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INTRODUCTION: DEFINING THE DESERT SYSTEM

1.1 Defining the desert system

Deserts and semideserts are the most extensive of the Earth's biomes, occupying more than one-third of the global land surface. Of this area, approximately 4% is classified as extremely arid (hyperarid), 15% arid, and about 14.6% semiarid (Meigs 1953, 1957). In total, about 49 million km^2 are affected by aridity. If dry-subhumid areas are included in the classification, then drylands comprise about 47% of the Earth's land surface (United Nations Environment Program 1992). "True" deserts are considered to be the warm hyperarid and arid regions, and semiarid and dry-subhumid regions the desert fringes. Collectively, the dry areas of the world occupy more land than any other major climatic type.

1.1.1 Physical, biological, and temporal components

Deserts are characterized by their great aridity and may share in common features of climate, weather, geomorphology, hydrology, soils, and plant and animal life. However, defining a desert is not a simple matter, as witnessed by the many attempts at a systematic characterization based on aspects of climate (precipitation, evaporation, and temperature), geomorphic features, and flora and fauna. Although high temperatures, winds, and shifting sands may be present in some deserts, they are not components of all arid environments. In an attempt to define a desert, Shreve (1951) describes regions of "low and untimely distributed rainfall, low humidity, high air temperatures, strong wind, soil with low organic content and high content of mineral salts, violent erosional work by water and wind, sporadic flow of streams and poor development of nominal dendritic drainage." Although this definition is a good fit for many North American deserts, it poorly constrains others. For example, the Atacama and Namib Deserts, with their low average temperatures and high coastal humidities, do not conform to Shreve's description. However, it has proven difficult to arrive at a universally accepted definition, perhaps because deserts themselves show considerable individuality, and because of the existence of continuous transitions between the different types of deserts.

Considered from a biological standpoint, deserts may be considered to be areas where the availability of water is low. "True" deserts result from a deficiency in the amount of precipitation received relative to water loss by evaporation. For organisms, aridity may be a relative condition, as the amount of water available may be a function of several interacting variables, including precipitation, temperature, soil texture, groundwater seepage, and slope and aspect. Furthermore, some organisms obtain their moisture from fog or dew, a source of water that is not regularly measured.

Climate, vegetation, and fauna have all been used to delimit desert boundaries. Deserts may be divided into categories based on their temperature (hot; temperate; coastal) or moisture (hyperarid; arid; semiarid) characteristics. In many instances, the drier areas of the Earth are simply divided into two groups: arid and semiarid (or, synonymously, desert and semidesert; or desert and steppe). Plant and animal components are commonly incorporated in desert classification systems. Vegetative criteria of Shreve (1942) include floristic content, physiognomy and life forms, and structure and social organization. Herpetofauna and climate were used to set boundaries for the Chihuahuan Desert (Morafka 1977); and herpetofauna and plants for the eastern Sonoran Desert boundary (Lowe 1955).

The delimitation of desert areas is difficult, particularly the location of the outer boundaries. This is the case even for relatively well-studied deserts in populated areas. For example, the boundaries assigned to the Sonoran Desert vary widely according to the criteria used by individual researchers (MacMahon & Wagner 1985). Additionally, desert boundaries are often considered as shifting zones of

transition rather than lines clearly demarcated by climate or by abrupt changes in species or associations. Transitional boundaries may result from human impact or from decadal climatic fluctuations. Satellite imagery has allowed an annual examination of fluctuating boundaries, most notably the southern boundary of the Sahara (Tucker et al. 1991; Nicholson et al. 1998).

Understanding desert climates is essential because of strong linkages between climate, biological processes, and geomorphology. Indeed, studies of desertification suggest that human-induced ecological and geomorphic changes may induce climate change, or at least prolong natural drought episodes. These themes are explored more fully in Sections 3.4.2, 3.4.3, and 13.2.

Although all deserts are characterized by aridity, other climatic factors, such as temperature and humidity or season of precipitation, show considerable variation. The following climatic characteristics are common to many interior tropical and subtropical deserts: (1) high summertime temperatures, (2) an excess of potential evaporation over precipitation as a result of high temperatures, wind, and clear skies, (3) high variability of precipitation totals, distribution, and intensity, (4) a more prominent role for wind than in other zones, (5) clear skies prevailing over 70% of the time, and (6) low humidity (commonly 15–30% for inland deserts and as low as 5% in the Saharan Desert). Winter temperatures show large variations from place to place, largely a reflection of continentality and latitude. For coastal deserts, conditions are considerably different than for interior deserts, as proximity to cool ocean currents and the occurrence of frequent fogs give rise to cooler maximum and average temperatures and very high relative humidities for areas immediately adjacent to the sea.

As may be inferred from the difficulties in defining and delimiting deserts, they do not present a homogeneous landscape. Long-term differences in climatic, tectonic, biological, and geologic history cause deserts to be individually distinct. Each tends to have a unique assemblage of landscape elements and processes. Geomorphologically, the North American deserts are dominated by the erosional and depositional effects of surface water; the eastern Sahara by aeolian processes; and the Atacama by extreme aridity, barren landscapes, saline deposits, and mass wasting that is enhanced by earthquake activity (Oberlander 1994). Deserts also vary tremendously in their tectonic settings. The stability and age of Australian deserts contrasts sharply with the youth and tectonic instability of arid North America. Furthermore, unique landscape assemblages bear the imprint of climatic change over long time periods.

The Earth's climate has changed profoundly during the Quaternary and Tertiary, so many desert landscapes are palimpsests; that is, composed of relict elements produced under the influence of past climates and modern elements formed in the present climatic regime. Thus, it is impossible to understand modern desert environments without a consideration of earlier climatic, hydrologic, tectonic, geomorphic, and biological conditions. Deserts are superb repositories of these past legacies, as aridity and, in some cases, relative inactivity of the surface, act to preserve landscape assemblages. As noted by Williams (1994, p. 644), "one intriguing outcome of the polygenetic nature of desert landscapes is...the frequent juxtaposition of very old elements of the landscape with others that are very new." This book aims to examine the many forces that have shaped and continue to influence desert landscapes, and to provide a broad appreciation of how the legacy of the past informs the processes of the present.

1.2 Evolution of deserts

1.2.1 Global considerations

The arid regions of the world, other than those in the high Arctic, owe their origin to climatic, topographic, and oceanographic factors that prevent the incursion of moisture-bearing weather systems. Although the causes of aridity are discussed separately below, it should be noted that most deserts are arid because of a combination of factors. For example, west of the Andes in the Peru–Chile desert, aridity is a result of subtropical atmospheric subsidence, reinforced by upwelling of the cold Humboldt Current, and by the Andean rainshadow.

1.2.1.1 Subtropical high-pressure belts

The world's arid and semiarid regions are mainly subtropical in distribution, covering about 20% of the Earth's land surface (Glennie 1987) (Fig. 1.1). As shown in Fig. 1.1, the Equator is flanked to the north and south by Hadley cells, each composed of a rising branch in the rainy equatorial zone, and a descending branch near 30° North and South in the arid subtropical zones. In the equatorial zone, opposing

FIG. 1.1 Map of the global deserts. The world's deserts are largely subtropical in distribution. Cold currents are labeled and shown with arrows.

winds converge in the *intertropical convergence zone* or ITCZ, and feed air into the rising branches, favoring convective rainfall. The descending branch forms zones of elevated sea-level pressure, referred to as the *subtropical high-pressure belt* (McIlveen 1992). Although localized vertical motions of the atmosphere occur in this zone of subsidence, larger-scale vertical motion is suppressed by persistent thermodynamic stability, leading to a general lack of rainfall. Relative humidities throughout the troposphere are very low in the zone of subsidence, and only rarely do active disturbances penetrate to break the normal aridity.

The subtropical high-pressure belt is broken up into anticyclonic cells, so that the associated subsidence is discontinuous and aridity is not present in all longitudes. In the Northern Hemisphere, air moving clockwise around the equatorial sides of cells brings moist air to the eastern continental margins including the Caribbean, East Africa, and south and central China. Although subsidence dominates North India and Pakistan for much of the year, the summer monsoon brings 3 months of abundant rainfall except in the far northwest.

1.2.1.2 Continental interiors

Continental interiors are arid owing to the distance from the sea and sources of moisture. In central Asia, for example, a great mountain arc prevents the deep incursion of moisture-laden air of the summer monsoon. In winter, a vast high-pressure cell develops, with very dry subsiding air.

Interior deserts have a much greater range in annual temperature than those closer to a coast. Despite the high latitudes of Asian deserts, the summers are extremely hot, with maximum temperatures in excess of 38°C at all lowland stations. Winters are very cold, with minima ranging from −30 to −50°C (Fig. 1.2). The Great Basin Desert of North America also experiences great annual ranges of temperature and freezing conditions and snow in winter. The average temperature in January is −2°C. Nonetheless, summer temperatures in the southern Great Basin can be very hot (Laity 2002). The highest temperature ever recorded in the USA (57°C) was in Death Valley.

1.2.1.3 Polar deserts

Low levels of solar radiation at the poles result in very cold temperatures. Because of this, the atmosphere contains little moisture for precipitation, and although precipitation may be frequent, it is very light, with the depth of precipitable water not exceeding 10 mm at any time (Hidore & Oliver 1993). In Antarctica, mean annual precipitation ranges from 51 mm on the plateau to as much as 510 mm at some peninsular locations. Relative humidity values may be as low as 1%, with both humidity and cloud cover decreasing inland. Winds are also a predominant factor in polar deserts, making blizzards and drifting snows a common occurrence.

For reasons of space, polar deserts and periglacial environments cannot be addressed in this book. It is interesting to note, however, that they share several geomorphic processes in common with warm deserts, particularly as the paucity of vegetation cover allows the free sweep of the wind. Thus, aeolian features such as dunes and ventifacts are shared by both desert types.

1.2.2 Regional considerations

1.2.2.1 Cold-current influences

Cool coastal deserts form adjacent to cold ocean currents on the western margin of continents. They are often long and narrow in form, and may be bounded to the east by north–south-oriented mountain ranges. The climate is greatly moderated by the proximity to cold waters and is characterized by rainlessness, fog and dew, and cold temperatures. Coastal deserts include the Atacama, along the coast of Chile and Peru and adjacent to the Humboldt Current; the Namib on the coast of southwest Africa along the Benguela Current (Fig. 1.3); and the desert along the Pacific coast of Baja California, Mexico, adjacent to the California Current. Other deserts with cold-current influences are the coastal Sahara in northwest Africa, the Arabian Peninsula and Horn of Africa, and the western coast of Australia (Warner 2004). Subsidence from the subtropical high-pressure belt reinforces the effect of the cold coastal waters. Orographic barriers, such as the Andes Mountains, may prevent the incursion of moisture bearing systems from continental interiors.

The movement of water from polar latitudes to low latitudes, with associated upwelling of deep cold waters, produces cold currents. Warm air from the high-pressure cells is cooled by contact with the water and layers of fog form. The air that crosses the land is foggy (relative humidity at or near 100%) and chilled nearly to the temperature of the water, normally from 15 to 18°C. The affected layer is thin

Fig. 1.2 The deserts of continental interiors are arid owing to their distance from the sea and sources of moisture. Such deserts have a much greater range of temperatures than those close to the coast. Winters in the Asian deserts can be very cold, with minima ranging from −30 to −50°C. In this image, the shrinking Aral Sea appears in 2002, filling with seasonal ice, and the deserts of the Kyzylkum and Karakum (also known as Kara Kum) to the southeast and south of the lake, respectively, are blanketed in snow. The diversion of freshwater inflows to the saline Aral Sea for agriculture has led to a considerable loss of lake volume and quality. Source: NASA MODIS Rapid Response Team, NASA/GSFC. See Plate 1.2 for a color version of this image.

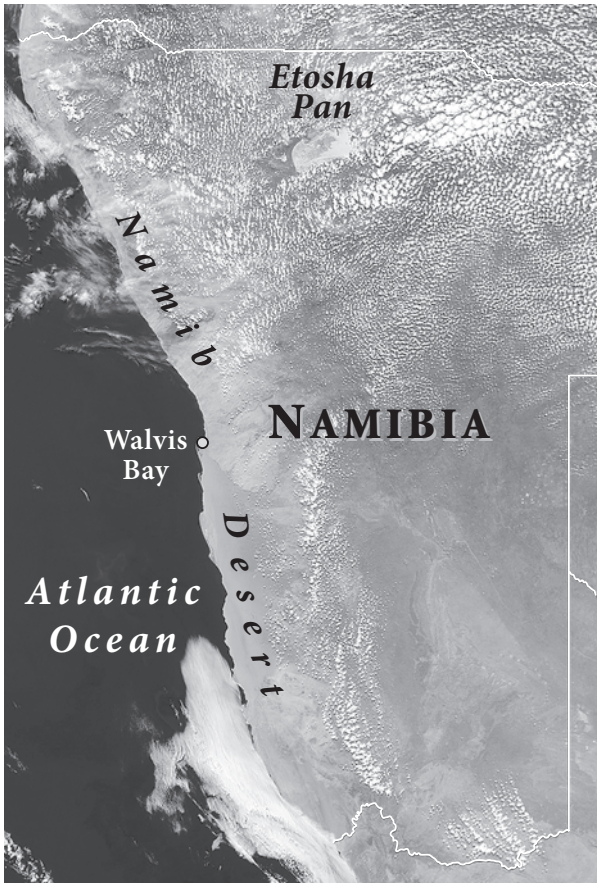

FIG. 1.3 Cool coastal deserts form adjacent to cold ocean currents on the west coasts of continents. The climate is moderated by the proximity to cold waters, which tend to impede convection. Moisture is largely provided by fog, shown here along the southern coast of the Namib Desert. True desert conditions with intense aridity occur in the Namib Desert, a strip 80–150 km wide along the Atlantic coast. To the east, on the right side of the satellite image, is the inland Kalahari Desert. Source: NASA Aqua/MODIS sensor. See Plate 1.3 for a color version of this image.

(150–600 m), and above these levels, hot and dry subsiding subtropical air prevails, causing a temperature inversion.

Rainfall amounts are very low because: (1) the air aloft lacks moisture, (2) the layer of cold air near the surface impedes convection, and (3) the moist surface air is too small in volume to provide an adequate moisture source. Condensation, however, occurs nightly and all exposed objects are wetted.

The seasons have little impact, with winter temperatures averaging only 3–6°C below those of summer. During the winter the sea breeze may weaken somewhat, but in general conditions vary little throughout the year.

1.2.2.2 Rainshadow effect

When air crosses mountain barriers, it rises on the windward side, and subsides on the lee side. Subsidence prevents convection and causes adiabatic heating that results in a pronounced drying effect. Thus, many of the world's arid areas lie to the lee of mountainous regions. In Australia, the Great Divide and other mountains on the east coast lie in the path of the prevailing southeasterly trade winds, creating a rainshadow effect that accentuates the aridity of the central continent. Aridity in the Patagonian Desert of South America results from the Andes mountain range, which blocks rain-bearing westerly air masses and gives rise to strong, dry adiabatic winds and dust storms. Little moisture results from cold air masses from the South Atlantic. Cool winters and mild summers characterize the Patagonian Desert, with temperatures decreasing southward. Similarly, the dry belts of Canada and the USA owe their origin to rainshadow effects resulting when westerly winds cross high-elevation mountains aligned north–south. Lying in the rainshadow of the Sierra Nevada-Cascade chain, the Great Basin Desert receives from 100 to 300 mm of precipitation annually (Fig. 1.4).

1.2.2.3 Edaphic environments

Edaphic deserts result in large measure from the influence of the soil. For example, in the Kalahari Desert, high evaporation rates and sandy soils that absorb rainfall produce a region that lacks surface water despite a rainfall range from 200 mm in the south to 500 mm in the north. Edaphic factors enhance the apparent aridity of this region, which is also fostered by continentality and atmospheric subsidence.

1.3 INDICES OF ARIDITY

Defining the margins of deserts and the boundary between arid and semiarid regions is difficult. Indices to determine aridity are based on rainfall alone, on water balance (the relationship that exists in a given area between precipitation (P), losses due to evapotranspiraton (ET), and changes in storage (S)), on soil type, or on vegetation.

FIG. 1.4 The subsidence of air to the lee of mountain barriers creates deserts in the rainshadow. In this image, the Sierra Nevada of California, which rises to over 4400 m, creates a rainshadow to the west in the Owens Valley. The decline in rainfall on the lee slopes can be seen as a decrease in vegetation. The Olancha Dunes are a small dune field formed in the southern section of Owens Valley. Vegetation within the dunes probably grows by exploiting groundwater. Alluvial fans can be seen along the basal slope of the Sierra.

On the basis of moisture indices, deserts are commonly divided into three categories: hyperarid, arid, and semiarid. Hyperarid regions have at least 12 consecutive months without rainfall and no regular seasonal cycle of rainfall. The Western Desert of Egypt and the Atacama Desert are hyperarid. Arid regions receive between 25 and 200 mm of rainfall annually, whereas semiarid lands have between 200 and 500 mm (Grove 1977). Semiarid grasslands are generally referred to as steppes, although this term is often ill-defined.

Most climatic systems used to define aridity are based on the concept of water balance. An example is the Thornthwaite Moisture Index (I_m) (Thornthwaite 1948).

$$I_m = \frac{s - 0.6d}{e} \times 100$$

In this equation, s is the sum of monthly surpluses of precipitation above the estimated potential evaporation; d is the sum of monthly deficits in precipitation; and e is the estimated annual potential evaporation based on mean monthly values of temperature, with an adjustment for season of rainfall, and including a factor for soil-moisture storage. Thornthwaite moisture value indices of 0 to −20 are considered dry subhumid; values of −20 to −40 are semiarid (200–500 mm precipitation); and values of −40 to −56 are arid (25–200 mm precipitation). Below −57, the region is considered hyperarid (generally <25 mm annual precipitation, with no seasonal rhythm of precipitation, and at least 12 consecutive rainless months) (Meigs 1953). Meigs (1953) further subdivided deserts according to whether there was no marked season of precipitation, summer rain, or winter rain.

Because evaporation or evapotranspiration increase proportionately with temperature, it is impractical to use a fixed precipitation figure for desert boundaries. Furthermore, the effectiveness of precipitation is strongly influenced by the season of the year (the higher temperatures of summer cause more rapid evaporation than the cooler conditions of winter), and a seasonality factor is therefore essential.

The United Nations Environment Program (1992) classification of drylands is similar to that of Thornthwaite, but uses meteorological data from 2000 meteorological stations over a fixed time period (1951–1980) rather than the full length of available record. It includes dry-subhumid areas in its classification, as these regions experience certain climatic characteristics of semiarid areas.

Whereas precipitation and temperature are easy to measure and have been recorded at stations for many years, evaporation and transpiration are more difficult to measure and the records are of shorter duration and less plentiful.

Furthermore, in a determination of Thornthwaite's index, evaporation cannot be considered a function of temperature alone. Other factors include the amount of soil moisture, soil type and texture, wind velocities, atmospheric pressure, relative humidity, plant cover, and land use. These latter contributions are more difficult to determine.

There are several problems with climatic measures of aridity. The effect of climate on plant growth, human occupation, and geomorphological process is not dependent on absolute amounts of precipitation. The temporal distribution of rain throughout the year is significant. For example, cold-season rainfall may be more effective for plant growth (if temperatures are sufficiently high) as less moisture is lost by direct evaporation than with hot-season rainfall. Another important factor is the variability of rainfall from year to year in both time and space. Additionally, human activities in the twentieth century have resulted in the expansion of arid surface conditions into semiarid environments, principally as a result of a decrease in vegetation cover.

Another means of determining the extent of arid lands is to determine the extent of certain soil types. Pedocals, poorly drained soils with free calcium in the profile, occur where evaporation exceeds precipitation in both middle and low latitudes. The distribution of these soils suggests that 43% of the Earth's surface is arid. By contrast, climatic and vegetation assessment suggests 35–36%.

1.4 Desert surfaces

Popular representations employ images of dunes to invoke the desert. However, sand covers only about 20% of desert surfaces, most of it in vast sand sheets and sand seas. In North Africa, such sand seas are referred to as ergs. Nearly 50% of desert surfaces are stone pavements or regs (Walker 1986). Pebbles (4–64 mm in diameter) surface most, but larger clasts, in the cobble range (64–265 mm), are also found. Hamadas are relatively level plains that are covered by boulders and exposed bedrock. In the Sahara, nearly horizontal Mesozoic marine and nonmarine sedimentary formations form extensive sandstone and limestone hamada plateaus (Williams 1994). A classic example is the Gilf Kebir in the hyperarid desert of southeastern Libya and southwestern Egypt. The remaining areas of desert surface are composed of bedrock outcrops, soils, and fluvial features including playas, alluvial fans and oases.

There are significant differences in the percentage cover of different surface types from region to region. In the Sahara, sand seas and regs are the dominant landform classes, covering 22 and 21% of the surface respectively, whereas alluvial fans cover less area (14%) (Ballantine et al. 2005). By contrast, in the southwestern USA, sand seas cover a mere 0.6% and alluvial fans 31% (Clements et al. 1957). The Peru–Chile desert also lacks extensive sand seas, being primarily a rocky desert (Berger & Cooke 1997).

1.5 Tectonically stable and unstable deserts

The tectonic setting of deserts plays a role in determining the relative and absolute relief of the region, affecting sediment sources and sinks, influencing timescales of relative stability or instability and, over the long term, the degree of aridity as mountain systems rise and block incoming moisture. Arid zones provide an important setting for tectonic study, as, owing to the lack of vegetation, features such as folds and faults are plainly visible on both remote imagery and the ground. In the Peru–Chile desert, for example, fault scarps, thrust sheets, and diverted drainage are clearly evident owing to active seismicity and very low denudation rates (Berger & Cooke 1997).

Tectonism provides a framework for basins and a source of renewed energy through uplift. The scale and alignment of relief features plays a critical role in climate, creating zones of enhanced rainfall and rainshadows, funneling winds, and providing numerous microclimatic environments. Tectonism also plays an important biological role, as fault-related springlines provide a source of water in many deserts.

Five types of tectonic setting are identified: cratons (shield and platform areas), which have shown relative stability since the late Tertiary; active continental margins, associated with Cenozoic orogenic belts, in a compressional setting, with thrust and transcurrent faulting; older, Phanerozoic orogenic belts, in which there is some reactivation of existing fault zones; inter-orogenic basin and range and inter-cratonic rift zones, with "pull-apart" basins in an extensional tectonic setting; and passive continental margins (Rendell 1997). Examples of deserts in these settings are shown in Table 1.1. The Saharan Desert is of such

Table 1.1 Tectonic settings and desert examples.

Tectonic setting	Contemporary deserts
Cratons	Kalahari Australian desert Saudi Arabia
Active continental margins and Cenozoic orogenic belts	Atacama Sahara Thar Sinai-Negev Arabian-Zagros
Older orogenic belts	China Sahara
Inter-orogenic, inter-cratonic	North American deserts: Mojave, Great Basin, Sonoran, Chihuahuan Sahara (Afar, Ethiopia) Monte Desert
Passive continental margin	Namib Patagonian

After Rendell (1997).

physical extent that it is included in more than one category.

These tectonic settings play a major role in determining the character of deserts. In the American southwest, the Basin and Range Province is distinguished by a distinctive physiography of narrow mountain ranges separated by broad, sediment-filled basins, within which are numerous playas (Leeder & Jackson 1993). Within this region the continental lithosphere has been stretched and thinned. Whereas many of the rocks exposed in this region are ancient, the landscape itself is modern, having largely acquired its form from extension during the late Miocene to Holocene (Baldridge 2004). Consequences of crustal stretching include faulting and volcanism. In 1887, a magnitude 7.2 earthquake in northern Sonora, Mexico, caused 50 km of ground breakage and developed a 3 m fault scarp (DuBois & Smith 1980). If an earthquake of similar magnitude were to occur today, it would have severe consequences for the heavily populated areas of southern Arizona. Volcanism is also widespread in the American southwest, although recent activity (the past few thousand years) has been largely confined to isolated, relatively quiet effusions of basaltic lavas. The high elevations and complex orographic conditions of the American west cause a patchy mosaic of climate and vegetation zones. Attempts to reconstruct palaeoclimates suggest very complex spatial patterns of hydrologic and vegetation change that reflect local topographic influences.

By contrast to this largely modern landscape, Mesozoic and Cenozoic uplands and lowlands in the Saharan desert are a legacy of a Precambrian and early Phanerozoic tectonic inheritance. In Australia, certain landscape elements are exhumed surfaces that developed well before the onset of aridity at about 0.91 million years ago (Ma) (Williams 1994).

The tectonic environment profoundly affects fluvial and lacustrine systems. In the stable tectonic settings of shield and platform deserts, such as Australia, arid alluvial fans are poorly developed (Mabbutt 1977a). In more active tectonic zones, hydrologic systems are altered when surface uplift increases erosion and changes the rate of sedimentary supply. Tectonic activity sometimes deflects, alters, or blocks drainages. The drainage history of the Mojave River in the southwestern USA has been difficult to decipher and remains controversial owing to tectonic disruptions during the Holocene (Brown et al. 1990). In Algeria, the 1980 El Asnan earthquake blocked the Chelif River and produced a 5 km^2 lake (King & Vita-Finzi 1981).

1.6 Deserts of the past

Aridity has existed on the surface of the Earth since Precambrian times, as shown by desert dune and evaporite sediments in the rock record (Glennie 1987). The earliest indicators of widespread dry conditions are 1.8 billion-year-old dune sediments in the Northwest Territories of Canada (Ross 1983). It is interesting to consider that prior to the colonization of the Earth's surface by plants, wind may have been a more potent agent of geomorphological change than it is today.

The location and extent of arid zones have shifted though time owing to changes in continental configuration, position, and relief. The onset of modern aridity can be traced back millions of years, with the development of drier conditions 80 Ma in the Namib and 150 Ma in the Atacama (Hartley et al. 2005). Other deserts, such as those of northern Africa and Australia, probably developed during the Tertiary (Thomas 1997). At a global level, it is thought that aridity was in place by 3 Ma (Williams 1994), related to declining temperatures in the late Cenozoic associated with the movement of continents towards their modern latitudes. As more land moved poleward, snow and ice expanded and global

albedo increased, causing global cooling, increases in latitudinal temperature gradients, and changes in global circulation as a consequence. The lowering of sea level during glacials also increased continentality, with the land area of Australia increasing by one-fifth (Williams et al. 1993). Although the first signs of aridity may be associated in some regions with events in early Cenozoic time, the system entered its most dramatic phase in the Quaternary, with strong oscillations in climate.

During the late Quaternary, all deserts experienced climate change, with alternations between more humid or more arid conditions, depending on location and time. Additionally, deserts expanded or contracted along their margins. In Africa, Australia, and Asia, the peak of late Quaternary aridity is thought to have occurred during the Last Glacial Maximum (LGM) (about 18–21 ka, where ka means thousand years ago), when deserts expanded up to five times their present extent (Sarnthein 1978; Stokes et al. 1997). The eastern Sahara, for example, was hyperarid (<10 mm annual rainfall) and unoccupied by humans. This was a period of intense aeolian erosion, during which many drainage systems were obliterated or inverted, and the region became pockmarked with deflation basins (Haynes 2001). By contrast, the deserts of the American southwest experienced cooler and wetter conditions (Fig. 1.5) as the massive Laurentide Ice Sheet that covered much of Canada and the northeastern USA caused the westerly winds and jet stream to enter at more southerly latitudes than today. As a consequence of increased effective moisture, several hundred lakes formed in the southwestern deserts and woodlands expanded (Benson et al. 1990, 1995; Orme 2002). Thus, climate changes are not always globally synchronous in deserts.

In order to fully assess the role of tectonism and climate change in the development of arid-zone landscapes, a clear chronological framework is necessary. However, many challenges remain in dating sedimentary deposits and surface exposures. The preservation of organic carbon (for ^{14}C dating) is very poor in arid environments and radiometric dating of geomorphic features in deserts is very difficult. There are, as yet, limited applications of other techniques, many of which are suitable only when favorable geomorphic/geologic settings are present. Luminescence techniques have found widespread favor for the investigation of aeolian deposits (Munyikwa 2005), particularly as they have undergone methodological innovations, such as the development of optically stimulated luminescence (OSL), which yields more precise dates for construction of high-resolution chronologies. OSL dates represent the last sunlight exposure event before deposition. Buried

Fig. 1.5 During the Quaternary, all deserts experienced climate change. In the American southwest, cooler and wetter conditions were experienced. Geomorphic indicators of a more humid climate include palaeoshorelines, shown here at Shoreline Butte in Death Valley. In this image, the butte is covered in wildflowers owing to an exceptionally wet winter season.

mineral grains, such as quartz and feldspar, gain energy from decaying radioactive isotopes. The energy is stored as trapped electrons within crystal lattice defects: as these traps are light-sensitive, they can be zeroed by exposure to sunlight. The burial age is calculated by measuring the stored energy (palaeodose), in conjunction with an evaluation of the annual energy-accumulation rate (Munyikwa 2005). Environments that have been dated by luminescence include loess terrain (Yu et al. 2007), desert dunes (Stokes et al. 1997; Kar et al. 2001; Twidale et al. 2001), and lunettes (Dutkiewicz & Prescott 1997; Lawson & Thomas 2002; Stone 2006). OSL dates have been instrumental in showing that dune processes may be different or more complex than previously thought (Hollands et al. 2006; Tooth 2007). Luminescence dates are increasingly being used to determine the timing of landscape response to late Quaternary climate changes (Munyikwa 2005). To date, however, there remains considerable uncertainty in the results, and it is unclear whether they reflect actual differences in geomorphic events and timing between locations, or differences in sampling strategies, laboratory practices, or improvements in luminescence dating procedures over the years (Tooth 2007). The cosmogenic nuclide age-determination technique has been applied to alluvial deposits (Repka et al. 1997), but there is a large age uncertainty and the practice is costly (Liu & Broecker 2008). Varnish microlamination dating is a correlative age-determination technique used on surfaces where rock varnish has formed, such as alluvial fans and exposures of desert pavement (Liu & Broecker 2008).

The use of geomorphic features as climatic indicators involves the application of a uniformitarian approach, using modern analogs as indicators of past climate. Palaeolake shorelines, karst and fossil-spring deposits, lake muds, palaeosols, wadi gravels, and shorelines are used to indicate wetter conditions, whereas degraded and fossilized sand dunes, yardangs, or deflation zones suggest more widespread aridity. Some of these features, including shorelines and fossil dunes, may be difficult to decipher or be masked at the ground by vegetation, and are more apparent in remotely sensed imagery.

Notable fossil dune systems include those of Africa: south of the Equator, relict dunes are widespread in Botswana, Angola, Zimbabwe, and Zambia (Thomas & Shaw 1991; Stokes et al. 1997) and may extend as far north as the Congo rainforest; whereas, north of the Equator fossil dunes extend south into the savannah and forest zone of West Africa. These ancient dunes are considered indicative of the nature and extent of past periods of greater aridity (Goudie 1996). Aeolian dune systems of the Mega Kalahari (2.5×10^6 km^2) of southern Africa indicate that there were many cycles of dune activity associated with Quaternary glacials. Chronologies established with optical dating techniques suggest significant events at approximately 95,000–115,000, 41,000–46,000, 20,000–26,000, and 9000–16,000 years before present (BP) (Stokes et al. 1997). Within this region there were latitudinal gradients, with the northeastern desert margin having more episodic activity than the southwestern desert core, where aridity was more sustained.

Relict dune systems, yardangs, and ventifacts may also be used to infer palaeocirculation patterns (R.S.U. Smith 1984; Thomas & Shaw 1991; Laity 1992, 1994; Corbett 1993; Stokes et al. 1997; Lancaster et al. 2002; Kocurek & Ewing 2005). In Australia, there is a vast anticlockwise whorl of longitudinal dunes, which covers approximately 40% of the continent and represents 38% of the Earth's aeolian landscape (Wasson et al. 1988). Individual dunes are up to 300 km in length and 10–35 m in height. During the period of peak aridity (18–20 ka), the Australian desert expanded on its southern margin and the dunes were active. Today, vegetation is insufficient to inhibit sand movement, but the modern environment is less windy than in glacial times, and the majority of the dunes are no longer mobile (Ash & Wasson 1983).

Whereas ancient aeolian features indicate drier periods in the past, relict lacustrine phenomena are evidence of formerly more humid conditions. During humid phases, bodies of water appeared in even the driest parts of the Sahara, and pre-existing lakes, such as Lake Chad, enlarged. Evidence of lake expansion (lacustral phases) includes fossil shorelines, calcareous deposits, and archaeological sites (Williams 1982). In Australia, raised shoreline features around the southern margin of Lake Eyre and in the Murray Basin of southeast Australia (Stone 2006), and deep-water lacustrine facies in stratigraphic sequences, are used to infer major lake expansions during the last interglacial period. It is thought that the arid belt of Australia may have disappeared completely during the more humid phases of the last 400,000 years (Croke 1997). In the Darb el Arba'in Desert of the eastern Sahara, rainfall increased from LGM values of less than 10 mm year^{-1} to perhaps 100–600 mm year^{-1} during the period between 9800 and

4500 years BP (Haynes 2001). This pluvial period, which followed Younger Dryas time (the Younger Dryas was a brief cool period, from 11.5 to 13 cal ka BP), consisted of three wet phases, and resulted in the deposition of playa muds in deflation basins. Palaeolake systems are discussed more fully in Sections 5.2.3 and 5.3.

Additional advances in our understanding of past climates have come from an examination of ocean sedimentary cores, which retain information on aeolian and fluvial inputs, and from palynological and biological studies, which provide important data on the expansion and contraction (in both area and altitude) of deserts. In the central Saharan Desert, for example, the Nile crocodile (*Crocodylus niloticus*) is presently found only in pools in the Tibesti Mountains. As the crocodile could not migrate across the Saharan desert, its isolated presence inland attests to past pluvial conditions (Goudie 1996).

Faunal and floral evidence indicate that wetter conditions than today characterized much of Egypt and the northern Sudan during the early Holocene. The moist conditions fostered seasonal grassy plains and shrubs and trees of Sahelian-Sudanian affinities, with vegetation concentrated in wadis and around lakes and springs. Rhinoceros bones have been found at Merga in the Sudan, elephant and giraffe bones at Abu Ballas in western Egypt, and hippopotamus, ostrich, hartebeest, and gazelle from Dahkla, western Egypt (Nicoll 2004). In addition to allowing a broad interpretation of environmental conditions, biological indicators often allow constraint of temperature and rainfall values during earlier times. For example, pollen studies, and isotopic datasets for the middle–late Holocene in the eastern Sahara suggest that rainfall isohyets shifted northward by as much as 5° in latitude from their present position (Ritchie & Haynes 1987; Abel & Hoelzmann 2000; Rodrigues et al. 2000).

Archaeological evidence of human occupation also provides valuable information on changing desert climates. Chronologies are generated from ^{14}C (radiocarbon) age determination of organic-rich materials associated with archaeological sites, including hearth materials, eggshells, animal dung, and wood. Patterns of human occupancy suggest that rapid hydroclimatic change in Egypt and northern Sudan from the late Pleistocene through the late Holocene may have driven cultural innovation, settlement, and migration. Dwindling water supplies after 6000 years BP caused human migration towards more reliable water and may have aided in the formation of hierarchical societies in the overpopulated Nile Valley (Butzer 1959; Nicoll 2004). In the Atacama Desert of northern Chile, campsites intercalated between debris flows suggest that even in the hyperarid mid-Holocene period there were extreme, short-lived hydrologic events. Major storms had a recurrence interval of 500–1200 years, whereas moderate storms returned about every 100–200 years (Grosjean et al. 1997). These extreme but rare events highlight the nonlinear nature of climate and landscape evolution in arid regions, and the difficulty of survival in such areas.

The final phase of desert climatic history began with the origins of humans in Africa some 2.5 Ma, and their migration to other arid regions such as Australia and the Americas during the late Pleistocene or early Holocene. From that time forth, desert habitats and climate were unwittingly modified by human activity, with contributions to desertification or to the local expansion of desert margins. This aspect of the climatic history of deserts is further treated in Chapter 13.

1.7 Changing human perspectives on deserts

The human population in deserts increased greatly in the twentieth century, with an estimate of at least 900 million people living in arid zones (Thomas 1997). In Africa, 49% of the population lives in arid areas of the continent (United Nations Environment Program 1992).

As the population increases, and resources are more severely stressed, the human perception of deserts continues to evolve. In some areas, twentieth-century technological innovations, including large-scale water-transfer projects, have allowed very high population densities. In the southwestern USA, Las Vegas, Nevada, is the fastest-growing city in the country. The citizens of this arid area, living in air-conditioned homes and businesses, are divorced from the heat and aridity of the surrounding landscape. In most areas of the world, however, the limitations of arid regions still impose serious constraints on human activities and occupations.

The continuing growth of population in deserts raises a host of social issues and new problems. One of the most significant concerns is the availability and quality of surface and ground water. Legal arguments concerning the allocation of surface water (e.g. the Colorado and Tigris/Euphrates River basins) affect both intranational and international relation-

ships. Many communities rely heavily or exclusively on groundwater, most of which was recharged during earlier, wetter climatic periods, and the depletion of this resource has resulted in large-scale ground subsidence, the loss of surface water in streams, and the demise of ecosystems. Groundwater that was stored during earlier geological periods is being rapidly depleted and wells have become progressively deeper and brackish within the timescale of human memory, as seen in the New Valley, Egypt (Nicoll 2004). In China, the sustainability of groundwater reserves is a subject of impassioned debate as development plans for this resource in the arid basins of northwestern China are produced. Urban development and irrigated agriculture often rely on shallow groundwater reserves that are recharged from mountains or uplands surrounding the basins. Once new economic development is in place, the exploitation of groundwater increases rapidly, with consequent drops in the water table and loss of desert vegetation (Chen & Xue 2003).

There are many issues of geologic concern in deserts that have a uniquely human dimension. These include the disposal of hazardous and nonhazardous wastes, soil stability, flooding hazards, deforestation, and the extraction of hydrocarbon and mineral resources. Desertification, the degradation of drylands, is a multidimensional issue with biophysical and socio-economic linkages. It affects human welfare insofar as it influences the capability, sustainability, vulnerability, and resilience of the land and, ultimately, the carrying capacity of arid and semiarid regions (Geist 2005). Although some progress has been made in understanding desertification since the issue first reached the world stage in the 1970s, our knowledge is better at a local than a global level. The dynamics of landscape modification, the interconnections of natural systems, and the impending impact of global warming, need to be better understood if future human tolls, such as civil and nationalistic wars, famine, and the stagnation and decline of economies, are to be averted.