CHAPTER 16
Aeolian systems

Introduction

The power of the wind in mid-latitudes is more evident as a component of stormy weather than as a widespread geomorphic agent, although increasing accelerated erosion of dry, crop-free arable farmland makes it a less unfamiliar if occasional occurrence. This serves to emphasise the importance to the efficacy of aeolian processes of arid, vegetation-free environments with a ready supply of deflatable materials – primarily Earth's hot and cold deserts but also a narrow coastal fringe in almost all climates. Any temporary or sustained loss of vegetation in other areas immediately lowers the deflation threshold, as we see in cases of desertification and more parochially in urban areas and around construction sites.

Aeolian processes are introduced here as a variation of the general dynamics of entrainment, transport and deposition in a fluid environment, emphasising the effect of low air density on wind shear stress. Attention is therefore drawn to conditions which lower entrainment thresholds and enhance deflation rates, and also to the lesser constraints on airflow which permit long residence times and long-distance transport. The principal geomorphic effects of deflation are outlined, namely the winnowing of fines, the survival of coarse lags, abrasion of rock surfaces and deposition of sand and loess sheets. The role of aeolian processes in the rock cycle is indicated by the predominance of quartz sand and silicic silt in aeolian deposits, indicative of later fractionation. The chapter concludes with an outline of the influence of morphotectonics on the location of aeolian systems prior to more extensive cover of desert and coastal dune landsystems.

Chapter Summary

Aeolian processes

- Although aeolian processes of entrainment, transport and deposition are broadly similar to those of other forms of fluid motion, the much lower density of air means that wind applies a much smaller force per unit velocity.
- Lower density increases sorting efficiency, however, with entrained particles falling rapidly out of incompetent flow, and grain ballistic collisions lower the entrainment threshold of initially stationary particles. Turbulence is also much less constrained than in water channels.
- Effective wind velocities and deflation or entrainment depend on dry, vegetation-free surfaces and a supply of uncohesive fine-grained particles. Threshold velocities for sand decrease as air temperature falls, and density rises correspondingly, enhancing entrainment in cold climates.
- Particulate material becomes airborne through wind shear stress, turbulent lift and ballistic impact; volcanic ash, sea spray and many anthropogenic dusts are injected direct into airflow.
- Deposition occurs when wind falls below the threshold velocity for individual particle size. Fine dusts may have long airborne residence times and travel long distances.

- Deflation winnows fine particles from surface materials, leaving behind a lag deposit of coarser material. Entrained particles are capable of abrading softer materials with which they collide, and sands and silts are thoroughly segregated during transit.

Aeolian landsystems

- Aeolian environments cover about 20 per cent of global landsurfaces. They are associated with hot and cold desert environments, concentrated in zones of atmospheric divergence and light winds rather than in Earth's storm belts.
- Morphotectonic influences are evident indirectly where coastal orogens reinforce aridity through rain-shadow effects and in intercratonic basins which receive the deflatable products of desert mechanical weathering and ephemeral fluvial transport.
- Deflation strips sand, silt and chemical weathering residues from the landsurface, leaving behind sterile desert pavements of abraded bedrock surfaces and residual lag gravels.
- Abrasion picks out lithological weaknesses and exploits structural discontinuities aligned close to the predominant airflow. Resistant rocks survive as fluted yardangs, and deflation hollows are excavated into softer rocks.
- Deflation products form extensive leeward dune fields and active or dormant sand seas (ergs) which occupy large areas in the core of many hot deserts. Loess sheets are the product of cold desert deflation and blanket large areas of mid-latitude continents beyond the margin of Pleistocene ice sheet sediments which form their principal source.
- Sand bedforms ornament the surface of larger sand seas, with a variety of ripples and dunes from microforms less than 5 cm high to megadunes (draa) up to 40 m high.
- Dunes may be metastable in the lee of obstacles but their general habit is to advance by sand deflation from exposed windward to sheltered leeward slopes. Their alignment and individual shapes reflect complex regional and local airflow patterns.
- Coastal dunes are not climate-specific and are nourished by sustained raw sand supply into the backshore zone prior to deflation by onshore winds. These conditions of physiological drought suppress plant growth but coastal dune systems are eventually stabilised by a biogeomorphic succession.

CASE STUDY : Coastal dune systems of Wales

Aims and Objectives *The Website Case Study for Chapter 16 develops one of the component elements and boxes of the main text ~ temperate zone coastal dune systems. The coastline of Wales may not be exceptionally more prone to barrier dune formation than other areas of the long British coastline but its coastline is compact enough and the origin, nature and age of its coastal dunes varied enough, to provide it with the credentials of a good case study. The narrow strip of land involved may pale into* *insignificance alongside the vast expanse of continental desert dune systems, sand seas and loess sheets ~ or their plumes far out into the ocean ~ but coastal dunes are as good as aeolian systems get in Britain ! Their microcosm contains elements of formative geomorphic processes, recent environmental history and modern conservation and management.*

Introduction

The main text of Chapter 16 sets out the case for regarding coastal dunes as a distinct biogeomorphic system, depending on the predominance of effective, onshore winds and deflation of sustained sand supplies in the backshore zone. This is then, crucially, stabilized by a pioneer *psammosere* of highly-resistant vegetation species ~ with a sub-seral stages often dominated by *Ammophila arenaria* (marram grass) and *Agropyron* spp. (couch grass) in British dunes. It is tolerant of physiological drought, nutrient-poor and saline-rich embryonic soils, and wind shear and capable of growing through, and anchoring, repeated sand burial.

Progressive enlargement and colonization establish a fore- or *yellow dune* barrier, reducing local windspeeds and allowing diverse succession to develop in its lee. The dune is not yet fully stable, however, and parabolic blow-outs occur which advance the dune inland by 1–20 m yr^{-1}. In the sheltered conditions of the dune *slack* and *meadow*, soil develops and succession advances towards shrubs and woodland. *Hind* or *grey dunes* are more stable, although still vulnerable to climatic change and human disturbance (Figure 16.7 in the main text). Coastal dunes may individually reach 30-100 m high and dune systems may extend for 1-5 km inland.

Coastal dunes systems of Wales

There are a number of factors responsible for the relatively large number, if not great extent, of coastal dunes around Wales. The immediate sand source is the Irish Sea Basin, which is quite shallow for some distance off the west Wales coast. No doubt much of this material was derived from glacigenic sediments from the great Irish Sea Basin ice stream, draining the western portion of at least the last (Devensian) cold stage British Ice Sheet, and adjacent Welsh estuaries ~ many of which were carved as ice discharge routes during the same cold stage. It is thought that progressive post-glacial sea-level of > 100 m rise throughout the early-mid Holocene swept sediments onto the receding coastlines, effectively leaving a substantial near-shore sediment supply as sea-levels stabilised.

Thereafter, minor sea-level fluctuations coinciding with stormy periods (typical, *inter alia*, of short periods of global warming or cooling) probably stimulated episodic dune-building events, aided locally by other features of the Welsh coastline. Cardigan Bay ~ Wales' central, largest single coastal cell ~ lies across the predominant tidal and wind fetches from the southwest, although it is often observed that medium-coarse sand (requiring entraining wind velocities ≥ 6 m sec^{-1} or ≥ 22 km hr^{-1}) is often mobilised most during north-westerly gales. The north and south Wales coast cells are swept by tides and winds passing around the Llŷn and Pembroke headlands respectively, with longshore drift capable of extending sediment transfers. Tidal surge and sand transport directions shown in Figures 17.5 and Figure 17.6 in the main text underline their importance. Coastal dune systems in northern Cardigan Bay also strongly reflect north-east onshore and longshore drift sediment transfer influences on their location (Figure 17.18 in the main text).

By their very nature as soft-sediment landforms formed at the turbulent boundary of land, sea and air, coastal dunes are sensitive systems capable of rapid formation and decay. This is particularly well illustrated in the history of the Welsh coastline and other north-west European dune coats over the past millennium. The Medieval Climate Oscillation extended “trademark” climatic instability and more extreme weather events over several centuries, which we are experiencing again today with global climate change. Minor marine transgression and greater storm surge frequency pushed sediment shoreward and abandoned it during the subsequent regression. There are many cases of ports and farmland lost to storms, particularly on the European North Sea coast, and elsewhere onshore gales mobilized large volumes of dry sand in the backshore to form coastal dunes.

Many events of rapid dune development and the *ensanding* of settlements occurred on the coast of Wales during the later Medieval period. Approximate ages and rates of formation are known from radiocarbon dating, the dates of buildings and historical records. Dune slack peats yield ^{14}C dates showing rapid northward growth of a small dune system at Ynys Las in the mid-fifteenth century. The dunes surmount an older shingle ridge ~ a common occurrence on the Cardigan Bay and eastern Llŷn coastline ~ which bars the Dyfi estuary at Borth. Llangennith Burrows, a 3 km^2 dune ‘wedge’ enclosing the northern end of Rhossili Bay in Gower, finally ensanded a Norman church there after AD 1200 (Plate 1).

Plate 16.1 Looking north along the cliffs of Rhossili Down, on the western end of the Gŵr Peninsula (Gower), with Llangennith Burrows at the far end. Photo: Ken Addison

In Gower smaller dunes also bar Oxwich (Plate 2) and, at Three Cliff Bay, they ensanded Pennard castle, church and vicarage 50 m above sea level by AD 1525. The dunes cap a shingle storm bar, virtually blocking Pennard Pill's estuary to the sea and causing it to silt up with a tidal saltmarsh (Plate 3).

Plate 2 The dune system blocking Oxwich Bay on the south coast of Gŵr, trapping what is now a wetland nature reserve to its rear. Photo: Ken Addison

Plate 3 Late medieval dunes, now mostly eroded (far right) and an associated sand bar block. Pennard Pill, Gwr coast, south Wales, creating a salt-marsh lagoon. Photo: Ken Addison

The massive dune system of Newborough Warren and a smaller system near Dinas Dinlle straddle the western entrance to the Menai Straits (Plate 4), which separates Ynys Môn (Anglesey) from mainland north Wales, also lie across prevailing south-westerly tidal and wind flows. There are dunes at the eastern entrance to the Straits in their lee.

Plate 4 Semi-hard defences, in the form of a seawall fronted by constructed shingle banks and a transverse berm (mid-distance) protecting low-lying farmland and tourist infrastructure at Dinas Dinlle, on the Irish Sea coast of north-west Wales. A line of low dunes crests the shingle bank in the distance at the western end of the Menai Strait, across which can be seen the outline of Newborough Warren on Ynys Môn (Anglesey).

Dune formation initiated in a single storm on 6 December 1330 blocked the harbour and estuary at Aberffraw, on Anglesey, and ensanded valuable arable land (Plate 5).

Plate 5 The single barrier dune which blocks the old harbour at Abberfraw, impounding a wetland on its landward side. Photo: Ken Addison

Aberffraw was the ancestral court of the kings of Gwynedd and Princes of Wales. The mark of their eventual conqueror, Edward I, helps us to date the impressive dune systems of northern Cardigan Bay. Two large *morfa* or coastal marshes, each some 25 km^2, flank the coast for 20 km between the Mawddach estuary and Vale of Ffestiniog (see Plate 6).

Plate 6 Temperature and storminess in north-west Europe (a) The late medieval and pre-industrial period (AD 1000-1850), from proxy and documentary records. The broken line shows the long-term 'mean temperature'. (b) Observed and forecast changes 1850-2100, from direct observation and AOGCMs. Storm track activity is shown in geopotential metres (gpm) and the broken line shows the climate trend. Temperature forecasts after 2000 show 'the envelope of uncertainty' dependent on the nature and extent of human and natural systems responses. Source: (a) Partly after Lamb (1982), (b) Partly after IPCC (2001).

Their seaward edge is barred by shingle ridges capped with large dunes. Edward I's military strategy depended on a ring of seventeen castles isolating the granaries of Anglesey from the natural Welsh fortress of Snowdonia and – crucially – therefore stocked and garrisoned by sea. Harlech castle, built from AD 1283 with a water gate and small harbour like many others, was cut off from the sea by AD 1385 through dune formation 1 km seaward of the original rock shore (Plate 16.7). Dune formation and other coastal impacts of this stormy advent of the Little Ice Age changed the configuration and dynamics of substantial coastal stretches of Britain and Europe and built structures of known age help to date the geomorphic events.

Plate 7 The coastal dune system at Morfa Harlech, north Wales, which now isolates Harlech Castle (1 km inland, out of view) and formed subsequent to the castle's construction after AD 1282. Bare sand in the middle distance mark blow-outs associated with access routes to the beach. Photo: Ken Addison

These coastal dunes are now threatened, perhaps more than ever before, by a pincer movement between modern industrialisation, tourism and the impacts of global climate change shore (Plate 8).

Plate 8 Crymlyn Burrows in central Swansea Bay face Baglan oil refinery across the Nedd estuary ~ an agent, through carbon emissions and global warming that may soon engulf the dunes in rising sea level. Photo: Ken Addison

Tourism already threatens dune systems and their protected hinterland through trampling across the entire fore-dune front and blow-out along beach access routes, which rising sea levels, increased storm surge activity and offshore aggregates extraction will increasingly exploit. Dunes formed on offshore shingle banks, in particular, protect large areas of low-lying land to their rear, infilled by mud and peat in the shelter of the dune and shingle barrier. The protection of the unique natural habitats, human settlements and infrastructure on and behind dune systems, and the environmental history they reflect, is an important part of governmental and public-private agency work at the coastline. The Countryside Council for Wales (CCW ~ *Cyngor Cefn Gwlad Cymru ~ CCGC*) (see http://www.ccw.gov.uk) and National Trust (see http://www.nationaltrust.org.main/w-global/w-localtoyou/w-wales.htm) are major players in this respect on the Welsh coastline, *c.* 70% of which are protected under its designation as European Marine Sites, and the UK Biodiversity Action Plans contains a Habitat Plan specifically for coastal sand dunes (see http://www.ukbap.org.uk/UKPlans.aspx?ID=33).

Learning Objectives

- Appreciate the climatic and meteorological factors instrumental in establishing desert conditions, and the relative distinction between hot and cold desert environment.
- Understand the unique character of aeolian processes of weathering, erosion, entrainment and sedimentation.
- Describe the reasons for the development of significant dune systems at the land-sea interface in unlikely climate zones.

Essay Titles

1. Assess the respective rôles played by oceanic and tectonic influences on the location and form of desert landsystems?
2. Evaluate the important of weathering, running water and wind in shaping the hot desert landsystem and comment on the extent to which they are complementary.
3. Explain the ways in which layers of aeolian materials at the landsurface or in a stratigraphic sequence may assist in reconstructing environmental change.

Discussion Topics

1. Account for the geomorphic, microclimatic and biological ‘successions’ which characterise the progressive stabilisation of coastal dunes and highlight their current environmental sensitivities.
2. Compare the conditions which may enhance the risk of soil deflation from farmland in (a) Britain, (b) the United States or (c) Sudan.
3. Identify the processes which are important in the establishment of coastal dunes.

Further Reading

Goudie, A.S. (2002), *Great Warm Deserts of the World: landscapes and Evolution.* Oxford: Oxford University Press. An excellent compendium of the climatic background and geomorphological processes and landforms of Earth's hot deserts, by region.

Goudie, A. S., Livingstone, I., and Stokes, S. (1999) *Aeolian Environments: processes and landforms*, Chichester and New York: Wiley. A new compilation of work by authors who have previously published on aeolian subjects, which spans the full range of aeolian geomorphology. It commences with an historical perspective and concludes with the Quaternary context and predictions of future changes in the environment, all well illustrated graphically and with case studies.

Lancaster, N. (1995) *Geomorphology of Desert Dunes*, London and New York: Routledge. Sand dunes are the most widespread and evocative form of aeolian deposit, and this book focuses on dune processes, landforms and environments. The text is not unduly technical in style and is well illustrated.

References

Butzer, K. W. (1976) *Geomorphology from the Earth*, New York: Harper & Row

Carter, R. W. G. (1993) *Coastal Environments*, London and San Diego, CA: Academic Press

Collinson, J. D. (1986) 'Deserts' in H. G. Reading (ed.) *Sedimentary Environments and Facies*, second edition, Oxford: Blackwell, 95–112

Intergovernmental Panel on Climate Change (2001) *Climate Change 2001: the scientific basis*, Cambridge: Cambridge University Press

Lamb, H. H. (1982) *Climate*, *History and the Modern World*, Part I, Climate & History, London: Methuen, pp. 111-266

Livingstone, A. and Warren, A. (1996) *Aeolian Geomorphology: an introduction*, Harlow: Addison Wesley Longman

Warren, A. (1979) 'Aeolian processes' in C. Embleton and J. Thornes (eds) *Process in Geomorphology*, London: Arnold, 325–51

Web Resources

http://www.ccw.gov.uk/ The website of the Countryside Council for Wales (CCW ~ *Cyngor Cefn Gwlad Cymru ~ CCGC)*, accessible in Welsh or English, provides a wealth of knowledge, data, maps, images and policy statements covering all aspects of the protection and management of the Welsh landscape. Coastlines and coastal dune systems are entered under a number of headings worthy of exploration.

http://www.nationaltrust.org/main/w-global/w-localtoyou/w-wales.htm The website of the National Trust in Wales covering a number of aspects of the 133 miles of Welsh coastline it manages, including coastal sand dunes.

http://www.ukbap.org.uk/UKPlans.aspx?ID=33 The UK Biodiversity Action Plan's specific habitat plan for coastal sand dunes provides a detailed account of the typical dune habitat and includes access to a number of illustrations of dune ecology and processes.

A number of other useful websites are available under a search of *coastal sand dunes in Wales* and the Guardian newspaper published a topical article on coastal erosion in Wales in February 2007 available on
http:///guardian.co.uk/environment/2007/feb/13/frontpagenews.ruralaffairs

http://www.desertusa.com/life.html
An excellent and well-illustrated website of the southwest deserts of the USA ranging over their geological, geomorphological, climate, biosphere, peoples and cultural aspects. The site also runs a free newsletter and is a good source for images and videos of desert environments and alife.

http://pubs.usgs.gov/gip/deserts/contents/
Part of the US geological Survey website which, although not recently maintained, provides a comprehensive cover of desert climate, environments, processes, landsystems and further resources.

http://www.unccd.int/main.php
The website of the United Nations Convention to Combat Desertification provides an opportunity to look at dryland and desert areas from a wider and applied perspective than that of desert geomorphology but there are useful connections between both interests. The website provides access to scientific, socio-economic, management and policy aspects of desertification across the world.