15

Pans, playas and salt lakes

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15.1 The nature and occurrence of pans, playas and salt lakes

The arid zone contains few perennial lakes; examples such as the Caspian Sea, the Dead Sea and Lake Aral invariably have inflowing rivers rising in fringing uplands of distant humid areas. Instead, the majority of arid and semi-arid regions are characterised by endoreic (internal) drainage or, in extreme cases, may lack integrated surface drainage altogether. Under these circumstances surface depressions become important local and regional foci for the accumulation of water in episodic (termed here ephemeral) lakes. Due to the negative balance between evaporation and rainfall (often exceeding 10:1), these water bodies are often highly saline and, in some cases, supersaturated with salts. Such salt lakes, which have a minimum salinity of 5000 mg/L, in turn lie at one end of a spectrum of otherwise ephemeral and often relict closed basins of varying scales and origins, frequently termed playas or pans.

Pans and playas have been described in most hot dryland environments, particularly Africa, Australia, Arabia and in western USA (see Shaw and Thomas, 1997), but also occur in cold drylands such as Antarctic (Lyons et al., 1998). Although mostly associated with aridity – the majority of southern Kalahari and peri-southern Kalahari pans, for example, occur on the arid side of the 500 mm mean annual isohyet and the 1000 mm free evaporation isoline (Goudie and Thomas, 1985) – some comparable features are found beyond the limits of modern aridity, e.g. the Plains of Zambia (Goudie and Thomas, 1985; Williams, 1987) and the Darwin region of Australia (McFarlane et al., 1995).

Playas and pans vary in size from the frequently very small depressions of a few tens of square metres in the Kalahari, western Australia and Texas (Goudie and Thomas, 1985; Killigrew and Gilkes, 1974; Osterkamp and Wood, 1987) to massive tectonic basins, which may exceed 10,000 km$^2$ in area, such as Lake Eyre, south central Australia, and Lake Uyuni, Bolivia (Lowenstein and Hardie, 1985). Though pans and playas occupy as little as 1% of the total landscape, they are important and often numerous features. In parts of southern Africa pans attain densities of up to 1.14 pans per km$^2$ (Goudie and Thomas, 1985) and occupy 20% of the surface area (Goudie and Wells, 1995), while there are an estimated 30,000 to 37,000 basins on the southern High Plains of northwest Texas and adjoining New Mexico (Reddell, 1965; Osterkamp and Wood, 1987).

Playas and pans have been important to human populations from prehistoric times to the present day as sources of water and minerals. In modern times they have been used for urban development (Cooke et al., 1982), for airfields and racetracks (e.g. the Blackrock Desert, Nevada, USA) and in the case of Lop Nor, China and China Lake, USA, for testing nuclear weapons. Regrettably these uses conflict with the inherent value of pans and playas as extreme, unusual and often valuable habitats (e.g. Haukos and Smith, 1994; McCulloch et al., 2008), while development itself is not without difficulties, as the flooding of Salt Lake City in the 1980s shows (Atwood, 1994). Scientifically they have become increasingly important for the elucidation of palaeoenvironmental conditions from their sediments and landforms (e.g. Telfer and Thomas, 2007), while on the negative side, they are now recognised as major sources of atmospheric dust (Gillette, 1981; Prospero et al., 2002), and are monitored accordingly.

Arid Zone Geomorphology: Process, Form and Change in Drylands
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15.2 Playa and pan terminology

Arid and semi-arid lacustrine basins have a rich terminology, particularly in Asia and the Middle East (Shaw and Thomas, 1997). The most commonly used terms, pan and playa, are interchangeable, with an increasing tendency to use pan for small basins formed by arid zone geomorphological processes (Goudie and Wells, 1995) and playa for a depression with a saline surface (Rosen, 1994). However, the many descriptors in regional usage and with approximately equivalent meaning has led to confusion in terminology. For example, attempts to restrict the application of terms such as sebkha to the coastal environment have not been widely adhered to, while recent attempts to introduce broad terms such as semi-arid basin (Currey, 1994) have done little to clarify the issue. A major concern has been the permanence and provenance of the lacustrine system.

In a review of terminology, Briere (2000) attempted to group terms into the categories of playa, playa lake and sebkha (Figure 15.1) and offers the following revised definitions:

**Playa.** An intercontinental arid zone basin with a negative water balance for over half of each year, dry for over 75% of the time, with a capillary fringe close enough to the surface such that evaporation will cause water to discharge, usually resulting in evaporates (Briere, 2000, p. 3).

**Playa lake** An arid zone feature, transitional between playa and lake, neither dry more than 75% of the time nor wet more than 75% of the time. When dry, the basin qualifies as a playa (Briere, 2000, p. 3).

**Sabkha.** A residual marine mudflat where displacive and replacive evaporate minerals form in the capillary zone above a saline water table (Briere, 2000, p. 4).

These definitions have some merit, particularly as they eliminate the need for the definition of a continental or inland sabkha, a step not met with approval by some (e.g. Barth, 2001). They fail, however, to cover clay-floor pans with little hydrological input such as the features of Texas and the Kalahari.

A broader definition of pans or playas can be arid zone basins of widely varying size and origin, which, although generally above the present groundwater table, are subject to ephemeral surface water inundation of variable periodicity and extent. Their basal and marginal sediments often display evidence of evaporite accumulation, aeolian deflation and accumulation and/or lacustrine activity.

The term **coastal sabkha or sebkha** (Glennie, 1970) originally applied to saline flats in arid areas that occur above the level of high tide, but nevertheless receive periodic marine incursions and associated sediments. They have many of the features and processes of inland playas (Yechieli and Wood, 2002); indeed there is a recognised continuum between coastal flats and inland playas which receive sea water (Bye and Harbison, 1991). However, coastal sebkhas are not considered in this chapter.

15.3 General characteristics

Despite the variability of pans and playas, a number of common characteristics emerge. Most obvious is that pans occupy topographic lows, though not necessarily the lowest areas in enclosed drainage basins, because small pans can develop almost anywhere in relatively flat arid landscapes, e.g. along deranged drainage lines (Osterkamp and Wood, 1987). With larger playas there is inevitably a strong geological control on form (e.g. Salama, 1994).

Topographic position and geological framework may both influence a groundwater regime and hence the formation processes. This is nowhere more apparent than in the boinkas (groundwater discharge areas) of southeast Australia (Jacobson, Ferguson and Evans, 1994), where contemporary playas are nested in the topographic lows of larger groundwater-controlled landscapes and geologically older lake basins.

In terms of surface hydrology they are essentially ‘closed’ systems, having no surface outflow. The dominance of potential evaporation (PE) over precipitation (P) and other inputs is the essential contributory factor to closed status. Hydrological inputs may be direct precipitation, surface or subsurface inflow, or any combination of the three. Standing surface water is ephemeral, accounting for the distinct morphological and sedimentological differences between arid basins and those of more humid areas. The extent, frequency and length of surface water occupancy depends on climatological and hydrological regimes, and is a major source of pan and playa variability. Overall, arid and humid closed basins can be viewed as part of a climate-based spectrum ranging from 0 to 100% surface water occupancy at its extremes, each with a distinct morphology and processes (Bowler, 1986).

Much research has focused on the role of groundwater in pan formation and function, particularly in terms of interaction with surface processes (Fryberger, Schenk and Krystinik, 1988; Osterkamp and Wood, 1987; Torgersen, 1984; Torgersen et al., 1986; Rosen, 1994; Yechieli and Wood, 2002; Reynolds et al., 2007) and of the origins of the brines themselves (Bye and Harbison, 1991; Herczeg...
The nomenclature of playas, playa lakes and sabkhas (after Briere, 2000). In this scheme, each term in a given set has been used synonymously or interchangeably with the header of that set. Arrows connect sets that are joined by at least one common term. Asterisks denote terms that may help the reader follow the chart's flow. For original references see Briere (2000).

Figure 15.1 The nomenclature of playas, playa lakes and sabkhas (after Briere, 2000). In this scheme, each term in a given set has been used synonymously or interchangeably with the header of that set. Arrows connect sets that are joined by at least one common term. Asterisks denote terms that may help the reader follow the chart's flow. For original references see Briere (2000).
Figure 15.2 Playas and pans with contrasting groundwater depths: (a) Chott el Djerid, Tunisia, a discharge playa with groundwater at the surface (foreground) and evaporate mineral accumulation (background); (b) Silver Lake, USA, a clay-floored recharge playa, with little or no evaporate mineral accumulation at the surface.

and Lyons, 1991; Jankowski and Jacobson, 1989; Bryant et al., 1994a, 1994b). Not only is the role of groundwater important in pan and playa formation, but there is again a spectrum of conditions and subsequent effects present. These range from pans and playas where the groundwater table intersects the basin surface (Figure 15.2(a)), accompanied by surface evaporite accumulation and evaporative effects, as in the Chotts of Tunisia (e.g. Roberts and Mitchell, 1987; Bryant et al., 1994), to those where the water table lies at depth (Figure 15.2(b)). These latter features are usually clay-floored and percolating groundwater plays a major role in deep weathering and eluviation. Such variations are thus a function of topography and geology rather than climate.

Surfaces are usually vegetation-free, particularly at their lowest elevations. Episodic flooding, vertisol or solonchak formation and salt accumulation discourage vegetation growth, although halophytic plants and shallow rooting grasses may be established. Grasped pans exist alongside bare clay surfaces, as in the Kalahari (Boocock and Van Straten, 1962), suggesting small variations in soil alkalinity and wind action. Butterworth (1982) has proposed a cycle of development linking grassed and clay pans.

15.4 Origins and development of pans and playas

Pans and playas have a variety of origins, which can be classified into structural, erosional and ponding controls (Table 15.1 and Figure 15.3). A few have more dramatic origins: Pretoria Saltpan (South Africa), Zuni Salt Lake (New Mexico) and Meteor Crater (Arizona) have been
attributed to the impact of meteors or volcanic crater development (Wellington, 1955; Mabbutt, 1977; Goudie and Thomas, 1985).

Faulting and downwarping have led to the development of major regional basins of interior drainage in some arid environments. For example, Cenozoic tectonic activity, including block faulting, has been responsible for the concentration of the intermontane basins in the 'Great Basin' and the 'Basin and Range' desert regions of the southwestern United States (Smith and Street-Perrott, 1983, and see Chapter 4). Gentler Cenozoic tectonism has contributed to the development of the Etosha and Makgadikgadi basins in southern Africa (Wellington, 1955; Thomas and Shaw, 1988) and the Eyre Basin in Australia (Johns, 1989). Many of these large basins have responded to major local and regional hydrological inputs by developing massive lakes responding to Quaternary climatic fluctuations. These changes in hydrologic status are preserved in the sedimentary record or in former shorelines (strandlines), and have been termed playa-lake complexes by some authors (e.g. Eugster and Hardie, 1978; Eugster and Kelts, 1983). In some cases the lakes have lost their closed status and overflowed at times, as in the Bonneville and Lahontan Lakes of the Great Basin (Benson et al., 1990).

On a smaller scale, lineaments, by acting as conduits for groundwater movement, are the preferential sites for the development of smaller pans, as suggested for some of the features of the Texas High Plain (Osterkamp and Wood, 1987) and the south and southeast Kalahari (Arad, 1984; Shaw and De Vries, 1988). Intruded bodies at depth found in association with lineaments may also influence pan location, as indicated by the geophysical studies of Lokware and Mogatse pans in the Kalahari (Farr et al., 1982) and the influence of dolerite sills on the pans of the Lake Chrissie complex in the eastern Transvaal (Welling- ton, 1955). Ponding may also occur in the linear depressions (straats) between longitudinal dunes, as in parts of the Kalahari (Mallick, Habgood and Skinner, 1981), between strandlines of palaelakes, as in the Dautsa Ridge sequence of Lake Ngami (Shaw, 1985), or, by obstruction of ephemeral channels, the extension of dunes as cited with reference to western Australia (Gregory, 1914) and the Namib Sand Sea (Rust and Wieneke, 1974).
Erosional processes, such as deflation, contribute to the formation of the larger structural basins, as in the Qattara and Siwa Depressions, Egypt (Gindy, 1991), but are especially important in the genesis of smaller local or subregional-scale features. Both aeolian deflation and removal of material by solution during deep weathering have been proposed as erosional mechanisms, but, as the debate on small depressions in, for example, Texas and New Mexico (Reeves, 1966; Carlisle and Marris, 1982; Osterkamp and Wood, 1987; Wood and Osterkamp, 1987) shows, there is a strong case for a polygenetic origin for many small pans. Deflation has often been cited as an originator or contributor in pan development, e.g. Egypt (Haynes, 1980), the Kalahari (Lancaster, 1978a), Australia (Hills, 1940; Bowler, 1973), Texas (Reeves, 1960), the Argentine Pampas (Tricart, 1969) and Zaïre (de Ploey, 1965). For deflation to be effective the criteria necessary for aeolian entrainment must be satisfied, while a near-surface groundwater table in a playa can act as a base-level control on the depth of deflation. Of special importance is the susceptibility of surfaces to deflation (Goudie and Thomas, 1985), both in terms of material susceptibility and the absence of a protective vegetation cover. The latter may be affected by concentration of salts (Le Roux, 1978) or seasonal surface inundation (Bowler, 1986). In this respect Osterkamp and Wood’s (1987) observation that any slight depression in an otherwise flat surface has the potential to develop into a pan or playa should be noted.

The role of deflation in playa and pan development may be indicated by the presence of fringing transverse or lunette (Hills, 1940) dunes on the downwind margin of the depression, or, indeed, by orientation of the pan transverse to prevailing winds (see Le Roux, 1978; Goudie and Thomas, 1985; Bowler, 1986). Some authors (e.g. Wood and Osterkamp, 1987) have opposed the deflationary hypothesis on the grounds that the volume of sand in the fringing dune does not represent the volume removed from the pan. However, deflated sediment can be transported beyond the margins of depressions and into the atmospheric circulation (Reheis, 2006). A more serious objection is the observation that, in many Kalahari pans, the material comprising the lunette have different sediment characteristics to the pan surface (Goudie and Thomas, 1986).

Solution, piping and subsurface karstic collapse may be locally important mechanisms in areas underlain by carbonate and other sedimentary lithologies. Wood and Osterkamp (1987) propose a model for the formation of small clay-floor ed pans based on studies of the Texas High Plains, where pan development has taken place in post-Pliocene times under arid to semi-arid conditions in a variety of sedimentary strata in response to lowering of the regional water table. During initial development, depressions originate by various means, including deflation, drainage ponding and along structural lineaments. Proto-basins act as sites of seasonal runoff concentration on the relatively flat plains surface and through which groundwater recharge occurs. This results in subsurface locations in the unsaturated zone becoming foci for oxidation and carbonate dissolution, leading to piping development and the disintegration of the calcrete, thus contributing to basin enlargement.

This model accords well with other regions of small pans unaffected by groundwater inputs, such as the Kalahari, although here percolating water rarely reaches the water table under present climatic conditions, leading to the precipitation of fresh calcite at depth. The contention of Wood and Osterkamp (1987) that pans are capable of enlargement by peripheral weathering is backed by the observation of Farr et al. (1982) that some pans in the Kalahari are capable of migration over a long period of time.

The excavations and trampling of animals were seen as important factors in forming depressions by early investigators in Texas (Gilbert, 1855) and the Kalahari (Allison, 1899; Passarge, 1904). While clearly inapplicable to the evolution of larger basins, animal activity has been observed to contribute to depression development in areas of seasonally limited water supplies (Weir, 1969; Ayeni, 1977; see Thomas, 1988, for a review). Termites have also been implicated in the formation of small, highly saline pans on islands in swamp ecosystems, such as the Okavango Delta (McCarthy, McVeer and Cairncross, 1986).

The mechanisms proposed require suitably susceptible surfaces. In southern Africa, pans are preferentially found on lithologies, which readily break down to fine-grained sediments or which are generally poorly consolidated (Goudie and Wells, 1995). Susceptibility may be enhanced in lithologies that contain significant amounts of sodium sulfate, which enhances salt weathering and results in plant growth, or clays such as bentonite, which have high coefficients of expansion on hydration. Extensive low-relief terrain also seems to favour pan development, as in Texas and southern Africa. Such surfaces limit the potential to develop integrated drainage and promote the concentration of both moisture and fine-grained clastic material into surface depressions.

Playas are also aggradational features, deriving sediment through episodic inflows or aeolian inputs. The sediments that are received are almost exclusively fine-grained, which can be explained in three ways. First, where playas represent drainage terminals, only fine...
The aggradational attributes of playas contribute to their usually flat, horizontal surfaces, especially in the subenvironments subject to inundation. Given the fine-grained nature of the sediments, any irregularities, including those derived from evaporite growth (see Lowenstein and Hardie, 1985), are smoothed out by water movement and dissolution when surface water occupies the basin. Playas with highly infrequent (possibly not recorded in historical times) surface water inundation may develop uneven surfaces through evaporite growth or sand dune development. The extension of dunes (Bowler, 1986) and fluvial distributaries (Townshend et al., 1989) on to playa surfaces from surrounding areas may also lead to uneven margins.

15.4.1 Pan hydrology and hydrochemistry

Several sedimentary subenvironments exist in playas and pans. The processes involved can be grouped into those resulting in deposition on the basin floor, the basin sub-surface and the basin margins. Deposition in basin margin locations is not necessarily directly related to the processes operative in the basin itself. Depending on...
Figure 15.5 Sources of groundwater to a playa basin: 1, channelled flow in permanent or ephemeral streams; 2, unrestricted overland flow (sheet wash); 3, hydrothermal fluids from a deep source (may occur as a seep or spring or directly mix into the groundwater); 4, connate or formation water derived from when the formation was deposited; 5, meteoric groundwater derived within (hydrologically closed) or outside (throughflow) the immediate basin; 6, direct precipitation on to the playa surface or surrounding catchment (after Rosen, 1994).

individual basin settings, marginal sedimentation can be achieved by the activity of ephemeral rivers, alluvial fans, sand seas or, more rarely, by mass movement processes.

The dominant sediment types encountered within the basin are fine sediments brought in by surface flow or aeolian action, organic materials and evaporite minerals. The main ions encountered are SiO$_2$, Ca$^{2+}$, Mg$^{2+}$, K$^+$, Na$^+$, Cl$^-$, HCO$_3^-$, CO$_3^{2-}$ and SO$_4^{2-}$, which are derived from both the surface and groundwater catchments.

Hardie, Smoot and Eugster (1978) note that weathering reactions and catchment lithology are the first determinants of the types of salts precipitated within the basin, although airborne salts may be important in coastal locations (Jack, 1921; Eckardt and Spiro, 1999) and have, in the long term, contributed to inland playas as well (Chivas et al., 1991; Jones, Hanor and Evans, 1994). Precipitation, in turn, is controlled by salt composition and concentration and the relative influence of the surface and groundwater regimes (Rosen, 1994) (Figure 15.5). Given the range of solute sources, transport mechanisms and evaporative regimes in playa basins, it is important to note the geochemical diversity of the evaporite deposits that can accumulate within any one basin over time.

### 15.5 Inflow and water balance modelling

The hydrological regime affects pan development and morphology in two ways: first, in relation to external factors such as climate and catchment; second, in the relationship between the surface water and groundwater inputs within the basin. Bowler (1986) addresses this first control in his model of a six-stage hydrological sequence for closed basins in Australia. The stages range from a lake with permanent surface water at one end of the continuum to an ephemeral terminal sink totally controlled by groundwater at the other (Figure 15.6). A disequilibrium index, $\Delta L$, calculated from hydrological and climatic data, was also used to relate present conditions in a basin to those necessary to maintain a steady-state water cover, with values ranging from 0 in presently perennial basins to $-1000$ for those currently in the driest locales. While the results, in ignoring many of the other basin variables, are not universally applicable, they serve to emphasise the difference between surface water and groundwater processes, both in terms of the nature of the waters and sedimentation and in their interrelationships, particularly within the flooding–desiccation cycle.

Rosen (1994) addresses the second control and summarises the importance of groundwater depth in...
Hydrological classification, idealised morphology and groundwater–surface water interaction of evaporative basins

Eyre in 1950, which covered 8000 km², evaporated two years later to leave only a thin layer of halite over an area of about only one-tenth of the original flood, while Holser (1979) estimated that the evaporation of a 200 metre depth of surface inflow would be necessary to produce a 3 metre thickness of the same mineral. Smoot and Lowenstein (1991) point to the importance of repeated inflow into playa basins over long time periods in order to allow the development of stable surface salt deposits in the intervening dry periods through a net increase in the salinity of shallow groundwater, which eventually inhibits complete salt pan dissolution. The interval between episodes of surface inundation is therefore important for sedimentation, as surface water halts evaporation from subsurface water and leads to resolution of salts. Eugster and Kelts (1983) point out that the Great Salt Lake, Utah, has only deposited major halite beds in historic times on two occasions, 1930–1935 and 1960–1964, coincident with periods of drought.

Mass budget modelling (e.g. Yechieli and Wood, 2002; Tyler, Munoz and Wood, 2006) suggests that water and aeolian budgets in playas are often in dynamic equilibrium, while the salt budget may display a lag of thousands of years and reflect palaeohydrological conditions (e.g. Wood and Sanford, 1990). This, in turn, impacts on model parameters. In an open-system playa with constant water volume both the concentration and mass of solutes will increase with time, while a closed-system playa with declining water volumes, as implied by a drying climate,
Geochemical processes and mineral precipitation

Increasing near-surface salinity, resulting from either climatic or hydrological factors, can result in evolution from clay-filled pans to salt pans containing evaporites. As already noted, the chemistry of inflowing water is largely dependent on solute output from the catchment; the subsequent evolution of evaporites will be dependent on the ratios of solutes present and the precipitation gradient of the salts involved. From an understanding of fractional crystallisation of mineral phases resulting from the evaporation of seawater (e.g., a sequence with increased evaporation of calcite, anhydrite/gypsum and halite followed by epsomite, syline, kainite, carnallite and borates/celestite; see Valyashko, 1972), we can gain some idea of the relative type and proportion of evaporite phases that may be present in playa basins. However, given their extreme chemical variability, most nonmarine saline waters do not follow this template. Hardie, Smoot and Eugster (1978) identified four main brine types resulting from a series of evaporative concentration steps on undersaturated inflow for nonmarine brines, a model that has been subsequently modified by others (see Jankowski and Jacobson, 1989; Rosen, 1994). These represent an accepted set of geochemical pathways along which most nonmarine evaporites develop within playa basins (Figure 15.8(a)).

The three pathways outlined by Eugster and Hardie (1978) use the relationship between the molar content of bicarbonate (HCO$_3$) relative to molar Mg + Ca for all inflow waters to determine the ultimate brine type and mineral assemblage that may result from evaporation. In all, these authors identify five end-member brine types for nonmarine waters and a number of key mineral phases that are associated with their evaporation (Figure 15.8(b)). In this scheme, initial evaporation and degassing (Eugster and Kelts, 1983) leads to the progressive precipitation of low-Mg calcite, aragonite and high-Mg calcite (protodolomite), followed by gypsum (CaSO$_4$·2H$_2$O) at concentrations of 40–100 g/L (Bowler, 1986), dependent on the type and duration of processes in the evaporation zone. Gypsum precipitation is also dependent on the degree of carbonate depletion. Halite (NaCl) saturation occurs at around 200–350 g/L, while other
common salts include trona (Na$_2$CO$_3$, NaHCO$_3$, 2H$_2$O), thenardite (Na$_2$SO$_4$), epsomite (MgSO$_4$, 7H$_2$O) and burkeite (Na$_2$CO$_3$, 2Na$_2$SO$_4$). Where sodium-rich brines come into contact with deposits of gypsum or calcite, double salts, such as glauberite (CaSO$_4$, Na$_2$SO$_4$) or gaylussite (Na$_2$CO$_3$, CaSO$_4$, 5H$_2$O), may be formed. Less common evaporites are potassium and magnesium chlorides (e.g., carnallite), which are found in the Qaidam Basin of China (Yuan, Chengyu and Keqin, 1983; Chen and Bowler, 1986; Bryant et al., 1994a), and nitrates, as in the saltpetre-rich Matsap Pan of South Africa (Wellington, 1955). The three pathways (I, II and III in Figure 15.8) are generally found to be characteristic of volcanic terrains (path I), seawater (path II) and the recycling of ancient carbonate or evaporates (path III).

Evaporation and salt precipitation rates represented in the Eugster and Hardie (1978) scheme are controlled by the thermodynamic activity of the water (Langmuir, 1997); for any given set of pressure and temperature conditions an increase in dissolved ions reduces the ability of the water to evaporate. This relationship, expressed by the Pitzer equations (Pitzer, 1987), suggests that the evaporative potential of concentrated brine is about half that of pure water. There are also variations in the precipitation of individual salts, with those minerals of retrograde solubility, such as gypsum, anhydrite and calcite, precipitating at high temperatures, while sodium and magnesium chloride become supersaturated as temperatures fall. This leads to variations in salt populations on diurnal to seasonal scales (Yechei and Wood, 2002).

In broad terms the increasing concentration of brine leads to a zonation of the evaporates by solubility. In individual salt pans this leads to a "bulls eye" effect of lateral zonation of facies from carbonates at the edge, through sulfates to chlorides in the sump (Jones, 1965; Hunt et al., 1966). This zonation will also be apparent in the texture of...
of the pan surface, with a transition from the peripheral clay floor to a soft mud with surface efflorescence, described as ‘self-raising ground’ (Mabbutt, 1977), which represents the capillary fringe of the groundwater. This, in turn, gives way to a salt crust whose thickness is dependent on the frequency of surface flooding and groundwater characteristics, and to a brine layer if present. The concentric surface zonation of salts may be mirrored by a vertical zonation as a result of variations in solubility, with the most soluble minerals at the surface, or as a response to subsurface processes, particularly reduction (Neev and Emery, 1967; Rosen, 1991; Bryant et al., 1994a).

15.7 The importance of groundwater: classification of playa and pan types

The position of the water table has been used as the basis of classification of playas by Mabbutt (1977), Wood and Sanford (1990) and Rosen (1994) (Figure 15.9). In pans where the water table lies at depth, features defined as recharge playas by Rosen (1994), there will be little interaction between the surface and groundwater, and sedimentation will occur in a shallow surface and subsurface layer, with overall transfer of water towards the water table. These pans usually have clay or vegetated surfaces, with little sign of evaporite accumulation. Conversely, saline basins with near-surface water tables have complex transfers of water and salts along physical and chemical pathways in three dimensions, leading to the accumulation of surface crusts and displacive evaporites. Clay-floored pans are characteristic of regimes with low groundwater input or where the surface lies above the influence of capillary rise from the water table, a depth of usually about 3 metres (Rosen, 1994). Usually they are composed of a flat clay or sandy clay surface, either as the base of a pan or as a higher surround to a more saline basin (Mabbutt, 1977). The dominant sediment is clastic material deposited from suspension during inundation, although lenses of sand may be deposited under higher energy conditions. The clay surface, in turn, forms an impervious layer to groundwater recharge at the pan centre. Reynolds et al. (2007) describe clay-floored pans as ‘dry’ playas, which are unlikely to be susceptible to deflation or dust production (Figure 15.7(a) or (b)). Salt input is generally low to basins of this type. Precipitation of calcium and magnesium is common, producing a range of carbonates from calcite to dolomite, dependent upon the Ca/Mg ratio (Müller, Irion and Forstner, 1972), as cements, laminates, crusts or other structures (Eugster and Kelts, 1983). Gypsum efflorescence may follow the drying of the clay surface, while silica mobility is also apparent; silcretes as well as calcretes are found in both
the bed and periphery of pans in semi-arid environments (Summerfield, 1982).

Where the water table lies close to, but does not intersect, the pan surface (Figure 15.7(c)), three zones may be identified: (a) a saturated zone; (b) a porewater zone in which capillary rise, enhanced by surface evaporation, occurs; and (c) the surface crust (Tyler, Munoz and Wood, 2006). These zones will change in extent, laterally and vertically, with water table changes, leading to corresponding changes in the surface sediments. Evaporative concentration through this system, whether the groundwater intersects the surface or lies below it, is controlled not only by rates of evaporation but also by groundwater salinity and density, hydraulic conductivity of the aquifer and the depth of the porewater zone (Bowler, 1986). Changes within the porewater zone, termed ‘shallow interstitial waters’ by Bowler, have profound effects on the ultimate character of the playa. For example, evaporation within this zone will cause variations in water density, often to great depth, enhancing vertical and horizontal transfers of groundwater to balance the salinity gradient. Reynolds et al. (2007) refer to playas of this type as ‘wet’ playas and highlight the importance of groundwater depth to surface characteristics and deflation rates.

Salts precipitate within this system as surface crusts, or by interstitial crystallisation within existing sediments, or as subaqueous evaporites in brine pools. Salt emplacement can arise by direct crystallisation from the brine or by reaction between the brine and surrounding sediments and organisms.

15.8 Implications of climate change and human impacts on playa hydrology

It is important to understand how changes in water balance, driven either by climate forcing or human intervention, might affect any equilibrium that may exist between these components. Human impacts on the hydrology of playa basins can often be both rapid and quite dramatic. In recent years, a number of notable closed basin lakes or playas (e.g. Figure 15.7(d)) that were initially fed by perennial rivers have undergone dramatic changes in water balance due to upstream water diversions, e.g. Owens (dry) Lake, USA, and the Dead Sea in the Middle East. Subsequently, human interventions have resulted in either partial or complete desiccation of the lakes and significant associated falls in regional groundwater levels (e.g. Figure 15.7(c)). In each case, desiccation has led to an accumulation of evaporite minerals at the surface (e.g. Benson et al., 1996; Tyler et al., 1997) and aeolian deflation at the lake margins (Gill, 1996). In the case of the Salton Sea, USA, human intervention initially led to an accidental diversion of the Colorado River’s flow into the formerly dry Salton Sink in 1905. After this period, the lake, which sits 70 m below sea level, has been maintained through agricultural return flows from the Imperial, Coachella and Mexicali Valleys (90% of total inflow), and the lake has gradually become an important biodiversity and recreational resource. However, fluctuations in water balance and salinity have led to dramatic lowering in lake level and peripheral desiccation in recent years, with associated increases in salt deposition, aeolian deflation and environmental concern (Gill, 1996).

Tyler, Munoz and Wood (2006) use a coupled (soil physics, climate data, geochemical processes) model to understand water table responses to climate change. They found that for playas with a shallow water table (<=0.5 m) (Figure 15.7(c)), relatively modest changes in water table depth would result from an increase or decrease in water table balance (inflow/evaporation). They also note that the surface sediments of these playas often have a saturated vadose zone and therefore, due to a lack of storage capacity, can respond rapidly (e.g. by flooding) to changes in inflow (Bryant et al., 1994a; Drake and Bryant, 1994; Bryant and Rainey, 2002) or atmospheric pressure (Turk, 1975) without any necessity for climate forcing. However, where water tables are naturally deeper (>0.5 m) they found that water table changes may be much greater when accommodating similar changes in water balance, but the changes may also significantly lag behind climate forcing. When additional processes were factored in (e.g. the precipitation of minerals in the sediment column, influx of aeolian material) it was evident that changes in base level can occur without direct climate forcing due to changes in sediment pore space and associated hydraulic conductivity within the undersaturated zone above the water table.

In each case we can see that climate forcing and human intervention can lead to significant changes in ground-water levels, which can in turn impact on the status and equilibrium of playas. Playas have long been recognised as having recorded important information relating to past changes in climate (Jorgensen et al., 1996) and in most cases the surface hydrological regime responds in a predictable but lagged nature to climate forcing. However, it is also possible that, in some circumstances, changes in hydrological balance can occur in terminal discharge playas without the need for climate forcing. Human interventions in playa basins can at the very least allow us to study the impact of changes in hydrological regime on playa processes. Nevertheless, the rapid and short-term nature of changes in any hydrological/geomorphological
Pan topography

15.8.1 Influences of pan hydrology and hydrochemistry on surface morphology

Pan surfaces change over time in the course of the pan cycle (Lowenstein and Hardie, 1985). While Stage 1 (flooding) is normally very rapid, it is worth noting that Stages 2 to 4 can take a variable period of time (0.5-100 years) depending on the nature and level of groundwater interaction with inflow. In all cases, however, influx of surface water halts evaporative loss from groundwater, reverses many of the reactions in the interstitial zone and sets up new gradients between the surface and groundwater bodies. It also introduces 'fresh' clastic material from inflow and from the atmosphere, which settles on the lake bed and provides an environment for organisms that play a part in overall sedimentation (Bryant et al., 1994a). Diatoms, which store SiO$_2$ (Neev and Emery, 1967), and algal mats, involved in the precipitation of carbonates and the formation of kerogen-rich organic layers (Brock, 1979; Grant and Kelts, 1983), or when wet; on drying, crystal expansion and precipitation, producing thrust surfaces up to 2 m in diameter (Eugster, 1978). Surface flaking, with gypsum precipitation, is also common.

As surface waters evaporate (Stage 2) they become increasingly brackish, leading to precipitation of salts at the periphery of the water body and on the surface of the brine as precipitation thresholds are reached. These crystals, initially held by surface tension, sink to the lake floor and become nuclei for further, distinctive patterns of crystal growth (Lowenstein and Hardie, 1985). They may also be concentrated by wind action (Stage 3) into arcuate bands known as salt ramps (Millington et al., 1995), which persist as minor landforms after evaporation of the brine. The desiccation of the pan surface (Stage 4) will lead to further interstitial crystal growth and dissolution, and an eventual return to the groundwater dominated regime. In instances where these stages (1-4) represent the long-term drawdown of the groundwater table in response to climate changes or anthropic intervention, an additional stage (Stage 5) representing degradation and reworking of the pan surface through deflation of evaporate minerals and silt-clay sediment (e.g. dunette formation) and fluvial reworking can occur (Bowler, 1986). Given the continual reworking of surface crusts and sediments within the pan cycle, it is not surprising that evaporite deposits do not persist as sedimentary strata in many playas and, when they do so, may take thousands of years to accumulate. Many of the larger salt lakes owe their extensive evaporite deposits, usually in the form of a series of mud-salt (Hardie, Smoot and Eugster, 1978) or protodolomite-gypsparite couplets (Dukiewicz and van der Borch, 1995), to the gradual or repeated desiccation of larger water bodies by climactic change or tectonic activity, as in the case of Lake Magadi (Kenya), Lake Bonneville (USA), the Makgadikgadi Pans (Botswana) and the Dead Sea (Israel-Jordan). In a number of instances (e.g. playas in Tunisia and Australia) evaporate preservation is relatively poor, with salt crusts (often 0.1-1 m) often being partially or completely dissolved by groundwater or surface water inflow (e.g. Bryant et al., 1994a). This can lead to the net accumulation of clay-silt sediment, which is only capped by the thin salt crust during desiccation.

15.9 Pan topography

Pan surface morphology is the product of periodic flooding and desiccation, including: (a) rainfall effects, (b) groundwater depth, brine concentration and associated crystal growth and dissolution at or near the sediment surface and (c) aeolian deflation. Given the potential dynamism of these three factors, surface features themselves are among the most ephemeral of geomorphological phenomena, some lasting no longer than the interval between one rainfall event and the next. Haloturbation is an important process, usually involving gypsum or halite. In the saline mudflat and saline pan environments surface cracking is apparent, leading to polygon formation. Thin hard crusts of carbonates or puffy crusts of more soluble minerals may appear on drying (Hardie, Smoot and Eugster, 1978). Surface flaking, with gypsum precipitation, is also common. Salt crusts have smooth surfaces only while above the level of capillary action, as at Bonneville Flats (Eugster and Kelts, 1983), or when wet; on drying, crystal expansion leads to the formation of salt blisters and salt polygons, the latter up to 10 m in diameter (Kirmsley, 1970) (Figure 15.11). Plate boundaries become foci for evaporation and precipitation, producing thrust surfaces up to 50 cm above the pan floor and capable of lifting gravel size material. Extrusion at the plate edges may lead to the formation of mud and salt pinacles (Figure 15.12(a)). Subsequent inundation and desiccation leads to a fresh cycle of polygon development.

Under aridic conditions groundwater effluents may be marked by the growth of spring mounds or dissolution of salt karst chimneys (Last, 1993), known collectively as ouaan in North Africa (Roberts and Mitchell, 1987) (Figure 15.12(b)), and tufa deposits, partly organic in

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\text{equilibrium that can occur often lead to a range of significant and far-reaching and often negative environmental impacts (Gill, 1996).}
\]
Figure 15.10 The saline pan cycle for a typical playa; this example is taken from the Chott el Djerid, Tunisia, and charts the cycle (and associated brine geochemical evolution) as it occurred after an extreme flood event in 1990 (after Lowenstein and Hardie, 1985, and Bryant et al., 1994a, 1994b).
15.10 Surface dynamics: mapping pan surface morphologies using remote sensing

Because of the difficulties of field investigation of pans and playas (Millington et al., 1989), remote sensing data have been applied to the study of playa basins in a number
of instances in order to overcome these issues and gain important initial information or to augment ongoing research into: (a) surface geochemistry and geomorphic mapping, (b) hydrology and hydrological balance and (c) studies of dust emissions. Examples of each are outlined below.

As an understanding of surface mineral distributions can elucidate playa basin geochemical processes (Hardie, Smoot and Eugster, 1978) and groundwater regime (Rosen, 1994; section), remote sensing data have been used to map evaporite mineral assemblages on playa surfaces in a number of instances. Millington et al. (1989) use remote sensing data to undertake simple interpretation of playa surfaces. However, subsequent work by Crowley (1991) and Drake (1995) have allowed a link to be made between the mineralogy and surface reflectivity (0.4–2.5 μm) of a wide range of salt phases and geochemical contexts. These data have facilitated the application of a range of remote sensing approaches to both evaporite mineral mapping and facies mapping to a limited number of playas (e.g. Bryant, 1996; Castañeda, Herrero and Casterad, 2005a; White and Eckardt, 2006). Crowley and Hook (1996) and Katra and Lancaster (2008) have also utilised multispectral thermal infrared data to map mineral phases and surface types (Figure 15.13). However, despite the potential outlined in these studies, and the often routine use of playas as calibration sites for remote sensing systems, the use of remote sensing in this manner has perhaps been limited due to: (a) the often complex (heterogeneous) nature of many playa surfaces in relation to pixel size, (b) the changeable and intermittent nature of playa processes, (c) the often nonpristine nature of many mineral assemblages relative to reference data, (d) the presence of surface moisture (e.g. Bryant, 1996) and (f) the need for ground validation data (Bryant, 1996).

Changes in playa water balance can occur over short (e.g. day–month) or long (decade–century) timescales. Mapping presence or absence of surface water on playas is relatively straightforward (e.g. Prata, 1990; Verdin, 1996). In order to monitor and study the hydrological balance of playas, a number of workers have used long archives to generate monthly timeseries of high (e.g. Landsat) and moderate resolution (e.g. AVHRR, MODIS) remote sensing data spanning the last 30 years to monitor the presence, absence and magnitude of surface water bodies on playas. Bryant and Rainey (2002), Bryant (2003) and Bryant et al. (2007) use long times series AVHRR and MODIS data to study the hydrological balance of playas in Africa (e.g. Zone of Chotts, North Africa, and Etosha Pan and Magkadigkadi, southern Africa). These workers show that these data can be used to determine: (a) the groundwater regime operating within playas basins (as per Rosen, 1994), (b) the flooding/ponding frequency of playa basins in response to both climatic and nonclimatic factors (as per Bowler, 1986) and (c) the evaporation rate operating during lake desiccation following playa inundation. Similar approaches using a mix of high and moderate resolution data have also been used in the USA (e.g. Lichvar, Guitiña and Bohus, 2004; French et al., 2006), Spain (e.g. Castañeda, Herrero and Casterad, 2005b; Castañeda and García-Vera, 2008) and Egypt (e.g. Bastawesy, Khalaf and Arafat, 2008) to a similar end, and confirm the potential of the approach for the wider assessment, hydrological analysis and classification of playa basins. Wade, Archer and Millington (1994), Archer and Wade (2001) and Wade and Archer (2003) investigate the potential of sequential synthetic aperture radar (ERS-1) data for mapping sedimentation and evaporation rates on the Chott el Djerid, Tunisia.

Given the importance of the dust cycle of many playa basins, some workers have used remote sensing to map potential sites of dust emission on playas or observe dust emission. Katra and Lancaster (2008) use a time series of ASTER data to generate maps of surface mineral composition on Soda Lake, USA, that may be used to characterise preferential dust emission sites on the playa surface. Work by Chappell et al. (2007) in Australia also suggest that additional approaches utilising soil BRDF may be used to infer the erodibility of dust-producing playa surfaces. Bryant et al. (2007) evaluate the dust cycle of playas within the Magkadigkadi basin using a number of remote sensing data types and approaches, and are able to confirm links between the emissive nature of playas and climate feedbacks within southern Africa. Work by Bullard et al. (2008) in the Lake Eyre basin also demonstrate the ability of time series of remote sensing (e.g. MODIS) data to monitor in detail the dust cycle of playa basins to enable a better understanding of the spatial and temporal dynamics of dust sources.

Overall, it is apparent that the increased use of remote sensing data (particularly in the last 5–10 years) to monitor playa hydrology, mineralogy and dust emissions has enabled increased understanding of feedbacks that exist between these characteristics of playa basins and the possible wider impacts and feedbacks that exist between climate forcing and human intervention in drylands.

15.10.1 Aeolian processes in pan environments

Unvegetated and unconsolidated surfaces provide ideal conditions for aeolian activity. Pan surfaces experience deflation during dry periods, with transport in the dominant wind direction to form dunes on the pan and its margins.
Figure 15.13  An example of the use of remote sensing for mapping and monitoring playa surfaces. In this instance, Landsat TM data of the Chott el Djerid have been processed to produce maps of the surface concentrations of: (a) gypsum, (b) halite, (c) vegetation, (d) moisture/shade and (e) clastic sediments. These data are summarised in a map of process domains (f). A graph cross-section (A–A’ c. 20 km) through these data (g) show how data for these surfaces can be used to delineate and better understand the relationships that exist between the playa depositional subenvironments outlined in Figure 15.4. A location diagram is provided (h).
15.11 Wind action on the pan surface

Pan surfaces, composed of dry sands, clays and salts (e.g. playa margin or dry mudflat surfaces), are often vulnerable to wind erosion, although crusting (e.g. Rice and McEwan, 2001) and residual surface moisture (e.g. Reynolds et al., 2007) can reduce its effect. Wind scour can remove material to the level of the near-surface water table (capillary fringe), creating an unconformity known as a Stokes surface (Stokes, 1968; Tyler, Munoz and Wood, 2006). On the pan surface wind action initially entrains surface materials, mainly fine sands and small pellets of clay of equivalent dimensions, the latter produced by salt efflorescence or desiccation (Bowler, 1973). Where permanent or stable salt crusts are apparent, sand blasting and fluting of polygons and other surface forms is common. At the same time, winnowing and ejection of fine material from weak crusts and fractures separating surface plates also occurs. Removal of fines may lead to the formation of lag deposits composed of gravels, silcrete fragments or remnant crusts.

Depositional forms will include the formation of sand ripples on salt crusts, which may become accentuated by incorporation into the edges of polygon structures. Sediments will accumulate around plant stems to form phreatophytic mounds, which, in turn, may lead to the formation of nabkha dunes. On a larger scale parabolic or lunette dunes (Hills, 1940) form on the downwind side of the pan, particularly where wind direction is strongly controlled by basin structure (Hardie, Smoot and Eugster, 1978). These dunes may be modified by later inundation, as in the Makgadikgadi basin of Botswana (Cooke, 1980). In large basins with ample sediment supply, such as Lake Eyre, Australia, a range of dune forms may occur.

The wind may also be implicated in the movement of larger rocks, called sliding stones or playa scrapers, across the pan surface under low frictional conditions (Sharp and Carey, 1976). However, the hydraulic energy of surface runoff has also been proposed as a cause of this phenomenon (Wehmeier, 1986).

15.12 The emission of fine particles (dust): process and controls

Plays have for some time been recognised as a source of fine particles (e.g. Gill, 1996; Goudie and Middleton, 2001; Prospero et al., 2002; Washington et al., 2006; Reynolds et al., 2007), and aeolian processes associated with these environments are shown to be significant in determining solute concentration in groundwater in arid and semi-arid areas (e.g. Wood and Sanford, 1995; Eckardt and Spiro, 1999; Eckardt et al., 2008). Given the wider importance of dust for global climate, air quality with respect to visibility and human health, the fertilization of marine and terrestrial ecosystems, transportation and indications of desertification, an understanding of the processes and controls leading to dust emission from playas is essential.

Many studies have sought to characterise processes leading to particle entrainment and wind erosion on playas (e.g. at Owens (dry) Lake; see Box 15.1) using portable wind tunnels or combined aeolian sediment collection and detailed meteorological measurements (e.g. Cahill et al., 1996; Gillette, Ono and Richmond, 2003). However, although wind strength and the availability of sand-sized sediment within a playa basin are the most important drivers of the dust emission process, a number of hydrological and geochemical factors also exist that can significantly moderate or modify the process of dust emission.

Indeed, areas on playas that are found to be nonemissive are often covered by a durable salt/silt crust (Rice, Mullins and McEwan, 1997) or are wet (Reynolds et al., 2007). Given the dynamism of some playa surfaces in response to natural or human-induced changes in groundwater position and surface water ponding, the locations from which dust are emitted and the magnitude of emission from playa surfaces can vary substantially in space and time (Elmoge et al., 2008). Some workers (e.g. Mahowald et al., 2003; Bryant, 2003; Bryant et al., 2007; Reynolds et al., 2007) have shown conclusively that a reduction or cessation of dust emissions from playa basins accompanies significant inflow, ponding of water or increased groundwater levels. However, once the inflow waters have receded, Bryant et al. (2007) also note an enhanced emission of dust due to the increased availability of fine particles on the playa surface delivered through the flooding process itself. With regard to the inundation process, it is worth reiterating that these events are themselves often either difficult to predict (or are spatially/temporally discrete), as changes in hydrological balance of this nature can occur either in response to climate forcing, surface inflow or human intervention, or a combination of the three.

Kotwicki and Isdale (1991), Kotwicki and Allen (1998) and Bryant et al. (2007) do, however, show that flooding (and hence aspects of the dust cycle) within large playa basins can be closely linked to regional climate. To assess the gross impacts of hydrological changes, Reynolds et al. (2007) presented a conceptual model outlining the relationship between groundwater position and dust emission magnitudes based upon detailed observations from discharge (wet) and recharge (dry) playas in the southwestern...
15.13 Lunette dunes

Pan-margin dunes (Figure 15.4) are important landscape features in many regions, including southern Australia (Bowler, 1973), the southern Kalahari (Goudie and Thomas, 1986), Tunisia (Coque, 1979) and Texas (Huffman and Price, 1979). Although commonly between 10 and 50 m high, one example in Tunisia rises almost 150 m above the basin floor (Goudie and Thomas, 1986). The surfaces of lunettes are frequently vegetated, which contributes to their development through encouraging sediment accretion. Dune size is a function of a range of factors, but basin size, morphology and sediment supply are important. Cyclical episodes of lunette formation have been identified (Thomas et al., 1993; Dutkiewicz and von der Borch, 1995; Telfer and Thomas, 2007) on the basis of depositional hiatuses and palaeosol formation.

Individual pans and playas can possess more than one fringing dune, with as many as three identified on the margins of some southern Kalahari pans. Differences in morphology, orientation and sedimentology between dunes on the margins of individual basins have been interpreted as indicators of changing palaeoenvironmental (wind regime and hydrological) conditions (e.g. Lancaster, 1978b). In the southern Kalahari some pans possess an outer quartz sand lunette and an inner form that has a higher silt and clay content of between 12 and 20% by weight (Lancaster, 1978b). The former are interpreted as the outcome of deflation in the initial stages of pan development from the sandy Kalahari floor, under relatively dry conditions in an arid environment, in a manner comparable to parabolic dune development from partially vegetated surfaces. Conversely, in Australia, the orientation of quartz-rich fringing dunes reflects wet-season winds. They have therefore been seen as the outcome of deflation from pan and playa beach sediments during periods of high or seasonal lakes, in a manner comparable to coastal dune development (see, for example, Twidale, 1972).

Importance has been attached to the deflation of clay pellets from seasonally dry pan surfaces in the development of the clay lunettes of Australia (e.g. Bowler, 1973, 1986) and this is also the mechanism that Lancaster (1978b) ascribes to the development of the inner sandy-clay dunes found on pan margins in the southern Kalahari. As pellet formation is dependent on the break-down of basin-floor clays by salt efflorescence (Australian lunettes also contain high percentages of gypsum as well as clay), clay lunette development is unlikely in extremely dry or surface water-dominated environments (Bowler, 1986).

![Dust emissions from playas](image)

(a) A model, drawing on the classification system of Rosen (1994), which outlines the importance of groundwater regime and depth on the morphology of surface crusts type and dust emission potential from playas from the southwestern USA (after Reynolds et al., 2007). (b) A dust storm observed emanating from the margins of Sua Pan, Botswana (photo courtesy of Frank Eckardt).

Figure 15.14 Dust emissions from playas. (a) A model, drawing on the classification system of Rosen (1994), which outlines the importance of groundwater regime and depth on the morphology of surface crusts type and dust emission potential from playas from the southwestern USA (after Reynolds et al., 2007). (b) A dust storm observed emanating from the margins of Sua Pan, Botswana (photo courtesy of Frank Eckardt).
Box 15.1 Owens (dry) Lake, USA

Owens (dry) Lake, USA, was a perennial lake at the terminus of the Owens River for most of the last 800,000 years (Smith, Bischoff and Bradbury, 1997). During the late 1800s and early 1900s the lake fluctuated between about 7 and 15 m deep and had an area of about 280 km$^2$, depending on drought conditions and irrigation diversions (see Figure 15.15). As a result of the diversion of inflow waters beginning in 1913 the pre-existing perennial saline lake (e.g. Figure 15.7(d)) developed into a wet groundwater discharge playa by 1928 (e.g. Figure 15.7(b)), which has subsequently been the largest single source of particulate-matter emission (by one estimate, 900,000–8,000,000 tonnes/year) in the United States (e.g. Gill and Gillette, 1991; Cahill et al., 1996; Gillette, Ono and Richmond, 2003). Research on this playa has led to a greater understanding of the processes involved in the emission of dust from playas. Gillette, Ono and Richmond (2003) outline the process whereby emission of dust is initiated through creep (reptation) and saltation of sand-sized particles across the playa surface, which loosen other particles and sandblast the surface, causing finer particles, including dust, to be ejected and to mix vertically in the turbulent air stream. The amount of dust emitted was therefore suggested to be proportional to this horizontal saltation flux on any playa surface. During the period 2000 to 2006 a wide range of dust-control measures (including the use of shallow flooding, controlled vegetation and gravel) were implemented on a large part of the former lake bed.

![Figure 15.15](image-url)
Up to 80% of the material in Australian lunettes is in the form of clay pellets (Bowler, 1973), though overall dune sediments range from sandy clay, comparable to that forming the inner Kalahari lunettes, to almost pure gypsum (Bowler, 1976). Analyses of the Australian clays show that the material persists in pelletal form after deposition (Bowler and Wasson, 1984), whereas in Nevada Young and Evans (1986) report that clay pellets break down after deposition on the dunes when the binding salts are broken down in subsequent rainfall events. The resultant landform is termed a mud dune.

15.14 Yardangs

On a large scale differential erosion of horizontal sediments may lead to the development of yardang topography (Figure 15.16), with a relief of up to 20 m (Mabbutt, 1977). The kalut landscape of the Kerman basin in Iran, a series of parallel ridges and troughs with a relief of 60 m (Dresch, 1968; Krinsley, 1970), is an extreme example of this landform suite. On the regional scale, playas with falling water tables may be lowered by deflation and groundwater weathering to form pan and escarpment landscapes, as in the Oasis Depressions of North Africa, including the Qattara Depression at 134 m below sea level.

15.15 Pans and playas as palaeoenvironmental indicators

Pans and playas have long been important sources of palaeoenvironmental reconstruction in arid environments, particularly in Australia (e.g. Harrison, 1993), Africa (Street-Perrott and Roberts, 1983) and the southwest USA (Benson et al., 1990), even though the evidence they preserve is often discontinuous and absolute dating has been problematic. Within the past two decades absolute dating has moved on from radiocarbon (e.g. Bowler et al., 1986) to the application of Th/U isotopes (e.g. Herczeg and Chapman, 1991), amino acid racemisation (Miller et al., 1991) and luminescence techniques (e.g. Chen, 1995), bringing better temporal resolution over longer time spans. Alongside this, the understanding of pans and playas as dynamic, three-dimensional landforms involving the interface of aeolian, groundwater and surface water processes has reduced the degree of ambiguity in palaeoenvironmental interpretation. The evidence is based upon three aspects of playa research.

15.16 Identification and dating of pan shorelines

The mapping and dating of shorelines makes it possible to recreate past water budgets on the assumption that most playas are ‘amplifier lakes’ (Street, 1980) in that, lacking surface outflow, they tend to emphasise the influence of precipitation on the water budget. The evidence usually takes the form of a lake of successively decreasing volumes represented by a suite of strandlines, each controlled by a threshold within the hydrological system, such as lake morphology, or sometimes an overflow. Shorelines have been dated by thermoluminescence (TL; see Magee et al., 1995) and optically stimulated luminescence (OSL; see Burrough et al., 2007) dating techniques, a key factor being improved sampling to depths of 15 m using lightproof augers.

15.17 Dating and stratigraphy of lunette dunes

The study of landforms associated with pans, in particular the stratigraphy of lunette dunes (Chen, 1995; Dutkiewicz...
15.18 Stable isotope studies and pan hydrochemical evolution

Recent advances in the multidisciplinary study of playas as three-dimensional features, with distinct hydrological, sedimentary, chemical and organic basins, has allowed the identification of distinct facies associated with the saline pan cycle, and thus allowed the interpretation of their sedimentary record, even where it is discontinuous (Chivas, 2007; Yechieli and Wood, 2002). Geochemical studies have contributed greatly to this, in particular the recognition that common minerals such as gypsum may take on different crystal forms in lacustrine groundwa-

ter, aeolian and pedogenic environments (Magee, 1991; Magee et al., 1995). Building on the work of Eugster and Jones (1979), a number of workers (e.g. Risacher and Fritz, 1991; Bryant et al., 1994a; Yan, Hinderer and Einsele, 2002; Eckardt et al., 2008) have undertaken systematic analyses of surface waters in order to under-

stand and model sources of solutes and geochemical brine evolution processes associated with playa systems (Figure 15.8). In order to look more closely at the geochem-

ical pathways associated with brine evolution over long time periods, trace element and stable isotope approaches have been used to trace the often complex geochemical provenance of evaporite deposits (e.g. groundwater, sur-

face water or atmospheric sources; see Figure 15.5). Typ-

ical trace element analyses include determining the Br/Cl content of halite (e.g. Hardie, 1984) and the strontium content of gypsum (e.g. Rosell et al., 1998). More gen-

eral bromine geochemistry of playa halite has also been undertaken (e.g. Bryant et al., 1994a; Risacher and Fritz, 2000) to attempt to understand their source, preserva-

tion and diagenetic history. However, given that modern playa evaporites can display a marine-like geochemical signature, these approaches have fundamental limitations (Bryant et al., 1994a). As a consequence, Chivas et al. (1991), Vengosh et al. (1992), Ramesh, Jani and Bhusan (1993) and Eckardt et al. (2008) successfully use a combi-

nation of strontium, oxygen, boron and sulfur isotope compositions of waters and mineral phases (e.g. calcium

$^{87}$Sr/$^{86}$Sr, gypsum $^{18}$O/$^{16}$O, borates $^{10}$B/$^{11}$B) to de-

termine the sources of the geochemical evolution of ter-

estrial evaporites deposited in a range of playas from Australian, USA and Africa. In order to elucidate geomorphic processes and dat-
ing of recent surficial deposits on playas, Reynolds et al. (2007) have utilised radionuclide analyses ($^{137}$Cs) to de-

terminate recent erosion and sediment accumulation rates for playas in the southwestern USA. At the same time, the geochemistry and regional impact of dust emanating from playas has also received much attention (e.g. Gill et al., 2002; Reheis, 2006). Although organic materials do not display the same degree of preservation that oc-

urs in temperate environments, studies involving pollen, diatoms (Burrough et al., 2007), stromatolites (Casanova and Hillaire-Marcel, 1992), ostracods (Lister et al., 1991) and even ostrich shells (Miller et al., 1991) have added to the debate.

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