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Introduction

The world's arid lands are some of the most beautiful landscapes on Earth, and their paucity of vegetation often makes it possible to see landforms and structures with great clarity (Figure 1.1). In addition, they have many characteristics both in terms of landforms and geomorphological processes that render them different from other major environments (see, for example, Laity, 2008; Parsons and Abrahams, 2009; Thomas, 2011a). In this section we first consider how ideas about dryland geomorphology have evolved, before moving on to a consideration of what desert environments are like now and how they have varied over time.

1.1 The History of Ideas

The study of the geomorphology of arid lands has a long history and has been truly international in scope. Its history has been characterised by rapid shifts in the importance attributed to such processes as wind erosion and physical weathering. It has also been characterised by differences in approaches adopted by different national groups, by a tendency to concentrate on the bizarre and by a propensity to develop a complex multinational terminology (Cooke et al., 1993). It also needs to be appreciated that drylands cover around one-third of the Earth's land surface and have varied settings and environmental histories (Goudie, 2002), so different approaches and emphases have developed in different countries. Some classic papers that reflect this have been collected together in Goudie (2004).

In many desert regions, the landforms and processes are not necessarily so diagnostic of aridity or so different from landforms and processes encountered in more 'normal' humid environments. Most arid areas have experienced a great range of climatic changes that have caused them to both expand and shrink. Nonetheless, the roles of wind and salt are plainly very significant in certain drylands, and the limited vegetation cover is a critical control of the operation of fluvial and slope processes.

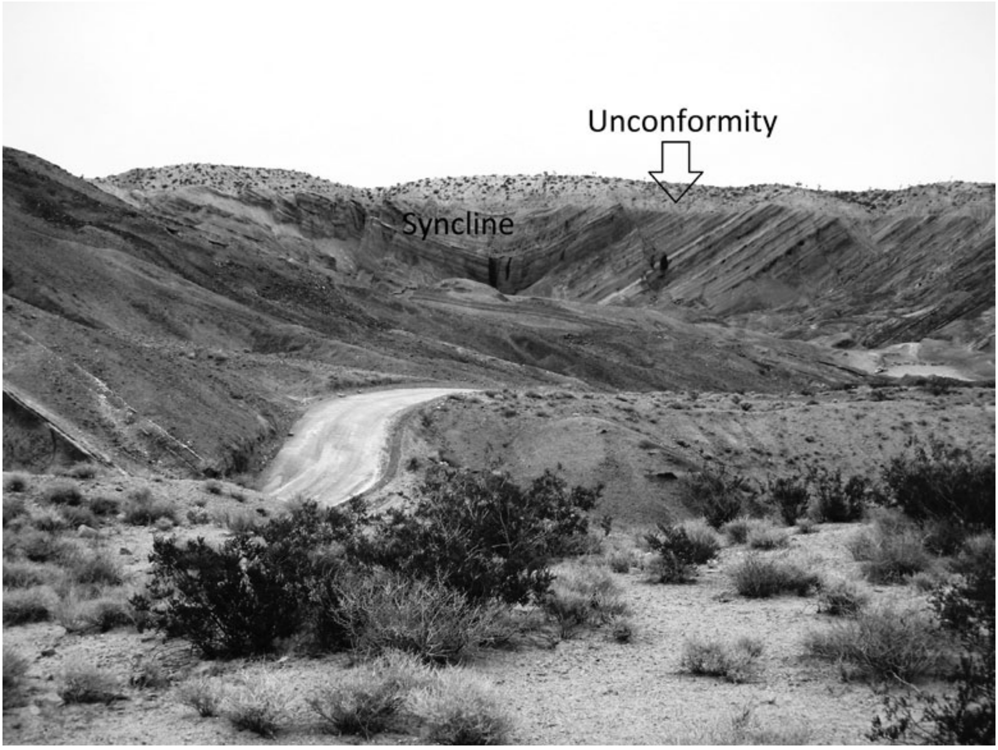

Figure 1.1 The Barstow Syncline in the Mojave Desert of California and an erosional unconformity in the upper part of the section are revealed with great clarity as a result of the limited vegetation cover. (ASG)

The impact of these changes on their landscapes and those of their neighbours has often been profound.

Detailed studies of desert geomorphology began with exploration and colonial expansion in the second half of the nineteenth century. John Strong Newberry, one of the greatest explorers of the Colorado Plateau in the 1850s, recognized these classic desert landscapes as having been ‘formerly much better watered than they are today’ (1861, p. 47). Such work reached a climax when Gilbert and Russell examined the desiccated lake basins that were such a feature of the western United States (see Orme, 2008, for a full discussion). Geologists of the U.S. Geological Survey made other highly important investigations in the American Southwest. Especially influential was the work of John Wesley Powell and Clarence Dutton on the landforms of the Colorado Plateau. American scientists also contributed greatly to the development of knowledge on desert aeolian processes (Udden, 1894; Free, 1911). Also remarkable was the work of W.P. Blake on stone pavements, desert varnish, old lake basins, calcretes (caliche) and wind grooving of rock surfaces (e.g. Blake 1855, 1904). Moreover, it was in the American West that W.J. McGee (1897) drew attention to the role of sheetfloods on

Figure 1.2 Johannes Walther was a German pioneer of desert geomorphology in the early years of the twentieth century. (Source: http://www.geolsoc.org.uk/gsl/info/collections/archives/page5150.html) (accessed March 11, 2011).

pediment surfaces. Also notable were Gilbert's studies in the Colorado Plateau on rates of denudation in arid regions (Gilbert, 1876) (see Section 5.4).

The French acquisition of its North African territories – Algeria, Tunisia and Morocco – led to some major expeditions into the great sand seas of the Sahara and some fundamental studies of dune forms (Goudie, 1999c). As early as 1864, Henri Duveyrier classified the main types of dune, related their orientation to that of the winds, estimated their area and argued that much of the sand was the result of intense rock disintegration (Duveyrier, 1864). French scientists were very active in the western Sahara and accumulated a great deal of vital information on the full range of desert landforms (see Gautier 1908 and Chudeau, 1909).

The Germans for their part took over South West Africa (now Namibia), and individual German geomorphologists worked in the Middle East (e.g. J. Walther) and in the Kalahari (e.g. Passarge, 1904). They made major studies of weathering phenomena, wind erosion and the development of inselberg landscapes. Walther (Figure 1.2) studied the deserts of North Africa, Sinai, the United States and Australia. His *Das Gesetz der Wüstenbildung in Gegenwart und Vorzeit* (1900) was the first full-scale book devoted to desert geomorphological processes, and he championed the role of such mechanisms as thermal fatigue weathering, salt weathering and deflation.

In central Asia, the Swedish explorer Sven Hedin (1903) discovered wind erosional landforms – yardangs – and the American geographer E. Huntington found dramatic evidence for changes of climate in historical times (Huntington, 1907). Other influential work included that of Sir Aurel Stein on wind erosion (Stein, 1912) and Berkey and Morris (1927) on pans and weathering in Mongolia.

With respect to the British, the most sustained work on desert geomorphology in this pioneer era was undertaken by surveyors and geologists in the Western (Libyan) Desert of Egypt, of whom Ball, Beadnell, Hume and King were the leading figures, particularly in the study of dunes and weathering (Goudie, 2008b).

In Australia, Jutson was initially a major exponent of the role of wind in moulding desert surfaces (see, for example, Jutson, 1917), contributing to the development of salt lakes and leading to the wearing back of scarps. He recognized that wind operated in tandem with salt weathering. Later, however, Jutson (1934) recognized the role of fluvial processes in moulding the planation surfaces of the arid landscapes of Western Australia (Brock and Twidale, 2011).

In the first six decades of the twentieth century, geomorphology as a whole was often dominated by either those with an interest in long-term landscape evolution or those who were concerned with the development of ideas of climatic geomorphology. Towering figures such as W.M. Davis (1905, 1938) and W. Penck (1953) developed models of landscape development that were relevant to arid regions, and debates raged about the relative importance of wind and water erosion in creating desert plains (see, for example, Bryan, 1923). The maverick American C. Keyes (1912) was an especially vigorous and repetitive exponent of the power of wind erosion (Goudie, 2012).

In continental Europe, the French and German schools of climatic geomorphology sought to establish the broad links between climate and morphogenetic regions, and notable figures included Birot, Dresch, Tricart, Cailleux and de Martonne in France, and Passarge, Mortensen and Büdel in Germany. A body of important French work is reviewed by Tricart and Cailleux (1969).

W.M. Davis is perhaps best known for his evolutionary model of landform development – the cycle of erosion. This was originally developed in an essentially humid temperate environment, but Davis recognized that it needed to be modified in other types of environment where processes were different. Building on the work of Passarge, a German geomorphologist who had worked in the Kalahari (Passarge, 1904), Davis saw wind action as a factor in the cycle's operation under arid conditions, especially in its later stages. He also, however, recognized the role of water, especially in the earlier stages of the arid cycle. Thus he did not adopt the extreme views of Keyes, but neither did he reject the role of aeolian denudation as Penck was to do (1953 translation, p. 327). The views of Davis (1905) can be appreciated by considering these statements which relate to the progressive evolution of an arid area:

> In the early stage of the arid cycle the relief is slowly diminished by the removal of waste from the highlands, and its deposition on the lower gentler slopes and on the basin beds of all the separate centripetal drainage systems. . . . Streams, floods, and lakes are the chief agencies in giving form to the aggraded basin floors, as well as to the dissected basin margins in the early stages of the cycle; but the winds are also of importance. (pp. 383–84)

He then goes on to describe the mature stage:

> The obliteration of the uplands, the development of graded piedmont slopes, and the aggradation of the chief basins will be more and more extensive. (p. 387)

> As the processes thus far described continue . . . the initial relief will be extinguished . . . the plains will be interrupted only where parts of the initial highlands and masses of unusually resistant rocks here and there survive as isolated residual mountains. (p. 388)

Finally, in old age:

> During the advance of drainage integration the exportation of wind-borne waste is continued. . . . The tendency of wind-action to form hollows wherever the rocks weather to a dusty texture would be favoured by the general decrease of the surface slopes, and by the decrease of rainfall and of stream-action resulting from the general wearing down of the highlands. . . . [R]ock masses that most effectively resist dry weathering will remain as monadnocks – Inselberge, as Bornhardt and Passarge call them in South Africa. (pp. 390 and 392)

By the 1940s, however, the role of wind erosion in moulding desert landscapes was becoming the subject of doubt, and Cotton (1942, p. 3), for example, remarked that ‘few if any major relief forms owe their origin or shape to wind scour and that the sculpture by wind of features even of minor detail in the landscape is rare and exceptional’.

In the 1930s, the High Plains of America, stretching up from Texas to the Dakotas, had a run of years that were torridly dry and hot. They coincided with a phase of agricultural intensification and extension that was facilitated by the widespread introduction of the tractor, the combine and the truck after the First World War. This created conditions for the Dust Bowl, which saw ‘black blizzards’ of topsoil being stripped off agricultural lands recently subjected to ‘the busting of the sod’. This disastrous decade led to the establishment of the Soil Conservation Service under the directorship of H.H. ‘Big Hugh’ Bennett. In 1935, he addressed a Senate committee in Washington, D.C., about the need for a soil conservation act. As he was speaking, the sky darkened with the passage of a dust storm originating from the Great Plains to the west, and so the act was recommended (Brink, 1951). This marked the start of intensive work on the nature and dynamics of wind erosion of soil.

Of particular note in this respect was the work conducted by W.S. Chepil and his collaborators at the U.S. Department of Agriculture's Wind Erosion Research Center at Kansas State University, established in 1947. They were concerned with establishing the fundamentals of soil movement by wind, the properties of soils which influenced their susceptibility to wind erosion, the sedimentary characteristics of dust storms and the effects of various land-cover treatments (mulches, field size, maintenance of crop residues, type of ploughing, etc.). They also developed technology for advancing aeolian research, including dust samplers and portable wind tunnels. This type of work was further developed by Dale Gillette and colleagues (Marticorena, 2008).

In addition, after the Second World War a number of countries established research stations in their own desert regions. These permitted long-term monitoring and provided bases for sustained investigations. Such stations included those at Jodphur in India, Bardai in the central Sahara, Gobabeb in the Namib, Sidi Boqer in the Negev, Fowlers Gap in New South Wales (Australia), the Jornada Experimental Range in New Mexico, the Walnut Gulch experimental watershed in Arizona, the Zzyzx station of California State University, the Desert Institute of Turkmenistan, the Taklamakan Desert Research Station in north-west China and the Lanzhou Institute of Desert Research. Indeed, a feature of the last three decades has been the impressive growth of high-quality research by Chinese colleagues.

In Australia, the Commonwealth Scientific and Research Organization (CSIRO) undertook land-resource surveys of the interior drylands, and these surveys had a major geomorphological component. In the UK, groups of geomorphologists were employed as consultants to advise on building developments in the Middle East that resulted from the oil boom of the 1960s onwards, developing studies of, for example, flood hazards, slope instability and salt weathering of foundations (Cooke et al., 1982).

One of the most striking developments in recent decades, however, has been the growth of process studies. In some respects this mirrors developments in geomorphology as a whole, but in other respects desert geomorphology was ahead of the rest of the discipline, largely because of the fundamental studies of sediment movement by wind undertaken in the field as well as the wind tunnel initiated by R.A. Bagnold in the 1930s (Bagnold, 1935, 1936, 1937, 1941). Wind tunnel research has generated a great deal of fertile research, some of it on the scale of individual grain transport. Nickling and McKenna-Neuman (1999) provide good reviews of this type of work. Recent years have also seen many detailed studies of weathering processes, including salt weathering (see reviews in Goudie and Viles, 1997), sediment movement on slopes and in channels and dust transport and deposition (see the review by McTainsh, 1999). The data-logger revolution has facilitated process studies in the field by enabling monitoring of wind conditions, temperature and humidity cycles as well as sediment movement (Livingstone et al., 2007).

In the 1960s and 1970s, some remarkable work was done in the Negev Desert (see Section 5.15). Scientists from the Hebrew University in Jerusalem applied to arid environments the developments in quantitative process geomorphology that were being made at that time. Through intensive monitoring of conditions on slopes and in channels, they began to give a clear indication of how runoff and erosion occurred in dryland basins. A leading figure was A. Schick, who developed studies of the effects of floods and who set up experimental catchments that provided some decades of data (see, for example, Schick and Lekach, 1993). Also important was the work done by Evenari et al. (1982) on the hydrological conditions that had permitted runoff farming in arid areas by Nabatean farmers.

Yet another major influence on studies of desert geomorphology in recent years has been the development of remote sensing. Air photography was essential for providing information on large tracts of terrain that were inaccessible on the ground, and it was especially useful in ascertaining dune patterns (see Goudie, 1999c, pp. 7–8 for a review). Satellite-borne remote sensing became increasingly important in the 1970s for, inter alia, mapping dunes at a regional and subcontinental scale, for tracing dust events and for investigating fluctuations in areas inundated by lakes. Livingstone et al. (2010) provide an illustration of the wealth of databases on landform morphology that can now be assembled based on remote-sensing and digital-elevation models.

Beginning in the 1970s, geomorphologists sought analogues for Martian features on Earth, and this gave a considerable boost to studies of a range of arid zone processes and phenomena, including sapping phenomena (Laity and Malin, 1985), salt weathering (Malin, 1974) and aeolian forms (see Section 6.17). The U.S. space programme enabled the geomorphology of Mars to be investigated in detail for the first time. The images revealed volcanoes, lava plains, immense canyons, cratered areas, evidence of surface water and a whole range of wind-formed features. The aeolian phenomena of Mars were indeed both diverse and impressive (Wells and Zimbelman, 1997). Dust events range in size from dust devils to dust storms that may obscure the entire planet. Extending from many topographic highpoints, especially crater rims, are light (depositional) and dark (erosional) wind streaks. Yardangs are also plentiful, especially on the equatorial plains. The dunes on Mars, many of which occur in a large dunefield that encircles the northern polar cap, are largely barchanoid and transverse forms. Aeolian features are known from other parts of the solar system, including Titan, and have been reviewed by Greeley and Iversen (1985) and Craddock (2011).

Since the Second World War, the ability of desert geomorphologists to date phenomena has expanded markedly. Such techniques as radiocarbon and uranium series dating have been applied to desert sediments as they have been to other environments, but luminescence dating has proved to be particularly useful for dating dune sands and other aeolian materials. Optical dating (Figure 1.3) is now used routinely

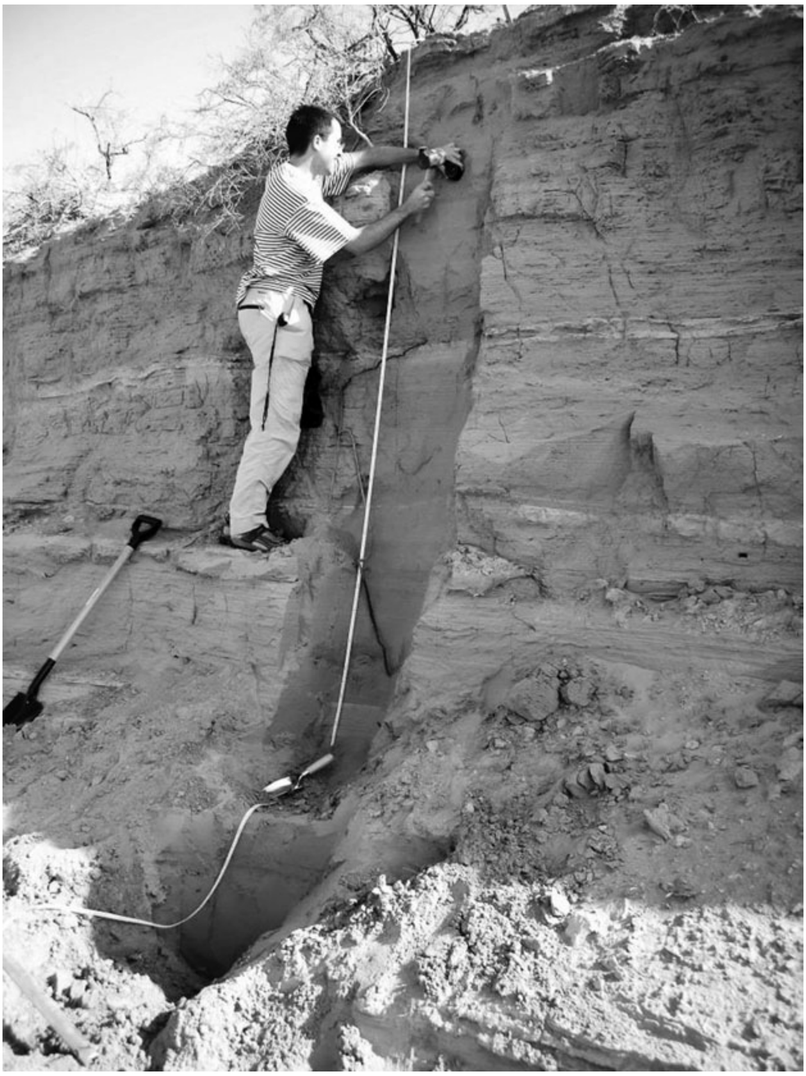

Figure 1.3 The collection of samples from aeolian deposits (such as this dune sand in the United Arab Emirates) for optical dating has revolutionized our knowledge of the timing and rates of dune deposition. (ASG)

to provide dates that enable phases of dune accumulation to be established as well as the rates at which dunes accumulate (Singhvi and Porat, 2008). On longer timescales, cosmogenic nuclides have been used extensively to date surfaces, to estimate rates of erosion, to date lake shorelines and to estimate sand residence times in dunefields (see, for example, Wells et al., 1995; Fujioka et al., 2005; Nishiizumi et al., 2005; Kober et al., 2007; Hall et al., 2008; Vermeesch et al., 2010; Kurth et al., 2011; L.A. Owen et al., 2011) (see also Section 5.21).

Finally, environmental change has become an increasingly important field of research. Geomorphologists have become very involved with the study of anthropogenic degradation of desert surfaces (desertification). They have also become increasingly interested in the evidence for and causes of natural changes in climate, a quest that has been facilitated by increasing availability of high-resolution dating techniques (e.g. optical dating) and by studies of long-term sediment sequences in ocean cores and lake basins. There is also a fascination regarding how deserts may be impacted by possible future global warming (see Section 6.13).

1.2 Climatic Conditions: Aridity

Drylands, which cover about a third of Earth's land surface, occur in every continent (Goudie, 2002). Predominantly, because precipitation is low, there is a severe shortage of moisture. In some deserts, aridity also results from high temperatures, which means that evaporation rates are great (Mainguet, 1999). Good reviews of desert meteorology and climates are provided by Warner (2004) and Nicholson (2011).

Aridity can be defined by the water balance concept. This is the relationship that exists between the inputs of water in precipitation (P), the losses arising from evaporation and transpiration (evapotranspiration) (E_t) and any changes that occur in storage (soil moisture, groundwater, etc.). In arid regions there is an overall deficit in the annual water balance, and the size of that deficit determines the degree of aridity. The actual amount of evapotranspiration (AE_t) that occurs varies according to whether there is available water to evaporate, so the concept of potential evapotranspiration (PE_t) has been devised. This is a measure of the evapotranspiration that could occur from a standardized surface never short of water. The volume of PE_t varies in response to four climatic factors: radiation, humidity, temperature and wind. Thornthwaite (1948) developed a general aridity index based on PE_t: When $P = PE_t$ throughout the year, the index is 0. When $P = 0$ throughout the year, the index is –100. When P greatly exceeds PE_t throughout the year, the index is +100. Areas with values below –40 are classified as arid, those between –20 and –40 as semi-arid and those between 0 and –20 as subhumid (Meigs, 1953). The arid category can be subdivided into arid and extreme arid, with the latter being defined as the condition in any locality where at least twelve consecutive months without any rainfall have been recorded, and in which there is not a regular seasonal rainfall rhythm. Extremely arid areas, such as the Atacama, Namib, inner Arabia, the central and eastern Sahara and the Taklamakan, cover about 4 per cent of Earth's land surface, arid about 15 per cent and semi-arid about 14.6 per cent.

In addition, deserts can be classified on the basis of their proximity to the oceans or their continentality. Coastal deserts, such as the Namib or the Atacama, have very different temperatures and humidities from those of continental interiors. They have modest daily and seasonal temperature ranges and are subject to fogs. They also have very low rainfalls. In addition to the coastal and inland deserts of middle and low latitudes, there are also the cold polar deserts. The precipitation of the Arctic regions can be as low as 100 mm per year, and at Vostok in Antarctica it can be less than 50 mm.

1.3 Causes of Aridity

Most deserts are dry because they occur where there is subsiding air, relative atmospheric stability and divergent air flows at low altitudes associated with the presence of great subtropical high-pressure cells around latitude 30° (Nicholson, 2011). Such areas are only infrequently subjected to precipitation-bearing disturbances and depressions – either from the Intertropical Convergence Zone (ITCZ) or from the belt of mid-latitude depressions associated with the circumpolar westerlies. The trade winds that blow across these zones cause evaporation, and because of the trade wind inversion they are areas of subsidence and stability.

These global tendencies are often reinforced by more local factors. Of these, continentality can be dominant and plays a part in the location and character of the deserts of areas such as central Asia. The rain shadow produced by mountains ranges can create arid areas in their lee, as in Patagonia, where the Andes have an influence. Other deserts are associated with cold currents offshore (e.g. Namib and the Atacama). Winds that blow onshore tend to do so across cold currents (e.g. the Benguela and the Peruvian) and so are stable because they are cooled from beneath; they also have a relatively low moisture-bearing capacity. They reinforce the stability produced by the dominance of subsiding air. Aridity may also be reinforced by the high reflectivity (albedo) of desert surfaces themselves. This may cause net loss of radiative heat, create a horizontal atmospheric temperature gradient along the desert margin and induce circulation systems that either induce or reinforce subsidence. Finally, atmospheric dust palls may have a positive feedback effect, being both a consequence and an accentuator of aridity (Xu et al., 2011).

1.4 Desert Rainfall

The main characteristics of deserts are caused by the very low levels of rainfall, and these are a particular feature of some coastal deserts. For example, mean annual totals at Callao in Peru are only 30 mm, at Swakopmund in Namibia only 15 mm and at Port Etienne in Mauritania only 35 mm. Years may go by in such areas of extreme aridity during which no rain falls at all. The most intense aridity occurs in northern Chile, which receives less than 10 mm of rainfall per annum. Indeed, the climate station at Quillagua (mean annual rainfall 0.05 mm) can lay claim to be the driest place on Earth (Middleton, 2001). Very low precipitation amounts are also found in the centre