# Chapter 2

# Global Deserts and Their Geomorphological Diversity

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## Introduction

The world's deserts show great diversity in terms of both their landscapes and their geomorphological processes (Goudie, 2002). Climate is one major control of their character. Thus aridity determines the extent to which different types of salt can accumulate, but above all it determines the nature of the vegetation cover, which in turn controls the rate of operation of slope, fluvial and aeolian processes. For example, dunes will not for the most part move if is there is a substantial vegetation cover, nor will dust storms be generated. Deserts such as the Atacama, Libyan and Namib are hyper-arid, whereas those of the Thar, Kalahari and Australia are considerably moister. Some deserts are high energy wind environments, while others are not, and this helps to explain variations in dune forms, and the presence or absence of wind erosion features such as *yardangs*. Some have unidirectional wind regimes, whereas others are more variable. Some deserts, especially coastal ones such as the Namib (Fig. 2.1) and Atacama, are foggy and this may influence rates of weathering. Other deserts are cold in winter and to may be subject to frost processes. Climatic history is also important. Some deserts are very ancient, but others are less so. Some, because of continental drift show the imprint of having travelled through zones of different climates (e.g. Australia).

The other great control of desert character is tectonic history. Deserts on active plate margins (e.g. the Atacama) are different from those on passive margins (e.g. the Namib), while those on old shields (e.g. Australia) are very different from those where orogeny is active (e.g. Iran). Some deserts occur in areas of ongoing erosion and uplift, while others occur in areas of sediment accumulation and subsidence (e.g. the Kalahari).

**Fig. 2.1** The Namib Desert of southern Africa is a coastal, foggy desert, where fog precipitation may be greater than that provided by rainfall. This plays a major role in rock weathering

Let us now consider these general propositions by examining what it is that creates the distinctive nature of a selection of eight of the world's deserts. Descriptions of other deserts are given in Petrov (1976), while thorough treatments of particular deserts not covered here include Busche (1998) on the Sahara and Edgell (2006) on the Arabian deserts.

## The Libyan Desert

The Libyan Desert (which is called the Western Desert in Egypt) forms part of the eastern Sahara and is the

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largest expanse of profound aridity on the face of the Earth. It has been used as an analogue for Mars. For the most part it is rather flat and only limited areas reach altitudes more than a few hundred meters above sea-level. Much of it is underlain by relatively gently-dipping limestones, shales and sandstones that create low escarpments and gently sloping plateaus. Higher land only tends to occur in the south west of the region, where the Gilf Kebir forms a flat plateau of sandstone attaining heights of more than 100 m above sea-level, and where the granitic Gebel Uweinat rises to over 1900 m. The erodible sedimentary rocks that characterise most of the region, however, have been excavated to produce some great closed depressions – Fayum, Qattara, Farafra, Bahariya, Dakhla (Fig. 2.2), Kurkur, Kharga and Siwa – places where the underground aquifers approach to or attain the surface, so producing oases. The Qattara has been excavated to −133 m below sea-level. There has been considerable debate about the origin of these depressions, and they may owe some of their form to excavation by Eocene karstic processes or to incision by now defunct river systems, but wind action has certainly played a highly significant role, aided and abetted by salt attack (Aref et al., 2002). Indeed, because large areas only have a few mm of precipitation per year, and because they are subjected to the persistent northerly trade winds, aeolian processes are evident in the form of dune fields (Fig. 2.3) and wind fluted terrain (Embabi, 2004). It has been a classic area for dune research, (Bagnold, 1941.) However, the closed depressions of the Libyan Desert have been much affected by past humid climates in the mid Holocene and portions of the Pleistocene. Large

**Fig. 2.2** The Dakhla oasis in the Libyan Desert of Egypt is formed by aeolian excavation into limestones and shales, and contains Holocene lake beds which have been excavated by late Holocene wind activity

**Fig. 2.3** The Libyan Desert is a classic area for aeolian research and contains large expanses of classic barchans and linear dunes. These barchanic forms are in the Kharga depression

freshwater lakes existed as did active rivers such as Wadi Howar (Pachur and Kröpelin, 1987) and Hoelzmann et al. (2001), have established the existence of what they term the 'West Nubian Palaeolake.' This covered as much as 7000 km$^2$ between 9500 and 4000 years BP. The moist phases are also represented by widespread spring deposits and carbonate tufas, by large landslips in shales, and by groundwater-sapped cliffs. However, some of the distinctiveness of the Libyan Desert is created by the existence of The Nile, both in terms of its present and its former courses. The Nile as we see it today is a young river in geological terms. Its course has been affected by the retreat of the Tethys Ocean and the desiccation of the Mediterranean basin around 6 million years ago, and the plate splitting that led to the uplift of the Red Sea Hills and the mountains of Ethiopia (Issawi and McCauley, 1992; Goudie, 2005). For example, at the end of the Oligocene (c 24 Ma) a river, (the Gilf system) flowed westward from the newly uplifting Red Sea Hills through Aswan and Dakhla to Siwa, whereas in the middle Miocene (c 16 Ma) drainage in the area (the Qena system) was essentially south westwards from the Red Sea Hills towards the Chad Basin. Around 6 Ma, at a time of very low sea level in the Mediterranean (the Messinian Salinity Crisis), a precursor of the present Nile (the Eonile) cut back southwards along a great canyon to capture the Qena system.

## The Namib

The Namib is a very dry desert which extends for 2000 km along the South Atlantic coastline of southern

Africa, and occupies portions of South Africa, Namibia and Angola. It is, however, narrow (only 120–200 km wide), being bounded to its east by The Great Escarpment. It is hyper-arid (rainfall at the coast is often only 10–20 mm per annum), but is characterised by frequent, wetting fogs (Olivier, 1995).

Its landscape demonstrates the importance of tectonic setting. The Great Escarpment, the sloping plains of the Namib itself, and its major inselbergs, can be explained by the opening of the South Atlantic in the Early Cretaceous, the separation of southern Africa from South America, and the development of a major hot-spot track associated offshore with the Walvis Ridge and the Tristan and Gough islands (Goudie and Eckardt, 1999). Igneous extrusive and intrusive activity occurred, leading to the formation of large spreads of lava (the Etendeka lavas) (Fig. 2.4) and the development of some large plutons and associated inselbergs (e.g. Erongo, Brandberg and Spitzkoppje) (Fig. 2.5). The Great Escarpment formed as a result of uplift and incision following the break up of Gondwanaland, and is comparable to that of other passive margin settings. Deeply incised into it is the Fish River canyon, one of the world's largest examples of this type of feature (Fig. 2.6).

The Namib is also an ancient desert and this also must have been controlled to a considerable extent by its plate tectonic history, which influenced the opening up of the seaways of the Southern Ocean, the location of Antarctica with respect to the South Pole, and the subsequent initiation of the cold, offshore Benguela Current. The date of the onset of aridity is the subject of debate, but it could date back to the early Cretaceous, for dune beds are found inter-digitated with Etendeka lavas (Jerram et al., 2000). Ward et al. (1983) believe that the Namib has not experienced climates significantly more humid than semi-arid at any time during the last 80 million years. The present Namib sand sea is underlain by a lithified erg composed of the Tsondab Sandstone, and this dates back to at least the lower Miocene (Senut et al., 1994.) By the late Miocene, offshore dust inputs were increasing and river inputs were decreasing (Kastanja et al., 2006).

The Namib today has a wide diversity of landforms that includes wind fluted terrain (*yardangs*), especially in northern Namibia (just to the south of the Cunene river) (Goudie, 2007) and in the southern Namib near Luderitz. There are also four major *ergs* or sand seas (which from north to south are the Baia dos Tigres erg

**Fig. 2.5** Spitzkoppje is a granite mass that was intruded into the Central Namib in the Early Cretaceous, and which has been exhumed by subsequent erosion

**Fig. 2.6** The uplift of the western passive margin of southern Africa produced a Great escarpment into which the Fish River has become deeply incised

**Fig. 2.4** The opening of the South Atlantic in the early Cretaceous caused the eruption of large volumes of lava (the Etendeka lavas) in the Skeleton Coast

**Fig. 2.7** The Namib Sand Sea of the Central Namib, seen here at Sossus Vlei, contains some of the world's highest linear and star dunes

in Angola, the Cunene Erg, the Skeleton Coast erg and the Namib Sand Sea) (Fig. 2.7). The wind has also created pans, wind streaks and dust storms, and these have been created particularly by high velocity winds blowing out from the interior plateau (*Berg* winds) (Eckardt et al., 2001).

The coastal portions of the Namib Desert, because of the prevalence of fog and large quantities of salts, including gypsum (Eckardt and Spiro, 1999), are sites of very rapid salt weathering. As in the Atacama, this may explain the presence of extensive, featureless plains (Goudie et al., 1997). The salts themselves are derived from wind-blown aerosols that have accumulated since the initiation of the desert and which have been redistributed by wind action and sporadic surface runoff (Eckardt et al., 2001).

## The Kalahari

In the interior of southern Africa, much of it in Botswana, lies the Kalahari (Thomas and Shaw, 1991). Most of it is not a true desert but an extensively wooded 'thirstland'. Over enormous distances the relief is highly subdued and the landscape monotonous. In the extreme south west on the borders of Botswana, Namibia and South Africa, the rainfall (<200 mm per annum) is just sufficient to allow present day dune activity (Fig. 2.8), but to the north the Kalahari is largely a relict sand desert, which extends into Angola, Zambia, Zimbabwe and the Congo (Shaw and Goudie, 2002), and has mean annual rainfall levels that exceed 800 mm.

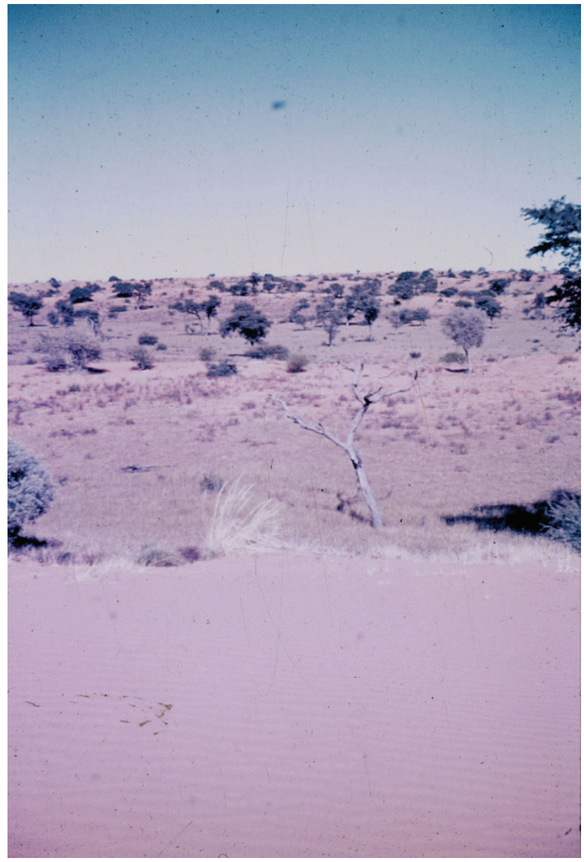

**Fig. 2.8** In the south western Kalahari, there is sufficiently low rainfall for linear dunes to be partially active, but many of the dunes of the mega-Kalahari are relicts of previously more extensive dry conditions

The Kalahari owes its gross form and subdued morphology to the fact that following the break up of Gondwanaland it became an area of down-warping that was bounded on the west by the highlands of Namibia and Angola, and on the east by mountains such as the Drakensberg and Lubombo. It became a basin of sedimentation and this largely accounts for its flatness. The Kalahari Beds that fill this basin are often over 100 m in thickness and in parts of the Etosha region of northern Namibia they are over 300 m thick. They consist of dune sands, alluvial deposits, calcretes and marls. Faulting within the basin has led to the formation of the great Okavango Delta (McCarthy et al., 1988).

Apart from its relict dunes (Thomas, 1984), the Kalahari contains large numbers of pans and associated lunettes (Goudie and Thomas, 1985), together with two large closed depressions – Etosha Pan and the Mkgadikgadi Depression. Today these are major

**Fig. 2.9** The Molopo River, on the border between Botswana and South Africa is probably a testament to former wetter conditions. It is incised into the thick calcretes that are a feature of the Kalahari basin

**Fig. 2.10** In the north of Pakistan is the Hunza Valley. At Pasu there are the huge peaks of the Karakoram Mountains

sources of dust plumes (Washington et al., 2003). During pluvials, and perhaps because of tectonically controlled water inputs form the Zambezi, the latter was occupied by a huge lake (Grove, 1968), which covered over 120,000 $km^2$. Waters may also have been contributed in the past by a series of fossil valleys – *mekgacha* (Shaw et al., 1992).

Another characteristic of the Kalahari is the excellent development that has occurred of calcrete, silcrete and combinations of the two (Watts, 1980; Nash et al., 1994). The reason why calcretes in particular are so well developed probably relates to the Kalahari's long history of gentle sedimentation, though the carbonates making up the calcretes are largely derived from the expanses of limestones and dolomites that occur on its margins. Ancient river systems, such as the Molopo, are incised into the calcrete (Fig. 2.9).

The Kalahari then provides a fine contrast to the Namib, because of its relatively high rainfall and because of its basinal form.

## The Thar

The Thar desert of India (Allchin et al., 1977), like the Kalahari, is not an area of profound aridity and very little of the area has less than 100 mm of mean annual rainfall. The Indian arid zone, however, shows greater diversity than the Kalahari, for there is a striking contrast in relief between the arid foothills and valleys of the Karakorams (Fig. 2.10) and Ladakh in the north, the enormous alluvial plain and delta of the Indus River, the salty sabkha of the Rann of Kutch in the south, and the ancient mountain stumps of the Aravallis in the east.

The Indus, which derives its waters from the high mountains of Asia (Shroder, 1993), is a dominant influence on the desert, but the mountains also provided in the past the discharge of a whole series of 'lost rivers' (Wilhelmy, 1969) that are a feature of the Punjab. Other rivers, such as the Luni, flow from the Aravallis, which are notable because they are one of the oldest mountains systems, still maintaining some relief, in the world (Spate, 1957). Indeed, four orogenic events have been identified, ranging in age from 3000 Ma to 750 Ma ago (Mishra et al., 2000).

The Thar is a relatively moist and low velocity wind environment, but it has large expanses of dunes, the sand for which comes from a wide range of sources: the coastline of the Arabian Sea, the large alluvial plains and the weathering of extensive areas of sandstones and granites. Uniquely in the world, many of the dunes are rake-like parabolics (Kar, 1993), which have formed transverse to the dominant early summer south-westerly monsoon winds. Dunes were, however, much more extensive under past more arid conditions (Goudie et al., 1973: Allchin et al., 1977), and this includes the highly lithified aeolianites (*miliolites*) of Saurashtra (Fig. 2.11) (Sperling and Goudie, 1975: Goudie and Sperling, 1977). The Thar contains some lake basins, created in part by aeolian disruption of drainage lines, and these provide evidence for former wetter conditions (Wasson et al., 1984: Singh et al., 1990), not least in early to mid-Holocene times (Fig. 2.12). Likewise there have been alternations of fluvial and aeolian accumulation in the southern Thar

**Fig. 2.11** On the coast of Saurashtra (Kathiawar) in northwest India, as at Junagadh Hill, there are lithified ancient dunes, called *aeolianite* (miliolite). The cross bedding structures are well displayed

**Fig. 2.12** At Pushkar, in Rajasthan, northwest India, there is a small lake basin, surrounded by dunes. Such basins were occupied by larger freshwater lakes in the early Holocene

during the late Pleistocene (Juyal et al., 2006). These reflect fluctuations in the nature of the south west monsoon.

## Atacama and Altiplano

To the west of the Andean cordillera between latitudes 5 and 30° S lies the largest west coast desert in the world (Bowman, 1926). It is also the world's driest desert and Quillagua (mean average rainfall 0.05 mm) can lay claim to the driest place on Earth (Middleton, 2001). There are fogs (the *garuá* of Peru and the *camanchaca* of Chile), and there are occasional high rainfall years associated with El Niño conditions that cause great floods (Magilligan and Goldstein, 2001), but aridity is intense. It has also persisted for a long time, and like the Namib, the Atacama has a very extended history that goes back to at least the late Eocene and possibly to the Triassic (Alpers and Brimhall, 1988; Clarke, 2006). One consequence of long continued intense aridity, is that the Atacama contains the most famous and important *caliche* (sodium nitrate) deposits in the world. Nitrate is highly soluble and can only accumulate under very dry conditions (Fig. 2.13). The nitrates mantle the landscape, break up the underlying bedrock and are largely derived from atmospheric sources that have provided material to old, desert surfaces (Ericksen, 1981; Searl and Rankin, 1993; Bohlke et al., 1997). Precipitation seems to have plummeted between 19 and 13 Ma (from >200 mm per annum, to <20 mm) as the uplift of the Andes blocked the ingress of the South American summer monsoon into the Atacama. Nitrate accumulation may have begun at that time (i.e. in the middle Miocene) (Rech et al., 2006). The combination of fogs and salt at altitudes below c 1100 m create an aggressive environment for salt weathering (Goudie et al., 2002).

Indeed, a major influence on the geomorphology of the Atacama has been the growth and presence of the Andes (Fig. 2.14). Tectonic uplift and eastward migration of the Andes volcanic arc associated with the subduction of the Nazca oceanic plate beneath the South American continental plate have created some of the greatest altitudinal contrasts to be found on Earth. Over a horizontal distance of no more than 300 km one moves from the Peru-Chile French (at some 7600 m below sea-level) to Andean peaks that rise up to over 6000 m above sea level. Thus, whereas the Namib is on a passive margin, the Atacama is on an active margin. It has much evidence of volcanic activity, folding and faulting, high mountain development and, in

**Fig. 2.13** In the Atacama of Chile, inland from Iquique, there are large expanses of salt deposits, which include the famous nitrate accumulations called *caliche*

**Fig. 2.14** Near Putre in the Atacama Desert of northern Chile, the snow capped Andes form an impressive backdrop to the world's driest desert

the Altiplano, basin and range topography containing large depressions (Lamb et al., 1997). The grain of the land runs approximately north to south with a very narrow or non-existent coastal plain, a coastal range (Cordillera de la Costa), a longitudinal Central Valley and then, to the east, the higher level Andes and Altiplano. The Altiplano is a high plateau composed of the sedimentary infill of a series of intermontane tectonic trenches. It is characterised by some large basins (*salars*) which have in the past contained large bodies of water (Rauchy et al., 1996; Placzek et al., 2001). One of these the Salar de Uyuni in Bolivia, is now the major source of dust in South America (Washington et al., 2003).

## Taklamakan and Tarim

The deserts of China and its neighbours cover a wide range of geomorphological and tectonic settings from the Turfan (Turpan) Depression (−150 m) to the high mountains of the Kunlun and Karakorams, where altitudes exceed 5000 m over extensive tracts. The Taklamakan, 'the place from which there is no return', is the largest desert in China and is very dry, with mean annual precipitation dropping to as low as 10 mm in its driest parts. It occurs within the Tarim Basin, which, with an area of 530,000 $km^2$ is one of the largest closed basins on Earth. The subsidence that produced it was initiated in the Oligocene, and there are huge thicknesses (up to 3300 m) of Pliocene and Pleistocene sediments underlying it. The largest part in the basin is 'the wandering lake of Lop Nor', at only 780 m above sea level (Zhao and Xia, 1984).

The Tarim Basin is bounded on the south by the Kunlun Mountains and on the north by the Tian Shan. Both ranges produce alluvial fans and gravel aprons and generally feed the basin with sediment. It is for this reason the Taklamakan can lay claim to have the most positive budget of any sand sea in the world (Mainguet and Chemin, 1986). At 337,600 $km^2$ it is indeed a huge sand sea with a diverse range of dune types, many of which are 80–200 m in height (Zhu, 1984).

It is likely that the winnowing of fine sediment from the Tarim Basin has been a major source of material for dust storms and for the great areas of aeolian silt (loess) that reach their ultimate development in the Loess Plateau downwind to the east. Indeed, the Taklamakan is one of the dustiest places on earth (Zhang et al., 1998; Kes and Fedorovich, 1976), because of its aridity, its plentiful supply of mountain-derived sediment, and it topographically funnelled winds (Washington et al., 2003). Dust from it is not only transported to other parts of China, but also to Korea, Japan and even North America. In addition, the area is the classic location for yardang formation and this attests to the importance of wind action (Hedin, 1903; Halimov and Fezer, 1989).

Aridity in the area may be of some antiquity. The uplift of Tibet took place in the Miocene, with a rapid rise at about 8 m.y. ago (Molnar et al., 1993). This caused a major shift in climate and a transformation in the nature of the monsoonal system at that time (Fluteau et al., 1999). Wang et al. (1999), on the basis of the study of sediments in the Qaidam Basin, argue that the Tibetan Plateau must have reached a threshold elevation in the latest Miocene that caused a drying in central Asia and the intensification of the East Asian monsoon. The Pliocene Red Clay Formation (PRCF) of China, which is in part a product of aeolian dust accumulation and has loessic characteristics, has been dated to around 7.2–8.35 million years ago (Qiang et al., 2001; Ding and Yang, 2000), though dust derived from the Tibetan Plateau and the Gobi is evident in ocean core deposits going back to at least 11 million years (Pettke et al., 2000).

## Australia

Australia is the world's second driest continent, but aridity is not especially intense and nowhere does mean annual rainfall drop below 100–125 mm. This reflects the inland setting of the arid zone, the absence of very high relief barriers against the inland penetration of moist air (particularly of tropical air from the north) and the lack of a definite cold inshore oceanic current along the west coast (contrast this with the hyperarid west coast deserts of the Namib and Atacama.) Australia is also for the most part at low altitude, with about 40% of its area standing less than about 200 m above sea-level. It is also dominated by large plainlands, associated with such typically Australian phenomena as stone mantles (*gibbers*) and duricrusts. Australia is also an ancient continent with extensive venerable shield areas and land surfaces that have been exposed to sub-aerial processes for hundreds of millions for years (Twidale, 2000). As Oberlander (1994, p. 26) observed, 'The erosional flattening of Australia is so thorough that any sharp protruberance constitutes a major landmark'. It is geomorphologically comatose and a museum of relict features, with some of the lowest denudation rates of any land surface in the world (Gale, 1992).

Australia is a fragment of Gondwanaland and its landscapes and its climates have been affected by continental drift that has been ongoing since the Middle Jurassic. Over that time it has moved northwards, and continues to do so. In the process it has moved through different climate belts. During the Tertiary it moved from being in a high-latitude near-polar climatic zone, through a mid-latitude humid zone, into a zone of tropical and sub-tropical climates (including desert). Ancient, broad, infilled valley systems, now dismembered and containing strings of salt lakes (Fig. 2.15), especially in Western Australia, may have been beheaded about 75 Ma by the rifting that initiated separation of Australia from Antarctica. Deep weathering profiles and etchplains, often associated with a range of duricrust types (particularly ferricretes and silcretes), are among the geomorphological phenomena that date back to the early Tertiary and before.

That said, other phenomena near witness to more recent climate changes, including a massive anticlockwise whirl of sand deserts (Wasson et al., 1988), composed very largely of linear dunes; great networks of anastomosing and anabranching rivers created by intense tropical storms (Tooth and Nanson, 1999; Bourke and Pickup, 1999); large numbers of salt lakes that were filled by large water bodies (Harrison and Dodson, 1993) at various times in the Pleistocene; and clay and sandy lunettes developed on the lee sides of many ephemeral basins.

**Fig. 2.15** In Western Australia, there are large, ancient valley systems that now contain strings of salt lakes which have been moulded by Aeolian activity

## North American Deserts

Two main physiographical provinces – The Basin and Range and The Colorado Plateau – contain the most important of the North American deserts, but there are marked differences between them. Within the former lies the Sonoran, Chihuahuan, Mojave and Great Basin deserts (Tchakerian, 1997). These are characterised by block-faulted, more or less north to sound trending mountain ranges and basins (Morrison 1991; Peterson, 1981), which started to develop in the late Oligocene as a response to crustal extension. The juxtaposition of topographic highs and

**Fig. 2.16** During the Pleistocene the Basin and Range province of America was occupied by many large lakes. This figure shows the shorelines of Lake Bonneville in Utah

lows provides a situation where there are many alluvial fans, extensive pediments, active runoff, and the formation of large numbers of closed basins, which in pluvial times contained large lake basins (Tchakerian and Lancaster, 2002). Notable among these were lakes Bonneville (Fig. 2.16) and Lahontan.

The Colorado Plateau is very different. It exhibits sedimentary strata, which on account of their very limited dips give rise to extensive mesa and scarp landscapes, sandstone canyons, and intricately dissected fluvial landscapes. Indeed, in the nineteenth century it became the epicentre for innovative fluvial geomorphology. The Colorado Canyon's initiation is relatively recent, having started around 5.5 million years ago. Incision has taken place at 470–800 m per million years (Patton et al., 1991). Rapid denudation has also created the great cliffs of the Plateau, with their magnificent escarpments, mesas, natural arches, box canyons and ground water-sapped alcoves (Laity and Malin, 1985.)

In the early Tertiary, the Colorado Plateau, made famous by the pioneer researches of John Wesley Powell and Clarence Dutton, was a low-lying basin. Uplift started in the Mid-Eocene, and lasted into the late Miocene, causing the plateau to become a high region into which drainage became incised. Tectonic activity also created some major igneous landforms, including the classic intrusions of the Henry Mountains and elsewhere (Gilbert, 1877).

Although these two provinces contain some dune fields (Algodones, White Sands etc.) and generate some dust from desiccated lakes, they are not areas where aeolian processes and phenomena are generally dominant. Fluvial and slope processes, driven by water and gravity, give the North American deserts their distinctiveness.

## Conclusions

There is a great diversity of landscapes both between and within deserts. One can, for example, distinguish at a gross scale between shield deserts and mountain-and-basin deserts, or, between deserts on active plate margins (e.g. the Atacama) and those on passive plate margins (e.g. The Namib), but within such deserts it is possible to subdivide landscapes into sand deserts, stony deserts, clay plains, riverine deserts etc. Equally there is a great diversity of climatic conditions in different desert areas and this serves to control the relative importance of different geomorphological processes. The range of desert landscape types is also diversified because of the near ubiquitous occurrence of relict landforms produced under a range of former climatic conditions. Each of the eight deserts discussed in this chapter has particular features that render it distinctive.

Plainly plate tectonic history has been crucial in many of them. In South America, orogeny and the eastward migration of the Andean volcanic arc, associated with the subduction of the oceanic Nazca plate beneath the South American continental plate, have created great contrasts in altitude, abundant volcanism and the many closed depressions of the Altiplano. In North America the Basin and Range Province is a classic area of crustal extension, volcanism and faulting. In northern Africa, the Atlas Mountains, the highlands of the central Sahara (e.g. Tibesti and Hoggar), the uplift of the Red Sea Hills and the evolution of the Nile have all been affected by plate tectonic processes and are major controls and features of the area's topography. In southern Africa the geomorphology of the Namib owes much to the opening of the South Atlantic by sea-floor spreading in the late Jurassic and early Cretaceous and the presence of the great hot-spot associated with the Walvis Ridge. In addition, uplift of the Great Escarpment and the basinal form of the Kalahari are associated with passive-margin evolution. In the Middle East, features such as the Red Sea rift, the Dead Sea fault, the Zagros Mountains 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 Asia the uplift of the Himalayas and the Tibetan Plateau radically modified climatic conditions and accounts for the development of major mountain ranges in close proximity to enormous closed basins (such as Tarim). By contrast, Australia is a low, dry, ancient continent with a long history of comparative orogenic stability over large areas, so that many of the present landscape features are inherited from a great variety of climates that may go back to the Jurassic or earlier.

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