CHAPTER VII

Deserts in the Past

The findings of historical geology are very clear that during the last 1,000 million years, for which good stratigraphical evidence is available, world climates have undergone several periods of great change, some of long duration but others much shorter. At the two extremes we have on the one hand the ice ages, when areas of continental dimensions were covered with ice sheets and mountain glaciers were greatly enlarged, and on the other, periods when tropical climates extended as far as 50–60° north and south of the equator and the polar regions were not ice-covered as they now are. In this changing scene the deserts of today were at times well-watered lands, and again, regions at present well watered were once deserts. No account of the existing arid areas can omit reference to the relatively recent climatic changes of the Quaternary era, which include several ice ages and interglacial periods, the effects of which on life and on geomorphology and soils in arid lands, as elsewhere, are still with us; but even the older events of the Tertiary era are also of direct significance, since fossil soils of Tertiary age are still preserved in the present land surface, especially in arid regions, and many major geological and geomorphological features were initiated during the Tertiary. In interpreting the record of the rocks as to climates during geological time, the conditions of present deserts afford an analogue for aridity. Reference will be made to this in later paragraphs, but the complexity of the topic is best seen by reference to the inferred changes that have affected existing arid areas, and evidence for the extension of contraction of the arid areas during recent times.

Criteria of climatic change in the recent past

LACUSTRINE CONDITIONS

Playas and salinas are characteristic of desert basins. Despite their being commonly termed 'lakes' they are dry except after the rare periods of heavy rains, but there is unequivocal evidence in the form of old beaches and other shore-line features, and of bottom deposits, that they were once, in reality, lakes. Perhaps the best known of these is Lake Bonneville in the USA [1], which in Pleistocene times extended over a maximum area of almost 20,000 sq. miles but which now is represented by the Great Salt Lake, a shrunken remnant varying in area between 1,500 and 2,200 sq. miles. Also in the Western Cordillera of the USA all that remains of Lake Lahonton, a vast Pleistocene lake, are several small lakes such as Pyramid Lake [2]. There are numerous playas of economic importance in the lower, western part of the Atacama desert basin, and here also there are indications that in times past the lake and drainage system was more extensive. In the Gobi Desert Berkey and Morris [3] noted at least seven old beach lines associated with a former lake, one shore line 29 feet higher than the 1922 level of the modern, shrunken lake. In Australia likewise there is evidence that the interior salt lakes were formerly more extensive and much deeper (see p. 65).

RIVER TERRACES

River terraces have been much used in the interpretation of climatic events. A river terrace may be arbitrarily defined as a former valley floor into which the river has incised and which is beyond the reach of present flooding. The incision in question may be caused directly by climatic change through variation in the discharge/load relationship of the stream, or indirectly through eustatic shifts of sea-level. It may, on the other hand, be initiated by tectonism. Interpretation is often complex because both climatic and eustatic factors operate simultaneously, and because climatic events in the headwater reaches of a river like the Nile may have far-reaching effects downstream. Despite these and other difficulties terraces have been widely used in the synthesis of climatic history, especially in Europe and Africa (see pp. 134–5).

PALYNOLOGY

Although most often applied in more humid environments the techniques of palynology (pollen-analysis) are applicable to the arid zone, as Pons and Quézel have shown in the Sahara [4]. Pollen is blown by the wind and settles on land as well as on water surfaces; in the first case the pollen will most likely decay, but in the second it will sink to the bottom of the lake or swamp and be incorporated in a sedimentary layer. By comparison with modern climates and associated vegetation complexes, the climates of the times can be inferred (see pp. 136–7), and climatic changes are reflected in the pollen spectra of successive sedimentary layers.

SEDIMENTS AND FOSSIL SOILS

A study of sediments and of soils may also suggest climatic change. They may be found in areas where they could not have formed under existing conditions, and are out of harmony with the modern environment. For example, there are lacustrine deposits in arid regions indicative of greater humidity at the time of their formation. In Mauretania, dunes dating from the end of the Flandrian transgression are covered with a red soil which could not have formed under desert conditions and which is at present suffering erosion [5].

DUNE FORMS

The occurrence of dunes beyond the confines of the modern deserts and in areas where (apart from coasts) dunes cannot now be supported is clear evidence of former aridity. Such dunes are now usually vegetated and fixed. In southern Australia, fixed longitudinal dunes cover great areas of Eyre Peninsula and the 'Mallee' country, areas noted today for wheat and sheep production (Fig VII-1). They occur also even in the eastern suburbs of Melbourne where the climate is now cool-temperate with a 25-inch rainfall. There are dunes now fixed by vegetation in the western Great Plains of the USA, also in the Sudan and West Africa, far south of the present Sahara Desert.

Fig VII-1. Ancient longitudinal dunes in the Mallee country, north-western Victoria, now under cultivation. (*RAAF photograph, reproduced with permission*)

DENDROCHRONOLOGY

Analysis of tree rings may be used to detect climatic changes during the very recent past. In regions with regular seasonal changes of weather trees generally produce one growth ring per annum. The thickness of growth rings varies with the age of the tree, those of youth being thicker than those of old age. Superimposed on this normal variation, however, there are variations imposed by differences in climate from year to year. Just which climatic factor is reflected in the varied thicknesses of growth rings is a matter of judgement, but in areas where rainfall is the critical factor influencing growth, a ring thicker than usual indicates above-average rainfall, whereas in the higher latitude and altitude areas peripheral to the tundra regions such thick rings probably indicate high summer temperatures. Very long climatic records, extending several hundred years back in time, have been obtained from some of the large trees of the American west, but it has been shown that in many instances their evidence is suspect and the contribution of dendrochronology has perhaps been fairly summarised as a valuable but not infallible guide.

ARCHAEOLOGY

Another line of evidence derives from anthropology and archaeology. Briefly, there is now abundant evidence that considerable populations once lived where life is now insupportable. Furthermore these peoples kept, hunted or had intimate knowledge of animals which we now associate with much more humid environments. Perhaps the most spectacular example of such a population that has come to light has been described by Lhote from the central Sahara [6], where frescoes at Tassili and elsewhere afford clear evidence of the former presence of animal life characteristic of much more humid climes (see p. 136).

Studies of written records, and of the ancient wells, water works, and other evidences of the climatic regimes of historical periods, yield valuable data, and all the evidence from the various lines of investigation discussed above may be synthesised to give an overall picture, which is unfortunately far from precisely accurate, of the succession of immediate past climates. Methods of dating have been improved, particularly by the study of radio-carbon isotopes in carbon-bearing deposits.

Of considerable interest is the question of the effects of quite small fluctuations in climate, such as might affect existing settlements either adversely or favourably, and the probability that such fluctuations may be cyclic.

Effects of small climatic changes

In order to appreciate the full significance of even minor changes of climate in the arid zone, one must realise that the vital natural resources of surface water and pasture vary greatly from place to place. The Sahara is a good example to illustrate this.

Fig VII-2. Saharan rock painting at Sefar, Tassili n'Ajjer, Algeria. (*Photo J.-D. Lajoux*)

Several latitudinal zones mark the transition from humid through sub-humid and semi-arid to arid on both the northern and southern peripheries of this desert subcontinent. There are no very sharp lines of delimitation, but in a very general way some of the areas with 10–15 inches of rainfall per annum will still support a lush grassland vegetation and permit agriculture without irrigation. Drier areas yet, with only 5–10 inches of rainfall, will support no more than a sparse desert grassland, which may still, however, form a suitable environment for nomadic herders during all or much of the year. Even more arid regions with 2–5 inches of rainfall may provide some grazing when occasional rains serve to revive the plant cover. Finally the great dry interiors with one inch, a half inch or even less, support no plant life whatsoever.

During periods of climatic amelioration the marginal belts of this type will both expand and shift towards the interior of the desert, thus reducing the size, although never eliminating that core region. Conversely, periods of climatic deterioration will lead to a contraction and outward migration of the marginal zones, corresponding to an expansion of the barren interiors.

Climatic changes do not only produce latitudinal shifts of different ecological belts. Equally significant is the diverse pattern of minute but extremely important changes recorded in the highlands and mountains common to most of the world's dry regions. These areas of greater elevation enjoy a higher local rainfall even today, and during periods of moister climate, rainfall values there would increase appreciably, so creating large islands of more attractive country.

In the Sahara Desert, periods of greater rainfall noticeably favoured the various highland zones, and the resulting ecological effects were disproportionately large. Rains falling in the high country were channelled into wadis which frequently discharged on to the neighbouring lowland plains. But before such occasional waters finally evaporated into the subsoil, they provided comparatively bountiful conditions along the length of the valley. Sporadic floodwaters thus encouraged higher plant life, while the persisting soil moisture supported herbaceous vegetation for many months or even years. Furthermore, shallow wells dug into the valley bed frequently provided water for man and beast long after the last rains. Finally, percolating waters in the higher country provided springs at lower elevations.

Corroboration of this view comes also from the American south-west, where it has been calculated that the physiographically substantial changes in the Lake Bonneville and Lake Lahontan basins were a reflection of climatic changes which in absolute terms were of no great magnitude. In fact it is suggested that an increase in rainfall from the present 10 to about 18 inches per annum and a temperature decrease of about 5°C would suffice.

The pluvial periods of the Quaternary era

Pluvial periods have been defined as phases of widespread, long-term rainfall increase of sufficient duration and intensity to be of geological significance.

Evidence of such moist intervals has been particularly well studied in western Asia and on the African continent, although they are of course known elsewhere, but because the sequence of events is known with a measure of precision in these Old World areas this statement refers specifically to the areas mentioned. The pluvial periods recognised to date have affected not only the great desert areas and their margins, but also wide expanses of semi-arid grasslands stretching from the equator to mid-latitudes.

It is known, for example, that about five million years or so ago, shifting desert sands reached from the Cape Province to the Congo River, at a time when man's sub-human ancestors were evolving on the African continent. On later occasions, the present Kalahari dry country practically disappeared [7, 8]. In East Africa, moist periods, on occasions, supported lakes in regions where even drinking water is unavailable today. The famous Olduvai Gorge of Tanzania, which has produced the earliest associations of artefacts and cultural traces of early man, is one such site [9]. And in the Sahara there is pollen evidence of cypress, olive, pine, oak and other trees which thrive in the slightly wetter high country [10].

The pattern of pluvial periods is associated with the Pleistocene period, which began about one million years ago, when climates changed markedly in most latitudes and on most continents.[1] Higher latitudes were alternately subjected to continental glaciation and deglaciation, in a rhythm of glacial and interglacial periods. The lower evaporation during glacial episodes was reflected by improved moisture conditions in the higher latitude dry lands, as, for example, central Asia, Mongolia, or the Great Plains.

In lower latitudes, an even more complex succession of moister and drier pluvials and interpluvials succeeded one another. These changes apply particularly to the Sahara, Arabia, the Kalahari and Numib of southern Africa, and to the great Australian interior. Several problems have been raised by these lower latitude pluvials. Have they been synchronous with the higher latitude glacials or with the interglacials? Have such pluvials been contemporary on the different continents and, if so, have they been synchronous on both latitudinal peripheries of each desert?

Considerable progress towards the solution of these questions has been made by geological and geomorphological investigation, particularly in dry areas contiguous to an ocean coast. During various Pleistocene glaciations, millions of cubic kilometres of ocean water were locked in the continental ice masses so that world sea-level was lowered by about 100 metres or so. During the warmer interglacials this water was released and occasionally augmented somewhat by a reduction of the existing highland glaciers and possibly also of the ice caps of Greenland and the Antarctic continent. Thus, since the water content of the world's glaciers is ultimately derived from the oceans, periods of low sea-level

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[1] An age of one million years, for some time accepted for the Pleistocene, may be an under-estimate and may also be varied according to stratigraphic reinterpretation. A period as short as 350,000 years has been suggested.

provide a good stratigraphic marker of glacier episodes, while periods of high (or higher) sea-level indicate interglacial periods. These glacio-eustatic fluctuations of sea-level, as they are called, have, however, no necessary relationship to the fluctuations of interior lakes.

Broad correlation between pluvial and glacial phases has been suggested on the basis of sea-level correlations, although in the case of the Mediterranean region it was possible to show that only the early parts of the low sea-level phases were moister, whereas the later parts were drier [11]. Again, in that area while some periods of interglacial time were quite dry, in the Sahara for example other periods were warm and moist.

The recent application of radio-carbon dating techniques to various samples from tropical Africa has shown that the last major pluvial episode of both East and South Africa began as long as 60,000–70,000 years ago, reached its maximum shortly thereafter, and waned after 38,000 years ago. Conditions were again moister from a little before 20,000 to about 12,000 years ago [12]. This second and last part of the last pluvial was less significant in the fully arid Sahara.

From the evidence available today, it can be suggested as highly probable that pluvial tendencies were contemporary in all drier latitudinal zones in the same way that glaciations were everywhere broadly synchronous. However, the correlation of pluvial and glacial is only a half-truth. There have indeed been moist cool intervals in the lower latitude dry areas. But there have also been dry cool intervals, moist warm intervals, and dry warm intervals [13]. For the time span of the last interglacial (ca 100,000–65,000 years ago) and last glacial (ca 65,000–10,000 years ago), the sequence recorded in the Sahara and on the Mediterranean borderlands seems to be broadly as follows:

Early last interglacial	Warm, comparatively dry
Late last interglacial	Warm, comparatively moist
Early last glacial	Cool, comparatively moist
Later last glacial	Cold, comparatively dry

The evidence in support of warm pluvials is mainly derived from fossil soils. Such soils are related to the red loams still forming in the tropical savannas today. Soils of this type are preserved as the *terra rossas* or red earths of the Mediterranean Basin, which no longer develop today, but which can be shown to be of interglacial age. They further include relict or fossil soils found on the terraces of the River Nile, in some of the Saharan highlands and on the coasts of Mauretania and Senegal, well beyond their present range of development. Each of these soils is testimony of former periods of warm, seasonally moist climate producing a rather intensive degree of chemical weathering. Similar fossil soils have been recognised in dry parts of East Africa.

Evidence for cool pluvials is of another kind. Such phases were not characterised by a close vegetative mat such as enabled the fossil red soils to develop, free from disturbances by erosion. Instead, intensive irregular rains provided great stream potential to erode, remove and transport large quantities of rock, sand and soil [11, 14]. These were accumulated along the stream beds and are now preserved as widespread alluvial deposits, frequently dissected since to form river terraces. The cool pluvials were rather distinct phases of accelerated stream erosion, transport and deposition in areas with little or no stream activity today. Intensive rainwash erosion of unprotected soils and loose surface materials, together with longer and more effective stream discharge, seem to be characteristic of such phases.

There is only limited evidence available in support of interpluvial phases drier than today. Some of the rare instances are blown sands in many parts of southern and central Africa, suggesting an absence of vegetation on the Kalahari Sands during various occasions of the Pleistocene. In West Africa and in parts of the Sudan, fossil dunes, under considerable vegetation today, may be found ten or even hundreds of kilometres beyond the contemporary limits of blowing sands [10]. In the Mediterranean region, coastal dunes were able to migrate many kilometres into the interior during several cool interpluvials, into areas well forested under natural conditions today. The general scarcity of good, stratigraphically dated evidence of intensified aridity seems to reflect on the absence of good indicators. Geomorphic processes in the deserts today are comparatively slow, and barring sand dunes, only produce distinctive features in the landscape after long periods of time. Excepting the subordinate role of wind, most of these processes are at work in more humid areas today. They would consequently be difficult to recognise in an ancient context, unless perchance suitable material was available for wind activity.

The last 10,000 years

It was suggested above that the maximum of the last Pleistocene pluvial phase dates back to over 50 millennia ago, and that all pluvial characteristics were over well before the close of the Pleistocene period some 10 millennia ago. This implies that the climate of the arid zones had approached a mean not unlike that of the present. In the succeeding millennia climate continued to fluctuate a little and, although such fluctuations were seldom of geological significance, they may well have exerted considerable influence on human life.

There is no general scheme of Recent or Postglacial climatic fluctuations that would be acceptable in more than one region. This is largely a reflection of how little is known of the major climatic changes of the late prehistoric and the historical eras. One particular moist interval may, however, prove to be of rather general occurrence during the millennia of maximum Postglacial temperatures, approximately from the late sixth to the late third millennium [10]. Pronounced aridity in the second millennium B.C. may also be another such feature of more general validity.

An area in which Recent climatic changes have had somewhat spectacular ecological effects has been the Sahara Desert. It can be said that full aridity had set in by about 8000 B.C., so that there is no question of any so-called progressive desiccation since that time. Yet between about 5500 B.C. (or a little earlier) and 2350 B.C. the climate was moister than today. The evidence is of three kinds: faunal evidence, largely on the basis of prehistoric rock-drawings; botanical evidence, including a fair amount of fossil pollen; and some limited geological evidence. The details of this moist interval or subpluvial period may be provided in a summary way.

The two oldest groups of late prehistoric rock-drawings of the Sahara belong to a group of big game hunters, and to a culture based upon beef-cattle raising, the earlier known group of nomadic pastoralists. Both of these peoples left an invaluable record of themselves and their way of life, as well as of a manifold natural fauna in many of the now deserted Saharan highlands of the Hoggar, Tassili, Adrar, Air, Tibesti and Uweinat [6]. The animals depicted along the dry wadis of the Fezzan include not only gazelles, antelopes and ostrich, but also tropical savanna species such as the elephant, both the single and two-horned rhinoceros, hippopotamus, crocodile, an extinct water buffalo and the giraffe. As an example, the African elephant is a woodland or parkland form, requiring some 300–350 pounds of green fodder daily. Study of the natural distribution of the four most indicative species with modern rainfall distribution suggests that rhinoceros and hippopotamus do not occur in any areas with less than 6 inches rainfall, the elephant in areas with less than 4 inches, the giraffe with less than 2 inches. Such are obviously theoretical values, but even in view of the local micro-ecology they do provide rather conservative estimates. On the basis of this rich archaeologically recorded zoological evidence – which is supported by fossils in several areas – a tentative attempt to reconstruct the approximate rainfall distribution for the period ca 5000–2350 B.C. is made in Fig VII–3. The hypothetical lines of equal rainfall so obtained suggest an increased precipitation both on the northern and southern margins of the Sahara, where the marginal belts of vegetation shifted 100–250 km towards the core of the desert. The central highlands appeared as selected areas of water and pasture rising above the desert plains.

Floral evidence of this subpluvial phase is available from several areas. For example, three stumps of acacia, tamarisk and sycamore have been observed (and archaeologically dated) in the deserts east and west of the Nile in Egypt [7]. They indicate a savannah-like vegetation with small trees or thickets at edaphically suited localities such as are provided in wadi beds. In addition to literary sources there is historical documentation on several very ancient Egyptian tomb and temple reliefs of vegetative growth in the desert. This was, of course, limited to the more elevated country or to the marginal tracts, for the core of the Libyan Desert would have remained as lifeless as today. Similar evidence is available from the northern Sudan.

In the western Sahara several rock shelters, often with rock-drawings, have provided pollen grains of cypress, pine, evergreen oak, wild olive, hackberry, juniper, tamarisk and a number of Mediterranean-type shrubs, as well as the lotus and cereals [10, 4, 18]. Various radio-carbon dates of 3450, 3445, 3070 and

2730 B.C. have been obtained for some such beds. This evidence suggests an open subtropical woodland at edaphically favoured localities in the Saharan highlands at the time.

Finally, the testimony of the rock-drawings and biological evidence is amply substantiated by local occurrences of geological sediments, including black organic soils found in wadi floors and formerly marshy depressions. These are particularly common in the Hoggar and Adrar areas, where they contain rich molluscan faunas as well as prehistoric fish-hooks and milling stones.

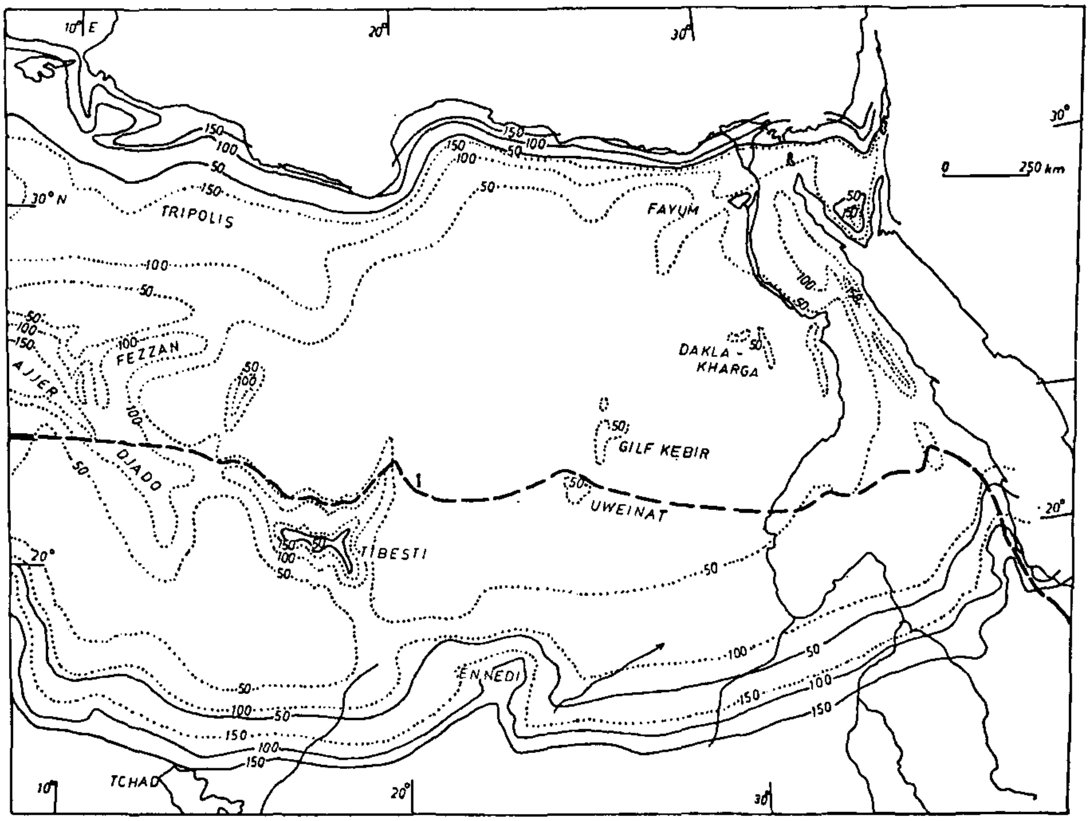

Fig VII-3. Modern and late prehistoric (5500–2350 B.C) distribution of precipitation in the eastern and central Sahara. Full lines indicate modern rainfall in millimetres; dotted lines indicate reconstruction of same for late prehistoric times. Heavy hatched line (1) indicates boundary between predominating winter and summer rains today. (*From 'Abhandlungen der Akademie der Wissenschaften und der Literatur' (Mainz), Math. Nat. Kl., 1958, No. 1, Fig 2*)

The subsequent period, ca 2350–800 B.C., was intensely dry. Geological and historical evidence in Egypt suggests that sand dunes invaded parts of the Nile Valley, that the Nile floods declined, that famines due to low floods were common, and that desert people were forced to immigrate into the Nile Valley. Conditions have remained more or less average during the last two millennia or so. As in other areas of the Near East, there is no sound evidence supporting a moister climate in Graeco-Roman times as has sometimes been suggested. This example of the Saharan area may give an impression of the kind of data available, and the degree of fluctuation verified.

Contemporary climatic trends

Meteorological records of a direct nature supplant geological and historical evidence in the late nineteenth and early twentieth centuries A.D. From all arid regions of the world, with the unique exception of the American south-west and northern Mexico, the records indicate a declining rainfall between about 1910 and 1940 (Fig VII-4). This was paralleled by a slight warm-up in higher latitudes. This warm-dry anomaly appears to have been interrupted or possibly reversed since 1940, however. The overall effects of this recent climatic fluctuation have had only limited impact on human existence in marginal lands. But the fluctuation has provided valuable actualistic experience for reconstructing interpluvial climates, and the observations provide at least some grounds for possible speculation on future development of precipitation trends in the arid zone.

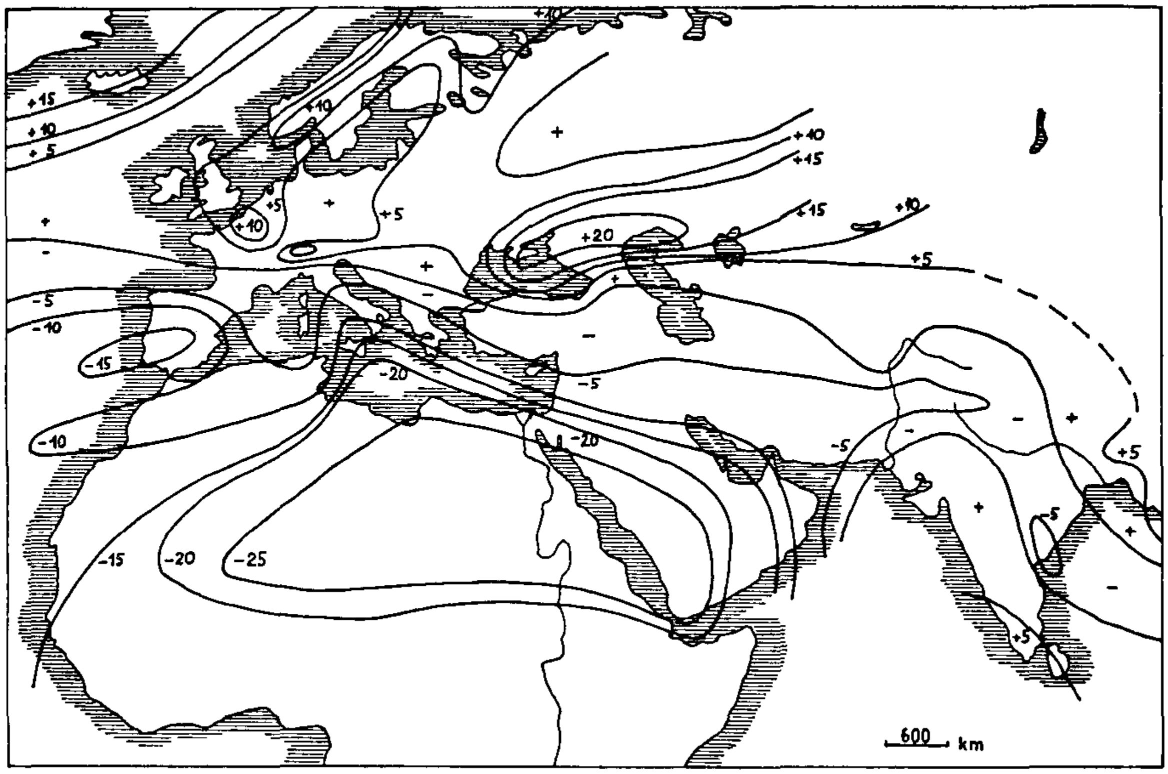

Fig VII-4. Precipitation anomalies 1881–1910 to 1911–1940 expressed in percentage deviations from the mean 1881–1910. Annual. (*From 'Geografiska Annaler', vol. 37, 1957, p. 107, Fig 3*)

A long-term weather prognosis advanced by one authority in 1951 [19] was a general amelioration of moisture conditions in lower latitudes during 1950–70. This forecast was made on the basis of expected sunspot developments, which have failed to materialise. Nevertheless the contemporary trend does at least not appear to be a negative one. Reliable explanations for the comparatively minor but ecologically important fluctuations within the general circulation of the atmosphere are still lacking. Until this is otherwise, no useful suggestions as to the future trend of the *dynamique* of arid zone climates can be offered.

Deserts of past geological eras

The deserts of the Quaternary era, in which we live, are perhaps more intensely arid than the dry lands of much of geological time, because of the intense mountain-building of Tertiary times, which created a more varied topography than obtained during long periods of relative quiescence between the orogenic revolutions. During such periods of stability the general circulation of the atmosphere was slack, with widespread regions of savannah type climate, relatively but not intensely arid.

It is probable, however, that in former geological eras with generally lower rainfall and higher temperatures, physiographic processes characteristic of very arid areas today could have been generated with less severe climatic conditions. Plants did not occupy the land until the Devonian, and even after that time the density of vegetative cover may reasonably be presumed to have been less than today especially as grasses did not appear until the Tertiary. Thus in the past, and especially in the more distant past, some areas which would not now be subject to physiographic processes characteristic of desert lands would have been affected by the sparseness of the vegetative cover; these are the biological deserts.

GEOLOGICAL CRITERIA OF ARIDITY

Many criteria have been advanced as evidence of past aridity, but few are conclusive and usually reliance must be placed on convergent lines of evidence. Dunes, including their external form, internal bedding structures, and size and shape of the component sand grains, are the most unequivocal evidence of the existence of deserts, coastal dunes excepted.

The outstanding example of an ancient desert which can be identified from dune forms preserved in the stratigraphic record comes from South America [20]. During Triassic times the Parana basin was an epeiric depression occupied by a vast sea of sands and dunes that covered an area of at least 1,300,000 sq. km. Preserved in the basin is a sequence of sedimentary and volcanic rocks resting uncomformably upon an ancient basement which includes Pre-Cambrian and Permian strata. The basal member of the sequence is of alluvial origin, the Piramboia sandstone. This is succeeded by the aeolian Botucatú sandstone which is intercalated with the alluvio-lacustrine Santana sandstone, and within which there is an extensive (1,200,000 sq. km) series of basaltic lava flows. There are aeolian sands above the lava in places. Reptilian and plant remains indicate an upper Triassic (Rhaetic) age.

The Botucatú sandstone is a fine-grained rock, some 70–90 per cent of its grains being in the diameter range 0·06–0·25 mm. It is predominantly quartzite, only about 5 per cent of its volume being felspathic. The large grains are well rounded, the small less well; they characteristically exhibit minute pitting and a veneer of red ferric oxide. These sedimentological features are typical of aeolian sediments.

A statistical study of the dune-bedding in the sandstone shows that the dunes formed and migrated under the influence of a northerly wind. In some few localities dune forms are perfectly preserved beneath the lava flows and conveniently exposed in railway cuttings. Individual dunes are up to 15 metres high. Arcuate slip faces can be traced in some places and are suggestive of barchans. The sandstones in many places display aeolian ripple marks.

The Botucatú Desert is but one of several postulated deserts of Permo-Triassic age, though it is the only one with dune forms both preserved and exposed.' In other areas the evidence is derived from a number of other features, the chief of which are sedimentary petrology, dune structures, evaporites (salt deposits), wind-faceted pebbles, evidence of a desert varnish and of sand-blasting, and a number of minor criteria.

The sedimentary characteristics of sandstones can be diagnostic of their origin and may be safely used. In particular, the grain size, range of size and shape of grain are indicative of the origin of the rock. There is a high coefficient of sorting and roundness. Aeolian sands range in size from 0·15 to 0·30 mm, and very commonly are well rounded to give a 'millet seed' texture. Aeolian sands very often possess a pellicule of ferric oxide which coats each grain and to some extent masks the minute pittings caused by collisions between individual grains.

Possibly more important and reliable are dune or aeolian bedding structures. In a vertical section the sequences of dune-bedding, separated by either planar or curved surfaces of erosion, display markedly contrasted angles of dip. From a study of such false bedding it is possible to deduce the wind direction at the time of deposition, and by tracing individual faces it is possible to reconstruct the morphology of a dune (Fig VII-5).

In the British Permo-Trias, sands that are of certain aeolian origin are fairly common. They are particularly abundant in the Lower Permian sand sea, where many dune structures are known: they were barchans driven by easterly winds. In the Triassic, however, only the Lossiemouth sandstone of Morayshire and a single lens of the Upper Bunter near Kidderminster are regarded as of certain wind-blown origin.

In the western USA dune-bedded sands are abundant. The Uinta (Lower Tertiary) sandstones of Utah and the Chuska sandstone of the same age, display dune structures to perfection in massive and precipitous bluffs. The Chuska sandstone was deposited by a southerly wind. Throughout Utah, Colorado and Wyoming there are aeolian sandstones ranging in age from the Pennsylanian (Upper Carboniferous) to the Upper Jurassic. The formations involved are the Entrada, Cow Springs, Navajo, Coconino, Tensleep, Weber and Casper sandstones [21]. Though some have doubted the aeolian origin of parts of these sequences, their structure and association in places with gypsiferous deposits make a desert origin probable. An analysis of their stratification shows that the dunes were moulded by a northerly wind.

The identification of some of the Permo-Triassic sediments of desert origin rested initially on the dominant red colour of the beds and on the presence of saline beds. A red colour *per se* has in the past been accepted as evidence of aridity, but brown, or yellow brown, is a more typical colour of desert sands, though some dune sands are red [22, 23]. The origin of the ferric oxide that imparts this hue is not known, but most workers are now agreed that red is more characteristic of weathering under humid tropical conditions. Some red-beds are accordingly interpreted as preserving their redness from the soils of a landscape previously humid, as with the Tertiary laterites that exist in many parts of Australia, and which break down to give red soils under the present-day climate. The most that can be said is that arid conditions are non-reducing and thus favour the retention of the red colour.

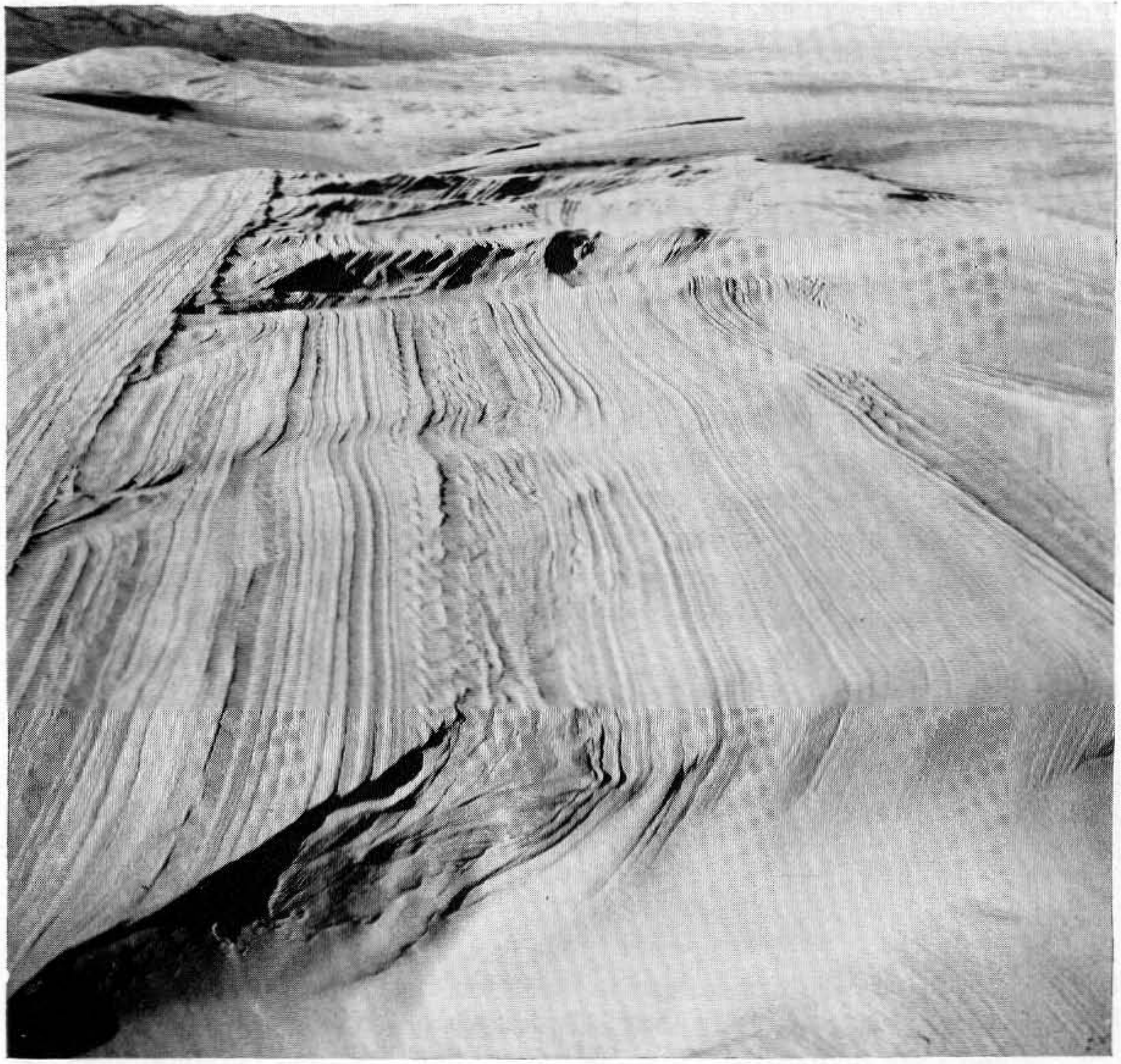

Fig VII-5. Bedding structures revealed in a wind-eroded wet sand dune, Kelso Dunes, Mojave Desert, California. Similar structures may be seen in fossil dunes. (*Photo R. P. Sharp*)

Thick salt deposits, sometimes regarded as due to evaporation in continental desert basins, are now chiefly attributed to evaporation in marine environments, particularly in almost landlocked gulfs. They are, however, a clear indication of hot dry conditions on the nearby land mass, although not themselves of lacustrine origin.

Modern stony deserts both hot and cold are characterised by the presence of ventifacts or wind-faceted pebbles, the *Dreikanter* of the German literature. The presence of such faceted stones in ancient deposits is evidence of aridity, either hot or cold. In the Trias of the Nottingham district in the English midlands they occur quite commonly. They are virtually the only evidence of aridity in two Pre-Cambrian formations, the Torridon sandstone of the north-west highlands of Scotland, and the Jotnian sandstone of southern Finland, Sweden and the Kola Peninsula.

The Trias of the English midlands contains, besides ventifacts, liver-coloured pebbles which are probably stones with a veneer of desert varnish, well known from modern arid environments. Polishing, fretting and fluting by the wind armed with sand is another sign of arid conditions. The classic example of fossil sand-blasted rocks has been described from the Charnwood forest of Leicestershire, England, where the local Triassic strata lie unconformably upon a Pre-Cambrian sequence of crystalline rocks [24].

Breccias and conglomerates, although not of themselves evidence of desert conditions, are common in an arid environment where there is considerable relief. Ancient fanglomerates are known, for example the Brockrams of the Lower Permian of north-western England. Likewise possible relict calcrete has been recognised in the 'Cornstones' of the Lower Devonian of Wales and the Upper Devonian of Scotland.

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