The first assesses the nature and uses of Googe Earth for investigating landscapes and landforms since it was launched in 2005. The second provides an overview of deserts: Their distribution, climatic conditions, tectonic settings and terrain types.

Keywords

Google Earth • Landforms • Landscapes • Aridity • Tectonics • Terrain types

1.1 Google Earth and Landscapes—Introduction

Google Earth is a phenomenally valuable tool for examining and appreciating phenomena on the face of the Earth. The aim of this book is to show its value for understanding the landscapes of the world's deserts and for appreciating their asthetics. Only vertical images are used in this book, but it is also possible to tilt them.

It was launched in 2005, and is a computer programme that renders a three-dimensional representation of Earth based primarily on satellite imagery. It maps the Earth by superimposing satellite images, air photographs and GIS data onto a 3D globe, allowing its users to see landscapes from a range of angles. It is regularly updated and in its basic form is free for users. It is easily accessed via personal computers. Imagery resolution ranges from 15 cm to 15 m. It provides a distance measuring tool.

Google Earth does not discuss the elevational accuracy of its data. However, in studies of dunes, Goudie et al. (2021a, b) found that heights determined from Google Earth were similar to those obtained by the use of maps and surveys by earlier workers. In addition, various studies have compared surveyed heights (e.g. of buildings) with Google Earth heights and indicate that the accuracy of Google Earth height estimates is a matter of a metre or a few metres (Qi et al. 2016; El-Ashmawy 2016; Farah and Algarni 2014).

Google Earth (https://www.google.co.uk/intl/en_uk/earth/) has now been used in many geomorphological studies, both for teaching (see Lisle 2006; Demirci et al. 2013; Tooth 2015) and for research (Scheffers et al. 2015). Among the phenomena that have been studied are tiger bush (Paron and Goudie 2007), coasts (Scheffers et al. 2012), salt marshes (Goudie 2013), lakes (Scheffers and Kelletat 2016), soil erosion (Boardman 2016), dunes (Goudie 2020; Goudie et al. 2021a, b, river morphology (Henshaw et al. 2020), channel patterns (Colombera and Mountney 2019), landslides (Fisher et al. 2012), wetlands (Amani et al. 2019) and permafrost landforms (Whalley 2021).

Google Earth provides near global coverage, so that it is immensely important for determining global distributions of particular phenomena (Goudie 2020; Traganos et al. 2018).

Google Earth can also be used to show change of landforms over the last four decades through its time lapse function and Google Earth Engine (https://earthengine.google.com/timelapse/) (Gorelick et al. 2017). This has been employed to show, for example, dune migration (Sparavigna 2016), shoreline change (Mao et al. 2021) and river channel migration (Tobón-Marin and Cañón Barriga 2020; Boothroyd et al. 2021). It can also be used to show changes in human activities such as irrigation (Deines et al. 2019) and land cover changes that can impact upon land degradation (Li et al. 2020). Various examples are given in this book (see, for example, Sects. 8.2 and 8.5).

In this book, the latitudes and longitudes of images are provided, so that they can be re-located by the reader, as are scale bars. Where possible and relevant, ground photos relating to particular Google Earth images are given.

A. Goudie, *Desert Landscapes of the World with Google Earth*,
https://doi.org/10.1007/978-3-031-15179-8_1

1.2 What Are Deserts?

The world's deserts occur in every continent (Fig. 1.1) including Antarctica. They are the most extensive of the Earth's terrestrial biomes, and are areas characterized by a severe shortage of moisture. This is primarily because precipitation is limited in amount (Warner 2004; Nicholson 2011). However, in some deserts aridity is in part also the result of high temperatures, which means that rates of evaporation and moisture loss are high. The driest deserts are often described as hyper-arid, and in some years may receive no rainfall at all. Extremely arid areas, such as occur in the Atacama, Namib and the central and eastern Sahara, cover about 4 per cent of the earth's surface, arid about 15 per cent, and semi-arid about 14.6 per cent. Combined, these amount to almost exactly one-third of Earth's land surface area (Meigs 1953).

Wind conditions are another factor that leads to diversity in desert types. Some deserts are high-energy environments, and this together with their directional regimes, helps to explain variations in dune forms, dust storm activity and the presence or absence of wind erosion features such as yardangs (see Sect. 3.2).

Introductions to desert conditions are provided by Goudie and Wilkinson (1977) and Laity (2008). Discussions of the main desert areas are provided in Parsons and Abrahams (2009) and Goudie (2002), while the landforms and land-forming processes are described in Goudie (2013) and Thomas (2011). There are also various local studies. Edgell's (2006) monograph on Arabia is a notable example.

In addition to being classified on the basis of their moisture deficits, deserts can also be classified on the basis of their proximity to the oceans. Coastal deserts, such as the Namib of south western Africa or the Peruvian/Atacama of western South America, have very different temperature regimes and humidity characteristics from the deserts of continental interiors. They tend to have relatively modest diurnal and seasonal temperature ranges and to be subject to frequent, wetting fogs though in general they tend to be extremely dry, so that salt accumulation is very significant (Fig. 1.2).

In addition to the coastal and inland deserts of middle and low latitudes there are also the cold high-latitude deserts (Seppälä 2004), though for the most part they are not dealt with in this volume. The annual precipitation of Arctic regions can be as low as 100 mm and at Vostok in Antarctica can be less than 50 mm.

The world's non-polar deserts occur in five great provinces separated either by the oceans or by humid tropical forests. The largest of these comprises the Sahara and a series of other deserts extending eastwards through Arabia, Iran, and further into Asia. For example, in the Indian sub-continent there is the Thar and the deserts of Baluchistan, while in China there are, *inter alia*, the Taklamakan and Kumtagh deserts. The southern African province consists of the coastal Namib Desert (Lancaster 1989) and the interior Karoo and Kalahari dry zones (Thomas and Shaw 1991; Eckardt 2022). The South American dry zone is confined to two strips—the Atacama and Altiplano along the west coast and the Patagonian Desert lying between the Andes and the

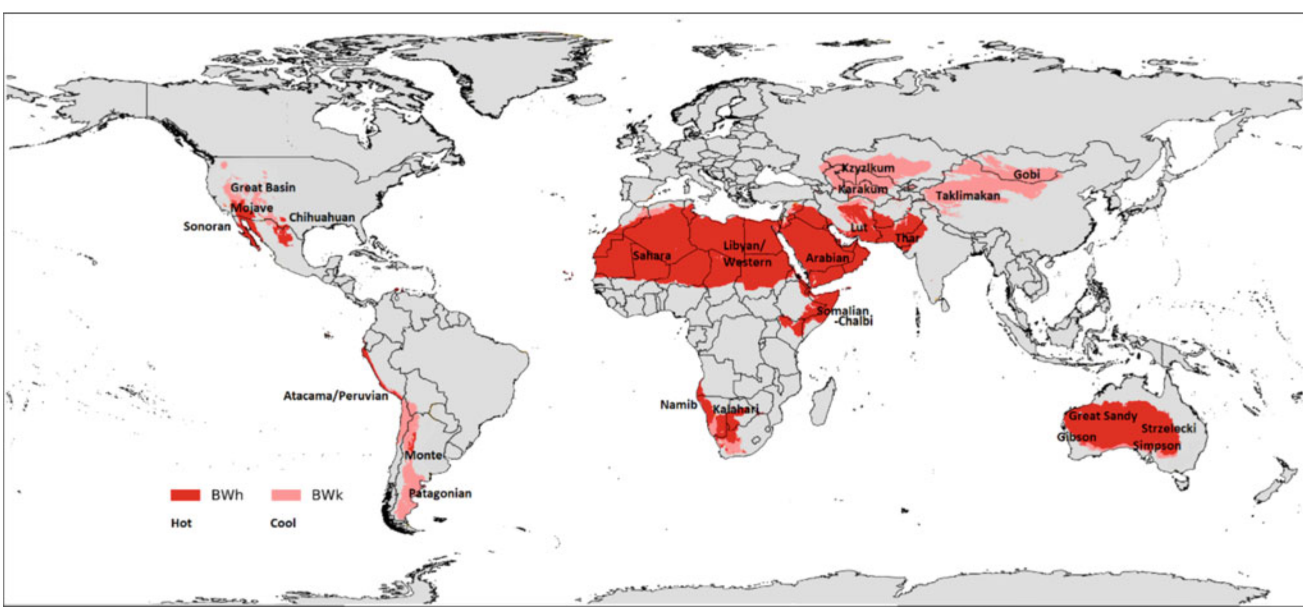

Fig. 1.1 Major non-polar deserts, showing the distribution of the hot and cool types according to the Köppen classification

Fig. 1.2 Atacama salt**.** Top: A salt flat in inland from Iquique in Chile. This is one of the driest areas in the world, and years can go by without any rainfall. Salt accumulations are widespread (Photo by A.S. Goudie). Bottom: The presence of salt and wetting fogs in the Atacama means that weathering phenomena, such as tafones, are common (Photo by A.S. Goudie)

south east coast. Within Argentina they are almost linked up by the Monte Desert. The North American desert province occupies much of Mexico and the south-western United States, including the Mojave, Chihuahuan, Sonoran and Great Basin Deserts. The fifth and final province is in Australia, which is the driest of the continents apart from Antarctica. Of the total surface area of the Earth with arid climates, Africa has c 37%, Asia 32%, North America 12%, Australia c11%, and South America c 9% (Laity 2008, p. 14).

Given, as we have seen, that one third of the Earth's land surface can be classified as desert, it is not surprising that there is a huge diversity of landscapes. Deserts may be divided into those where relief units are determined by geological factors and then may be sub-divided further into those which are distinctive owing to more specifically geomorphic factors. So, for example, while one can distinguish between shield deserts and mountain-and-basin deserts, on a more detailed scale these may be subdivided into such types as sand, stony, and riverine deserts.

Plate tectonic history has been crucial for explaining landscapes in many deserts (Goudie 2009). In South America, mountain building and the migration of the Andean volcanic arc towards the east, associated with the subduction of the oceanic Nazca plate beneath the South American continental plate, created great contrasts in altitude (Fig. 1.3), abundant volcanism and the many closed depressions in the Altiplano, such as the enormous Salar de Uyuni.

In the south west USA, the Basin-and-Range Province is a classic area of crustal extension, volcanism and faulting, and this accounts for the pattern of high uplands and very low basins (Fig. 1.4).

In Death Valley, high mountains rising to over 3000 m are close neighbours of salt flats which at Badwater lie below sea-level (see Sect. 6.2.2). In northern Africa, the Atlas Mountains, the central Sahara highlands (e.g. Tibesti, Aïr and Hoggar), the uplift of the Red Sea Hills between northern Egypt and the border between Sudan and Eritrea, and the evolution of the Nile's course, have all been affected by plate tectonic processes and are major controls and features of the area's relief. In southern Africa the Namib owes much of its character to the opening of the South Atlantic by sea-floor spreading in the late Jurassic and early Cretaceous (c 130 million years ago) and the presence of the great hot-spot associated with the Walvis Ridge. Magmatic activity led to great domes, such as the Brandberg (see Sect. 4.4.2). In addition, uplift of the Great Escarpment and the basinal form of the Kalahari are associated with passive-margin evolution. In Namibia, rivers like the Fish have incised themselves into the rising Great Escarpment, creating deep gorges (Fig. 1.5).

In the Middle East, the Red Sea rift, the Dead Sea trough, the Zagros Mountains (see Sect. 4.3.4) and the ophiolite ranges of Oman and the United Arab Emirates are a response to the area being at a crossroads of major plate boundaries. In the interior of Asia the uplift of the Karakorams, Himalayas and the Tibetan Plateau radically modified the climate and accounts for the development of huge mountain ranges in close proximity to enormous closed basins (e.g. Tarim), some of which extend below sea-level (such as Turfan), and to the creation of a rain-shadow that controlled the onset of loess formation (see Sect. 7.4.2). By contrast, Australia is an ancient, low, dry, and comatose continent with a long history of comparative orogenic stability over large areas, so that many of the present landscape features, including the many duricrusts, are inherited from a succession of climates that may go back to the Jurassic or even earlier (see Sect. 4.2.6).

The tectonic settings of contemporary drylands were discussed by Rendell (2011). She identified five types: cratons (shield and platform areas); active continental margins, associated with Cenozoic orogenic belts; older, Phanerozoic, orogenic belts; inter-orogenic basin-and-range and inter-cratonic rift zones; and passive continental margins.

Mountain ranges and their associated basins make up between 40 and 50 per cent of the land surface of the Saharan, Arabian and south-western USA deserts. The mountain-and-basin deserts are often undergoing present-day mountain building (orogenesis), and these tectonic processes create sharp fault junctions between mountain fronts and plains. Perhaps the finest example of this type of desert is the fault-block topography of the Basin-and-Range area of the southwestern USA. The high relative relief is one of the major controls of the types of geomorphological processes that operate. Thus alluvial fans often occur at the point where sediment-laden streams and mudflows debouch from the mountain fronts and spread out over the plains beneath (see Sect. 6.2.2).

Shield deserts, which occur in Africa, Arabia, Australia and India, have much less relief than the mountain-and-basin deserts, and this is rarely enough to lead to a moderation of aridity or to introduce forms which result from current freeze–thaw weathering. One of the features of these deserts is how monotonously flat they can appear. Areas of high relief are restricted in extent so that drainage systems are often poorly developed and erosion is modest. The preservation of extensive remnants of earlier, more humid weathering cycles, including duricrusts, is common and internal drainage, where the products of erosion are deposited and accumulate in playa lake systems (or inland sabkhas), are also a frequent feature of shield deserts.

Within desert regions of these two major structural types there are some areas which are dominated by erosion, others by deposition, water action, and wind action, while some are

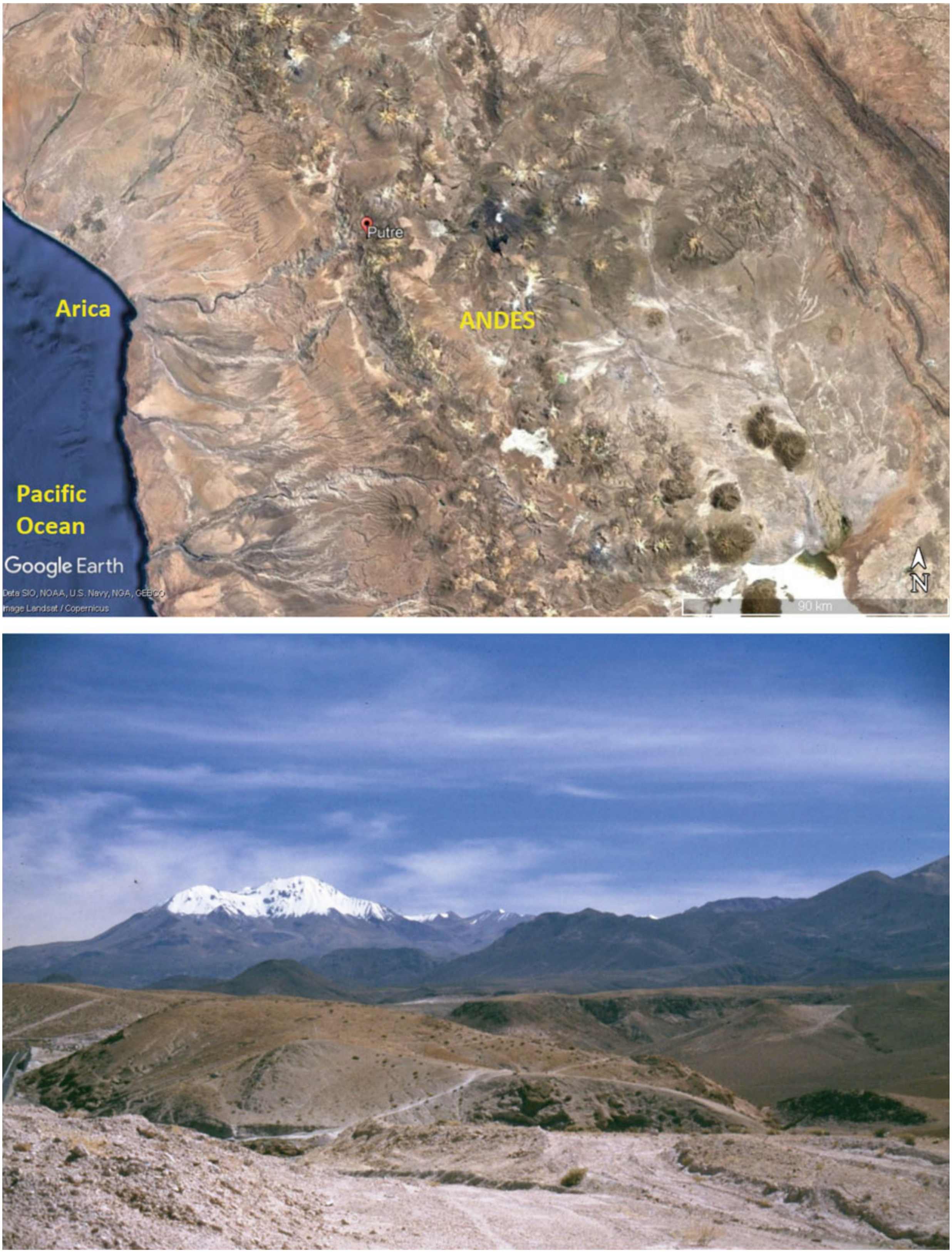

Fig. 1.3 Atacama Desert and the Andes. Top: Google Earth image of the Atacama and the Andes in northern Chile. Scale bar is 90 km. To the west is the Pacific Ocean and to the east are the volcanoes and salt lakes of the Altiplano. Bottom: The Atacama Desert and the Andes near Putre in northern Chile (Photo A.S. Goudie)

Fig. 1.4 The Basin-and-Range province, USA. Top: Google Earth image of the Basin-and-Range Province of the USA. Scale bar is 300 km. Bottom: A salty basin with a range behind. Soda Lake, Zzyzzx, San Bernadino, California. Coyote in foreground (Photo A.S.Goudie)

Fig. 1.5 Fish River Canyon, Namibia. Top: Google Earth image of the deeply incised meandering canyon of the Fish River at c 27°44'S, 17°35'E. Scale bar is 3 km. Bottom: The Fish River incised into the Great Escarpment. This is one of the largest canyons in the World (Photo A.S. Goudie)

zones of salt accumulation and some are zones of salt removal. The nature and location of the processes which operate are strongly influenced by topographic situation. Cooke et al. (1993) described various major landscape settings:

Desert uplands. Here geological controls of relief are important, bedrock is exposed, and relief is high. Examples in the Sahara include Hoggar (2908 m a.s.l.) and Tibesti (3415 m a.s.l.), both of whuch have volcanic components.*Desert piedmonts*. These are transitional zones separated from the uplands by a break of gradient but which none the less receive runoff and sediments from the uplands, and which have both depositional (e.g. alluvial fans and talus flatirons) and erosional landforms (e.g. pediments) (see Sect. 6.3).

Stony deserts. These consist of stony plains and structural plateaux (*hamada*), and may be armoured with a cover or lag of stone pavement, also called *reg* (western Sahara), *serir* (eastern Sahara), *saï* (central Asia) or *gibber* (Australia).

Desert rivers and floodplains. These are features of desert lowlands and may be fed by water derived from mountains outside the arid zone (e.g. the Nile (Fig. 1.6) and the Indus). One aspect of diversity between different deserts is the extent to which drainage is to interior basins (i.e. endoreic) or directly to the sea. Endoreic systems are widespread in arid areas, but are by no means universal (see Sect. 6.1). Nonetheless, there is a striking contrast, for example, between the Kalahari, where there is little surface drainage and large closed depressions (e.g. Mkgadikgadi, see Sect. 7.2.4), and the coastal Namib, where rivers with mountain source areas, such as the Kuiseb, Ugab and the Swakop, flow directly into the Atlantic.

Desert lake basins. These are sumps to which often disorganised drainage progresses (e.g. Lake Eyre in Australia and Lake Chad in West Africa) (see Sect. 7.2). They are often salty and may be the relics of former wetter (pluvial) conditions. In the early Holocece, for example, a series of megalakes transformed the Sahara (Drake et al. 2022) (Fig. 1.7). They may be major sources of duststorms. Some of them are currently becoming desiccated either because of increasing drought frequencies or because of human activities, such as inter-basin water transfers (see Sect. 8.2).

Sand deserts. Beyond the limits of active fluvial activity these often derive their materials as a consequence of wind deflating erodible material from floodplains or lake basins (see Chap. 2). The proportions of deserts that are covered by sand dunes vary greatly. In the Sahara (Fig. 1.8), Arabian Peninsula (Fig. 1.9), Australia and Southern Africa, active sand seas or ergs cover between 15 and 30% of the area classified as arid. By contrast, in the Americas aeolian sand covers less than 1 per cent. Some sand deserts are active, while others, because of past climatic changes may be stable (see Sect. 7.3) (Fig. 1.10).

Fig. 1.6 Google Earth image of the River Nile flowing through the hyper-arid heart of Egypt. The river, the longest on Earth, rises in the mountains of East Africa. Scale bar is 100 km

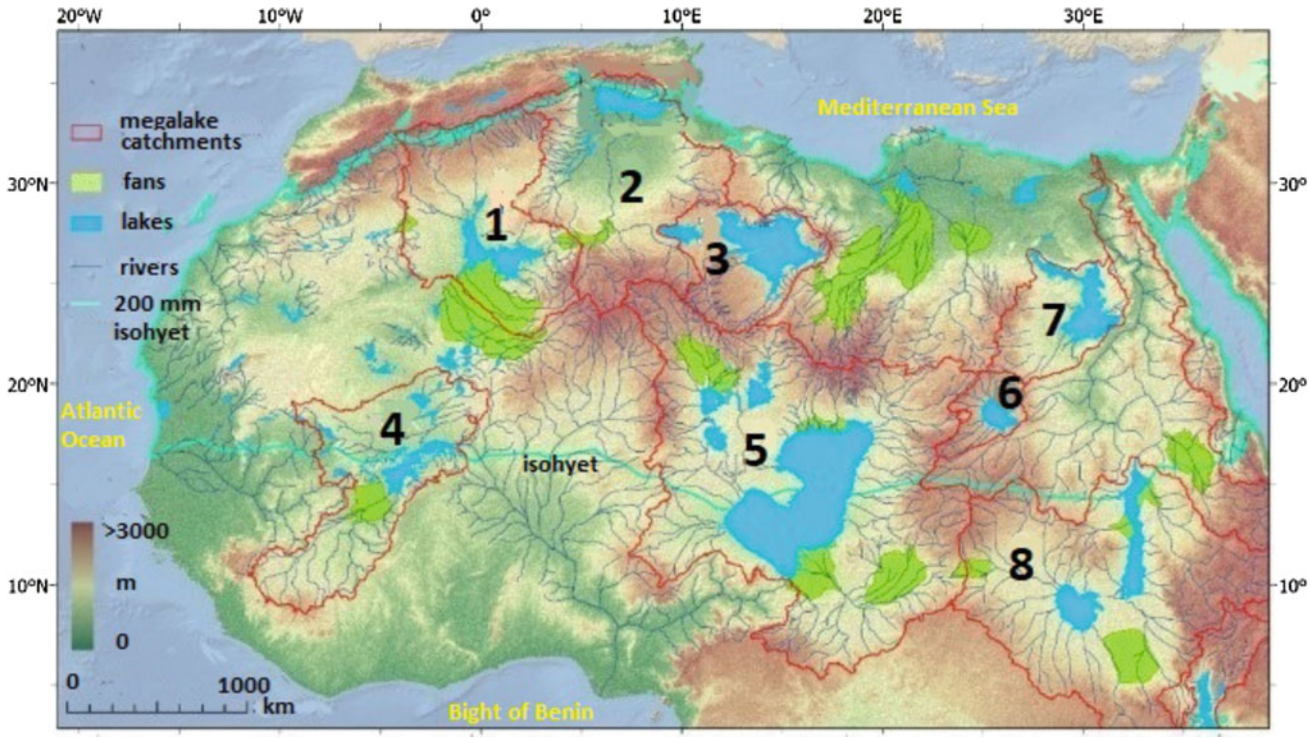

Fig. 1.7 Megalakes in the Sahara (modified from Drake et al. 2022, Fig. 1). 1: Ahnet-Mouydir, 2: Chotts, 3: Fezzan, 4: Timbuktu, 5: Chad, 6: Darfur, 7: Tushka, 8: White Nile

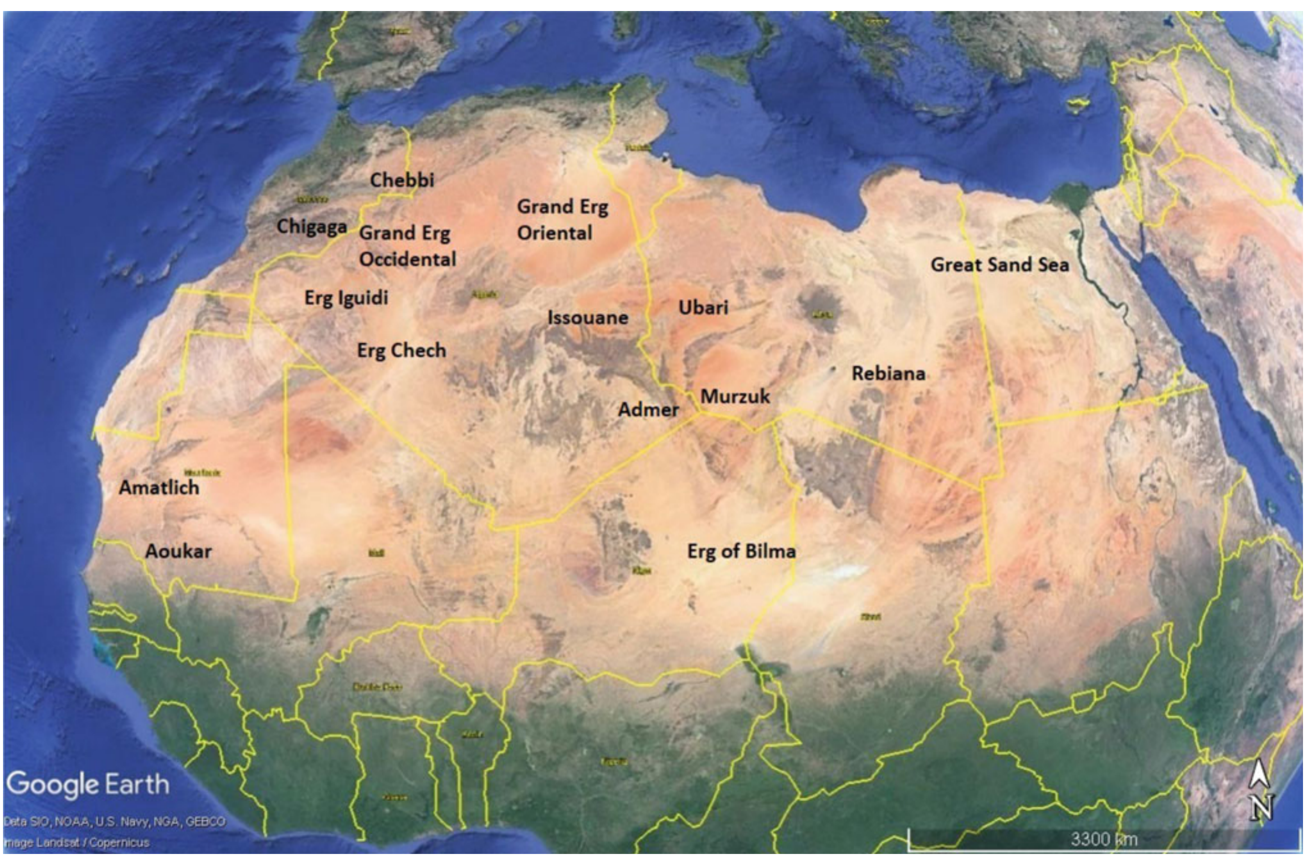

Fig. 1.8 Google Earth image of the Saharan Desert, showing some of the major sand seas (ergs). Scale bar is 3300 km

Fig. 1.9 Google Earth image of Arabia, showing the main sand seas. Scale bar is 1400 km. Sand seas cover nearly one third of Arabia, amounting to nearly 800,000 km^2. The Rub' al Khali is the biggest active sand sea in the world

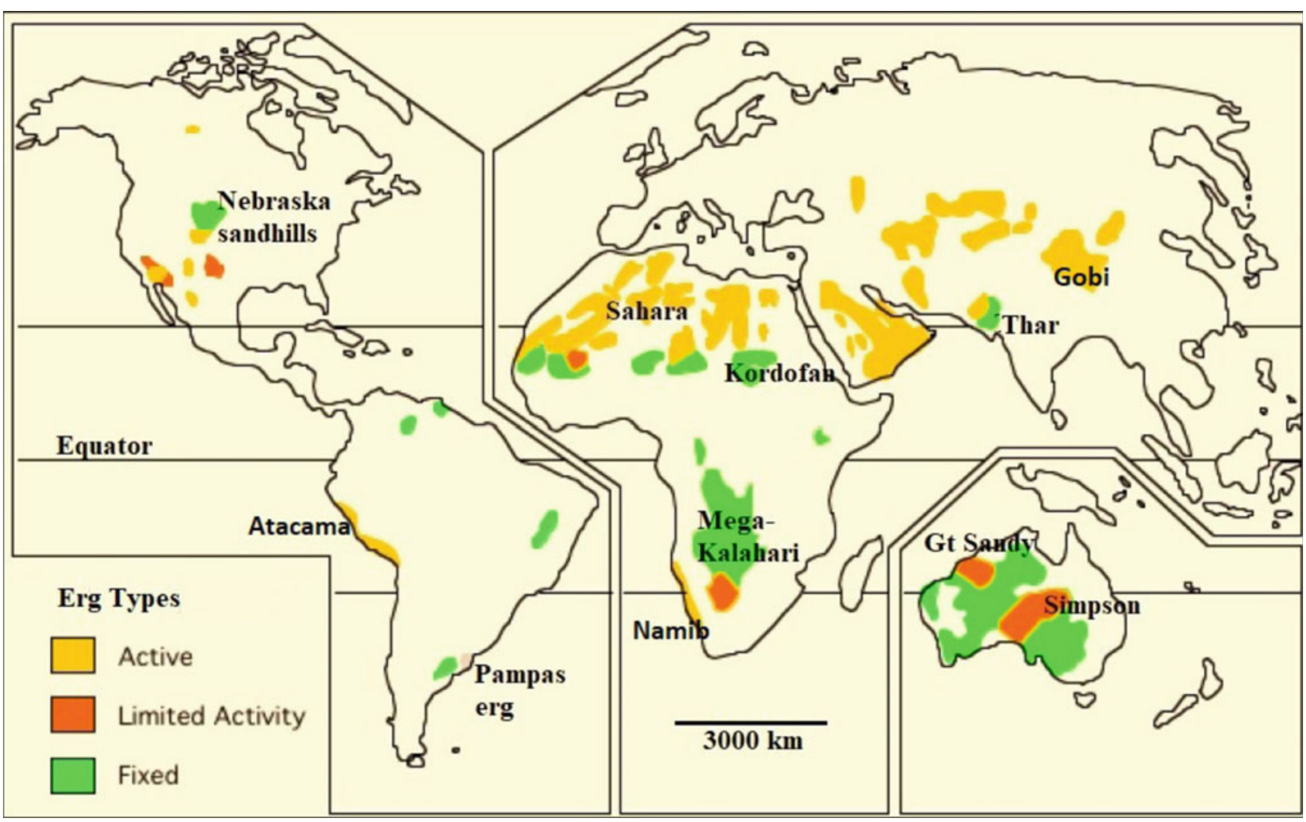

Fig. 1.10 Map of global ergs (sand seas), showing those that are active, have limited activity and which are fixed

Finally, it is important to recognise that deserts have been subject to long-term climatic change, and that they have in general been both wetter and drier than today (see Chap. 7) (Williams 2014). Some deserts are very ancient (e.g. the Atacama), and some, because of continental drift show the imprint of having travelled through zones of different climates over tens of millions of years (e.g. Australia). They are also being subjected to a whole range of anthropogenic influences that are creating major landscape changes (see Chap. 8).

References

Amani M, Mahdavi S, Afshar M, Brisco B, Huang W, Mohammad Javad Mirzadeh S, White L, Banks S, Montgomery J, Hopkinson (2019) Canadian wetland inventory using Google Earth Engine: The first map and preliminary results. Remote Sens 11(7) https://doi.org/10.3390/rs11070842

Boardman J (2016) The value of Google Earth™ for erosion mapping. CATENA 143:123–127

Boothroyd RJ, Williams RD, Hoey TB, Barrett B, Prasojo OA (2021) Applications of Google Earth Engine in fluvial geomorphology for detecting river channel change. Wiley Interdiscip Rev: Water 8(1): p.e21496

Colombera L, Mountney NP (2019) The lithofacies organization of fluvial channel deposits: a meta-analysis of modern rivers. Sed Geol 383:16–40

Cooke RU, Warren A, Goudie AS (1993) Desert geomorphology. UCL Press, London, p 534

Deines JM, Kendall AD, Crowley MA, Rapp J, Cardille JA, Hyndman DW (2019) Mapping three decades of annual irrigation across the US high plains aquifer using landsat and Google Earth Engine. Remote Sens Environ 233:111400

Demirci A, Karaburun A, Kılar H (2013) Using Google Earth as an educational tool in secondary school geography lessons. Int Res Geogr Environ Ed 22(4):277–290

Drake NA, Candy I, Breeze P, Armitage SJ, Gasmi N, Schwenninger JL, Peat D, Manning K (2022) Sedimentary and geomorphic evidence of Saharan megalakes: A synthesis. Quat Sci Rev 276:107318

Eckardt FD (ed) (2022) Landscapes and landforms of Botswana. Springer, Cham, p 403

Edgell HS (2006) Arabian deserts. Nature, origin and evolution. Springer, Dordrecht, p. 659

El-Ashmawy KL (2016) Investigation of the accuracy of Google Earth elevation data. Artif Satell 51(3):89–97

Farah A, Algarni D (2014) Positional accuracy assessment of Google Earth in Riyadh. Artif Satell 49(2):101–106

Fisher GB, Amos CB, Bookhagen B, Burbank DW, Godard V, Whitmeyer SJ (2012) Channel widths, landslides, faults, and beyond: The new world order of high-spatial resolution Google Earth imagery in the study of earth surface processes. Geol Soc Am Special Papers 492:1–22

Gorelick N, Hancher M, Dixon M, Ilyushchenko S, Thau D, Moore R (2017) Google Earth Engine: Planetary-scale geospatial analysis for everyone. Remote Sens Environ 202:18–27

Goudie AS (2002) Great warm deserts of the world. Oxford University Press, Oxford, p 476

Goudie AS (2009) Global deserts and their geomorphological diversity. In: Parsons AJ, Abrahams AD (eds) Geomorphology of desert environments, 2nd edn. Springer, Dordrecht, pp 9–20

Goudie AS (2013) Arid and semi-arid geomorphology. Camb Univ Press, Cambridge, p 454

Goudie AS (2020) Global barchans: A distributional analysis. Aeolian Res 44:100591

Goudie AS, Wilkinson JC (1977) The warm desert environment. Camb Univ Press, Cambridge, p 88

Goudie AS, Goudie AM, Viles HA (2021a) The distribution and nature of star dunes: A global analysis. Aeolian Res 50:100685

Goudie AS, Goudie AM, Viles HA (2021b) Dome dunes: distribution and morphology. Aeolian Res 51:100713

Henshaw AJ, Sekarsari PW, Zolezzi G, Gurnell AM (2020) Google Earth as a data source for investigating river forms and processes: Discriminating river types using form-based process indicators. Earth Surf Proc Landf 45(2):331–344

Laity J (2008) Deserts and desert environments. Wiley-Blackwell, Chichester, p 356

Lancaster N (1989) The Namib Sand Sea: Dune forms, processes & sediments. Taylor and Francis, London, p 192

Li Q, Qiu C, Ma L, Schmitt M, Zhu XX (2020) Mapping the land cover of Africa at 10 m resolution from multi-source remote sensing data with Google Earth Engine. Remote Sens 14(4) https://doi.org/10.3390/rs12040602

Lisle RJ (2006) Google Earth: a new geological resource. Geol Today 22(1):29–32

Mao Y, Harris DL, Xie Z, Phinn S (2021) Efficient measurement of large-scale decadal shoreline change with increased accuracy in tide-dominated coastal environments with Google Earth Engine. ISPRS J Photogrammetry Remote Sens 181:385–399

Nicholson SE (2011) Dryland climatology. Camb Univ Press, Cambridge, p 528

Paron P, Goudie AS (2007) Preliminary results about mapping and geomorphological correlation of tiger bush (Brousse tigrée) in Somalia, from a remote sensing and GIS analysis perspective. In: Goudie AS, Kalvoda J (eds) Geomorphological variations. Nakladatelství P3K, Prague, pp 37–86

Parsons AJ, Abrahams AD (eds) (2009) Geomorphology of desert environments, 2nd edn. Springer, Dordrecht, p 849

Qi F, Zhai JZ, Dang G (2016) Building height estimation using Google Earth. Energy Build 118:123–132

Rendell H (2011) Tectonic frameworks. In: Thomas DSG (ed) Arid zone geomorphology. Wiley-Blackwell, Chichester, pp 17–25

Scheffers AM, Kelletat DH (2016) Lakes of the world with Google Earth: Understanding our environment. Springer, Dordrecht, p 306

Scheffers AM, Scheffers SR, Kelletat D (2012) The coastlines of the world with Google Earth: Understanding our environment. Springer, Dordrecht, p 305

Scheffers AM, May SM, Kelletat DH (2015) Landforms of the world with Google Earth: Understanding our environment. Springer, Dordrecht, p 401

Seppälä M (2004) Wind as a geomorphic agent in cold climates. Camb Univ Press, Cambridge, p 368

Sparavigna AC (2016) Analysis of the motion of some Brazilian coastal dunes. Int J Sci 5(1):22–31

Thomas DSG (ed) (2011) Arid zone geomorphology. 3rd edition. Wiley-Blackwell Chichester, p. 648

Thomas DSG, Shaw PA (1991) The Kalahari environment. Camb Univ Press, Cambridge, p 298

Tobón-Marín A, Cañón Barriga J (2020) Analysis of changes in rivers planforms using Google Earth Engine. Int J Remote Sens 41 (22):8654–8681

Tooth S (2015) Google Earth as a resource. Geography 100:51–56
Traganos D, Aggarwal B, Poursanidis D, Topouzelis K, Chrysoulakis N, Reinartz P (2018) Towards global-scale seagrass mapping and monitoring using Sentinel-2 on Google Earth Engine: The case study of the Aegean and Ionian seas. Remote Sens 10 (8):1227
Warner TT (2004) Desert meteorology. Camb Univ Press, Cambridge, p 612
Whalley WB (2021) Geomorphological information mapping of debris-covered ice landforms using Google Earth: an example from the Pico de Posets, Spanish Pyrenees. Geomorphology 393: p.107948

2 Dunes

Abstract

This chapter discusses the major types of sand dunes and sand seas (ergs). It examines the following dune types: barchans, transverse ridges, reversing dunes, zibars, parabolics, linears, stars, domes, topographic (obstacle) dunes, lunettes, shadow dunes and nebkhas.

Keywords

Dunes • Sand seas • Tranverse dunes • Linear dunes • Topographic dunes

2.1 Introduction

There are many excellent books on dunes, and so the purpose of this chapter is not to give a comprehensive overview, or to discuss processes of sand transport or wind flow characteristics, but to illustrate the great range of dune forms that there are using the resources of Google Earth. The classic work on dunes was that of Bagnold (1941), while the classic attempt to use satellite imagery to map and describe dune types was that of McKee (1979). Since that appeared, other very useful works on dunes include those by Pye and Tsoar (1990), Lancaster (1995) and Warren (2013).

There is a huge diversity of dune forms, and they vary between and across dunefields (Fig. 2.1). They may also sometimes be superimposed on each other. Tsoar et al. (2004) classified them into three main types: migrating dunes (which include transverse ridges, barchanoid ridges, barchans, etc.), elongating dunes (exemplified by the various types of linear dune), and accumulating dunes (exemplified by star dunes). In addition, there are what are sometimes called anchored or impeded dunes, which are fixed in position by topography (e.g. climbing and falling dunes, lunettes), by buildings (e.g. shadow dunes) or by vegetation (e.g. nebkhas and parabolic dunes). Fryberger and Goudie (1981), analysing the maps in McKee (1979), showed that the most common type of aeolian depositional surface is that of sand sheets and streaks (c 38%), followed by linear dunes (c 30%), transverse crescentic dunes of predominantly barchanoid type (c 24%), star dunes (5%) and dome dunes (c 1%). There are, however, major regional differences between ergs. Star dunes occupy about 24% of the dune area in the northwest Sahara (but are nowhere else above 10%), while in the Thar Desert parabolic dunes cover around 29% of the dune area (and are generally relatively insignificant elsewhere). The Kalahari is notable for the predominance of linear dunes (c 86%), a characteristic that it shares with the Australian deserts, such as the Simpson and the Great Sandy, while the Ala Shan of Central Asia, which lies between the Tibetan Plateau and the Altai Mountains in Mongolia, has very few. Reviews of barchan, parabolic, star, nebkhas and dome dunes are provided by Goudie (2011, 2020, 2022), Goudie et al. (2021a, b). Which types of dune predominate in an area depends on a number of factors, including wind directional variability, the quantity and size of available sediment (Wasson and Hyde 1981, Fig. 2.2), and other such factors as vegetation cover and topographic position. Most dunes are predominantly composed of quartz, but clay pellet (see Sect. 2.13), gypsum (see Sect. 5.9) (Szynkiewicz et al. 2010), carbonate (see Sect. 5.10.1) and volcaniclastic varieties (Edgett and Lancaster 1993) are known.

2.2 Sandseas (ergs)

Most of the world's dunes occur in areas called sandseas or *ergs* (Wilson 1971). Notable examples include the Namib Sand Sea (Lancaster 1989) (Fig. 2.3), the Taklimakan Desert of China (Wang et al. 2004) (Fig. 2.4), and the Wahiba Sands of Oman (Goudie et al. 1987) (Fig. 2.5). The Namib Sand Sea is located between the Great Escarpment of southern Africa and the Atlantic Ocean. On account of the range and quality of its dunes it is now a World Heritage

A. Goudie, *Desert Landscapes of the World with Google Earth*,
https://doi.org/10.1007/978-3-031-15179-8_2

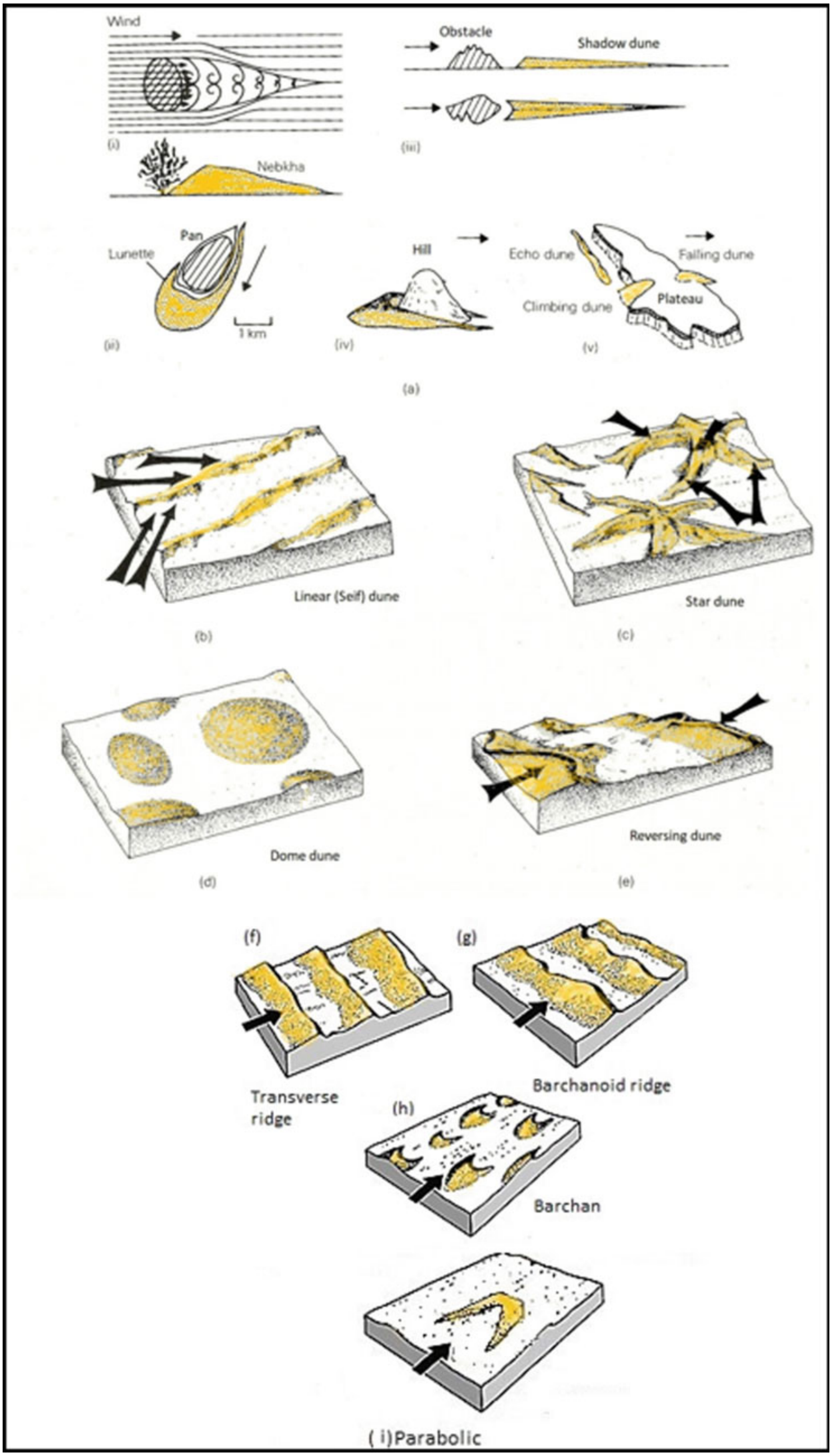

Fig. 2.1 Some types of dunes (modified from McKee (1979) and other sources)

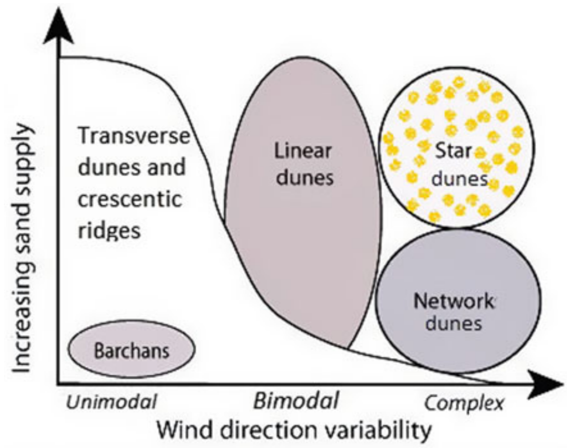

Fig. 2.2 The Wasson and Hyde (1981) model, modified by author

Site. It is quite small, covering an area of c 30,000 km^2. The Taklimakan is very much larger and is situated in a great basin, surrounded by mountains. It stretches over 320,000 km^2. The Wahiba Sands are located in Oman between Indian Ocean and the bordering mountains and their fans. They have an area of only 12,500 km^2, but have some strikingly beautiful linear dunes. The aeolianites than underlie the sand sea are discussed in Sect. 5.9.

2.3 Barchan Dunes

Probably the best known and most common basic dune form results from winds having a single dominant direction and the dune being oriented with its axis at right angles to (i.e. transverse to) the wind direction. Such dunes range from small crescent-shaped types, known as *barchans*, through to parallel rows of *barchanoid ridges*, to essentially straight ridges known as *transverse dunes*. These dunes are all characterised by slip faces in one direction and represent unidirectional wind movement. Figure 2.6 shows the global distribution of barchans.

The simplest form of barchan is the classic individual crescentic feature (Bourke and Goudie 2009). Some of these are elegantly slim and almost angular, as shown by examples on the rocky plains to the south and east of Luderitz in the Namib (Fig. 2.7). This slim symmetrical type of barchan is a feature of areas with unidirectional winds and with low sand influx and high values for shear velocity. Some simple crescentic forms possess a larger area in relation to their width than the example given above. The horns are relatively small in relation to the total mass of the dune. Such fat and podgy dunes occur in areas where there is a substantial sand influx and lower shear velocities (Parteli et al. 2007). They

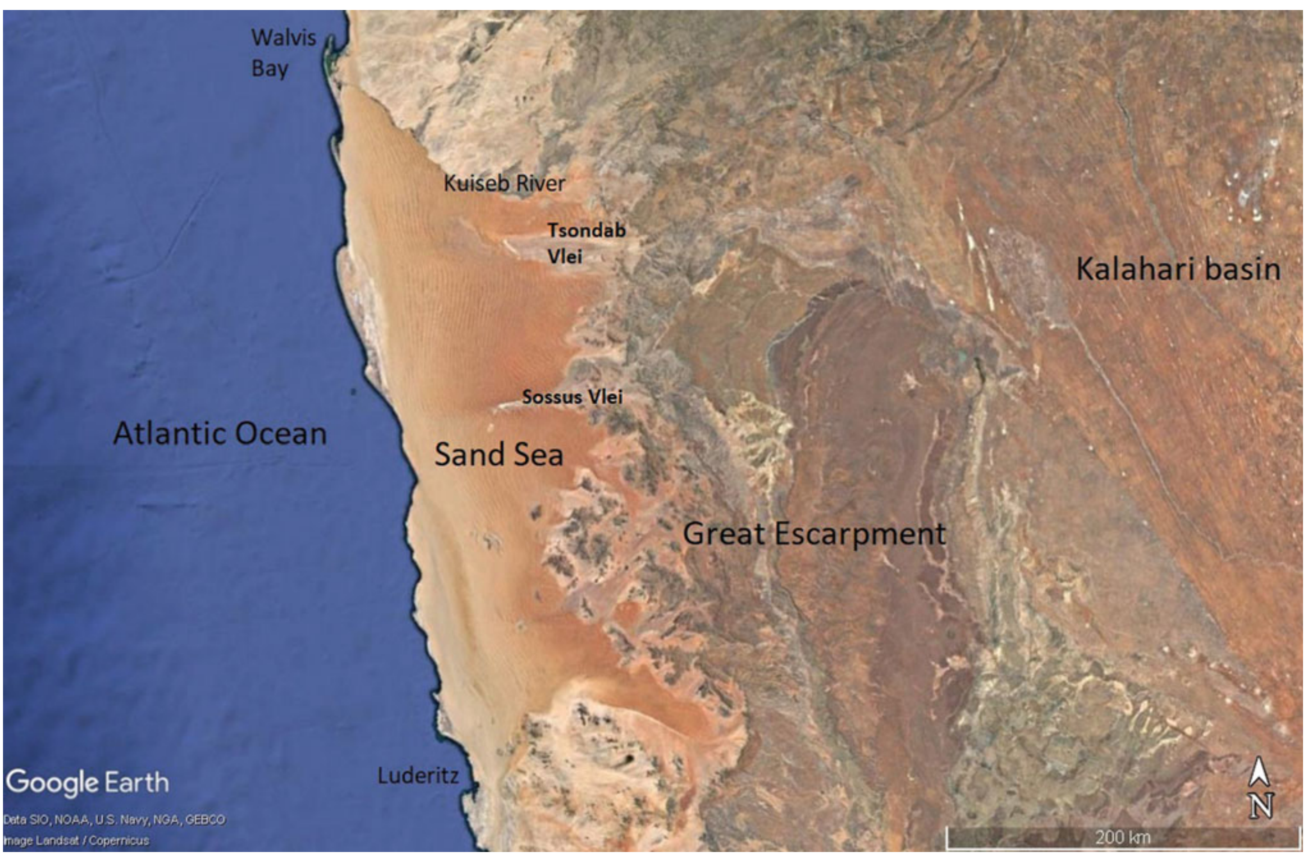

Fig. 2.3 Google Earth image of the Namib Sand Sea. Scale bar is 200 km

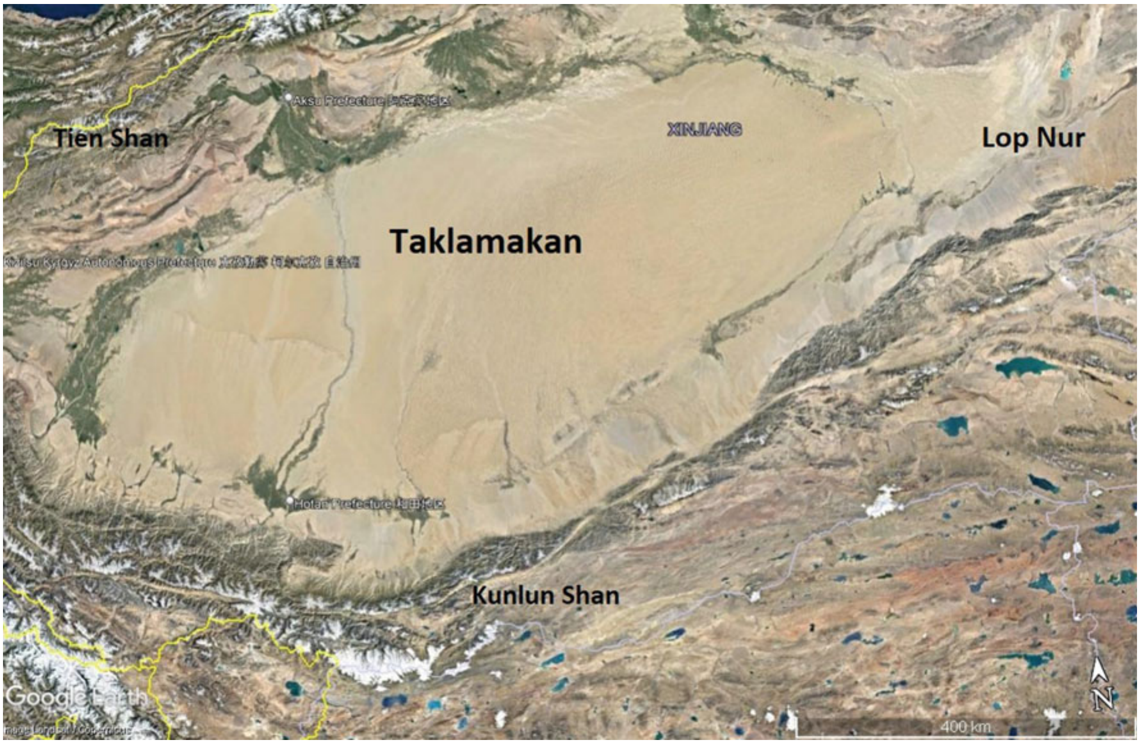

Fig. 2.4 Google Earth image of the Taklamakan (Taklimakan) Desert. Scale bar is 400 km

have the shape of a kidney or a bean (Fig. 2.8). Excellent examples are known from the Peruvian Desert.

Some barchans are asymmetric in form. This may be because they move into an area where wind directions have changed. In Mauritania there are many barchans that have a tadpole morphology (Fig. 2.9). Indeed, in Bagnold's classic model (Bagnold 1941) they may become so deformed that they are metamorphosed into a linear dune.

Barchan dunes occur where sand supply is limited, whereas transverse dunes occur where sand is abundant. At a global scale barchans are quantitatively of limited significance—less than 1% of all dune sand on Earth is contained within them, and they are almost unknown in Australia, where linear dunes are dominant. They are truly mobile, and can move at fast rates of up to tens of metres a year. They occur in two main situations: on the margins of sand seas and dune fields, and in sand transport corridors linking sand source zones with depositional areas. Some barchans form large trains, as downwind of the great escarpment behind the Kharga Depression in the Western Desert of Egypt (Stokes et al. 1999) (Fig. 2.10 top). They are disruptive to transport infrastructure (Fig. 2.10 middle).

The two horns of barchans face in the direction of dune movement. Sand avalanching takes place on their steep lee sides (Fig. 2.11).

They tend to occur in areas of limited sand supply, on planar surfaces, with precipitation usually less than 100 mm per annum, and where winds are narrowly bimodal in direction (with a directional index that is normally around 0.7–0.9). They are variable in size, ranging in height from a few metres to over 500 m in the case of mega-barchanoids. The Pur Pur dune of Peru is an example of a very large barchan (Simons 1956) (Fig. 2.12) and like many other large barchans it has a very irregular, corrugated windward surface with secondary bedforms (see Elbelrhiti et al. 2005).

In comparison with other dune types, barchans are fast-moving, and hence their migration history can be determined using combinations of maps, air photographs, and remotre sensing images. Sparavigna (2013a, b, 2014) has shown the utility of Google Earth for establishing rates of barchan migration in a number of desert areas including Peru and Egypt, while Schueth and Laycock (2022) examined Google Earth images from 107 dune systems and established that the fastest dunes were small barchans in the Sanlongsha Dune Field in the Kumtagh Sand Sea of northwestern China which move at rates of more than 70 m/yr.

Some barchans occur in swarms, and have the triangular shape 'assumed by a swarm of migrating geese' (Mainguet 1984, p. 37). Examples are known, *inter alia*, from the Erg of Fachi Bilma on the south side of Tibesti (Fig. 2.13), near Reggane in Algeria (at c 26°31′N, 0°09′E) to the east of the Gilf Kebir Plateau in Egypt, and in the southern Namib (Bourke and Goudie 2009). The Namib example was clear

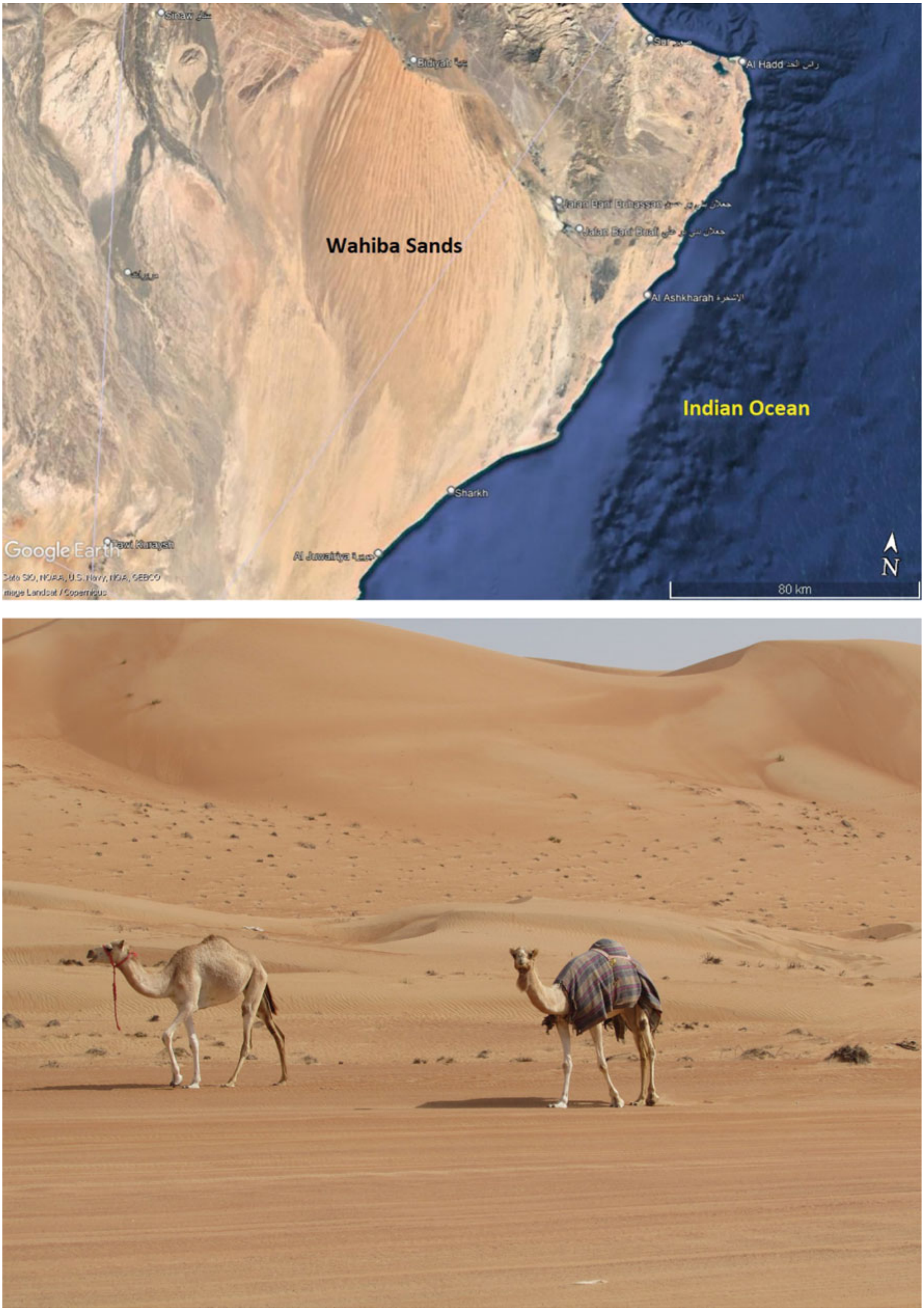

Fig. 2.5 The Wahiba Sands, Oman. Top: Google Earth image. Scale bar is 80 km. Bottom: Linear dunes and interdune corridor (*Photo* A. S. Goudie)