Chapter 16

Hemiarid Lake Basins: Geomorphic Patterns

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When the lakes of arid regions become extinct, either by reason of evaporation or sedimentation, evidence of their former existence remains inscribed on the inner slopes of their basins or concealed in the strata deposited over their bottoms. These records as a rule are much more lasting than those left by lakes in humid lands. . . .

Israel C. Russell (1895, pp. 94–95).

Introduction

Hemiarid ('half arid') lake basins are drainage basins that have arid lowlands, nonarid highlands, and topographic and hydrologic closure. As a result of these characteristics, hemiarid lake basins contain or have contained nonoutlet lakes in their lowest reaches. A rich body of lacustrine and palaeolake evidence is stored in many hemiarid lake basins, providing the basis for reconstructing basin hydrography and the underlying hydrology, hydroclimate, and tectonics. Much of this lacustrine evidence occurs in regional and local patterns of geomorphology, sedimentology, and stratigraphy, which in lacustrine geoscience, with an emphasis on the depositional record, differ more in etymology than substance. Regional and local geomorphic patterns are equally important in effecting the hydrographic and related reconstructions from hemiarid lake basins. Regional geomorphic patterns constitute the predictive basis for making local geomorphic observations, and local patterns are the observational basis for building and testing regional models.

Figure 16.1 illustrates the importance of regional and local geomorphic patterns, and the underlying tectonic, hydrographic, and hydrologic factors, in two substantially different hypothetical basins. The hypertectonic hemiarid lake basin (Fig. 16.1, A-A′) has highlands that yield significant runoff, lowlands that are typically segmented into closed subbasins by active alluvial fans, and subbasin floors that are likely to be locally depressed by active faulting. In contrast, the hypotectonic arid basin (Fig. 16.1, B-B′) has inselberg uplands that are unlikely to yield significant runoff, lowlands in which subbasins have long been aggraded and amalgamated, and a basin floor that in all likelihood is large and essentially flat. The occurrence of a lake or the geomorphic evidence of one or more Quaternary palaeolakes, large or small, has a substantially higher probability in the hypertectonic basin than in the hypotectonic basin. This chapter on hemiarid lake basins, therefore, considers lacustrine geomorphic, and related sedimentologic and stratigraphic, patterns in hypertectonic basins.
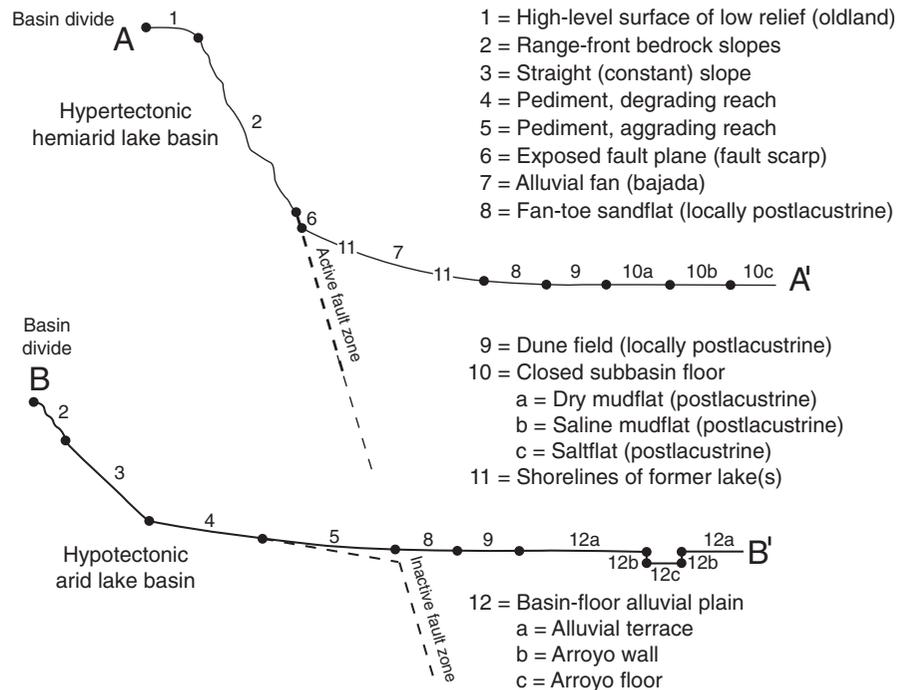
Lakebeds

From their greatest depths to their highest surges, lakes are in continuous to occasional contact with sublacustrine materials. Portions of lake-substrate interfaces have been referred to as beds, bottoms, floors, shores, mudlines, and other terms. In this

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Fig. 16.1 Schematic profiles showing regional (A-A′ and B-B′) and local (1–12) geomorphic patterns that are typical of hypertectonic hemiarid lake basins and hypotectonic arid basins

1 = High-level surface of low relief (oldland)
2 = Range-front bedrock slopes
3 = Straight (constant) slope
4 = Pediment, degrading reach
5 = Pediment, aggrading reach
6 = Exposed fault plane (fault scarp)
7 = Alluvial fan (bajada)
8 = Fan-toe sandflat (locally postlacustrine)

9 = Dune field (locally postlacustrine)
10 = Closed subbasin floor
    a = Dry mudflat (postlacustrine)
    b = Saline mudflat (postlacustrine)
    c = Saltflat (postlacustrine)
11 = Shorelines of former lake(s)

12 = Basin-floor alluvial plain
    a = Alluvial terrace
    b = Arroyo wall
    c = Arroyo floor

account, all lake-substrate interfaces in hemiarid basins are termed lakebeds. Conceptually, lakebeds are the desktops on which lakes encode and inscribe information about their environments, including their morphometry (Håkanson 1981), energy fluxes (Bergonzini et al. 1997, Menking et al. 2004), material fluxes, and sedimentology (Sly 1978, Håkanson and Jansson 1983). Information regarding lakebed depth (bathymetry), net balance of deposition and erosion (Håkanson and Jansson 1983), sediment size, mineralogy (Jones and Bowser 1978), and geochemistry (Ku et al. 1998, Parker et al. 2006) is of prime importance geomorphically.

A regional geomorphic model applicable to lakebeds in many hemiarid basins consists of topologically concentric, bathymetric environment zones (Table 16.1). Each isochronic lakebed that marks a successive stage in a lacustrine sequence is a special case of the general model. In each case the nearshore, foreshore, and backshore zones form a geomorphically dynamic lakeshore (Fig. 16.2). Lakebed sediment sizes, which are characteristically well sorted in accordance with turbulent energies, typically increase from the deepest part of the offshore zone to the middle of the foreshore zone.

Several spatial and temporal factors are represented in lakebed geomorphic patterns and their component sediment sources, pathways, and sinks. Given adequately georeferenced and chronoreferenced databases, individual isochronic lakebeds can be resolved into sets of linear patterns (e.g. mappable source-to-sink sediment pathways) and areal patterns (mappable polygons); successions of lakebeds can be resolved into volumetric patterns (mappable polyhedrons). Although minimal spatiotemporal resolution can be sufficient to distinguish among pre-lacustrine, co-lacustrine, and postlacustrine geomorphic features, high spatiotemporal resolution is required to quantify the kinematics of geomorphic and hydrographic change (e.g. Currey and Burr 1988).

Lakebed Sediment Sources

Lakebeds are surfaces underlain by lacustrine sediments that range in thickness from greater than 1 m in many offshore and lakeshore areas of net deposition, to shallow veneers on erosional platforms, to virtually nothing on steeply sloping bedrock headlands. Lacustrine sediments are of three types: (a) those that originate outside the water column, (b) those that originate in the water column, and (c) those that originate in fluid-filled pores under the water column. The

Table 16.1 Offshore, nearshore, foreshore, backshore, and rearshore bathymetric environment zones in and adjacent to lakeshores in hemiarid lake basins*

| Zones and zone transitions	Typical environments
Offshore deep	Deepest places in lakes; lakebeds commonly anoxic and fetid, with sediments commonly >1% plankton residues
Offshore zone	Depths typically >6 m; gently sloping lakebeds blanketed by marls (carbonate micrite muds), diatomaceous marls, terrigenous silts and clays, or volcanic ashes; soluble salts can precipitate offshore during major regressions
Offshore perimeter	Landward transition from low to moderate turbulence and from muddy to sandy lakebeds; basinward limit of lakeshore
Nearshore zone	Depths typically 2–6 m; low-gradient, basinward-sloping aprons of fine clastic sands, charaliths, or mats and heads of algaloid tufa; commonly ooid-producing; soluble salts can precipitate nearshore from cold, high-salinity waters
Nearshore perimeter	Landward transition from moderate-energy sandy lakebeds to high-energy gravelly lakebeds
Lower foreshore zone	Depths typically <2 m; moderately steep, basinward-sloping, surf-constructed subaqueous beach faces of medium to coarse sands and gravels; commonly bouldery; lithoid and algaloid tufas locally abundant as beach matrix and as coatings on rocky lakeshores; soluble salts can precipitate on lower foreshore from cold, high-salinity waters
Lower foreshore perimeter	Waterline; landward limit of open water under static water conditions, i.e. basinward edge of land
Upper foreshore zone	Heights typically <2 m above static water level; swash-constructed subaerial beach faces are landward extensions of subaqueous beach faces; locally bouldery
Upper foreshore perimeter	Crests of basinward-sloping, backset-stratified beach faces; landward limit of swash
Backshore zone	Inland-sloping foreset-stratified washover beach slopes, lagoons, primary dunes (foredunes), deltaic lowlands, mudflats, saltflats, and marshes directly impacted by overwash processes and episodic onshore surges
Backshore perimeter	Inland transition from direct to indirect lacustrine geomorphic impacts, i.e. inland limit of foredune accretion and flooding by onshore surges; inland limit of lakeshore
Rearshore zone	Secondary dunes derived from foredunes; floodplains and groundwater tables affected by fluctuations of lacustrine base levels
Rearshore perimeter	Inland limit of indirect lacustrine geomorphic impacts, i.e. inland limit of secondary dunes and base level effects

*See Fig. 16.2.
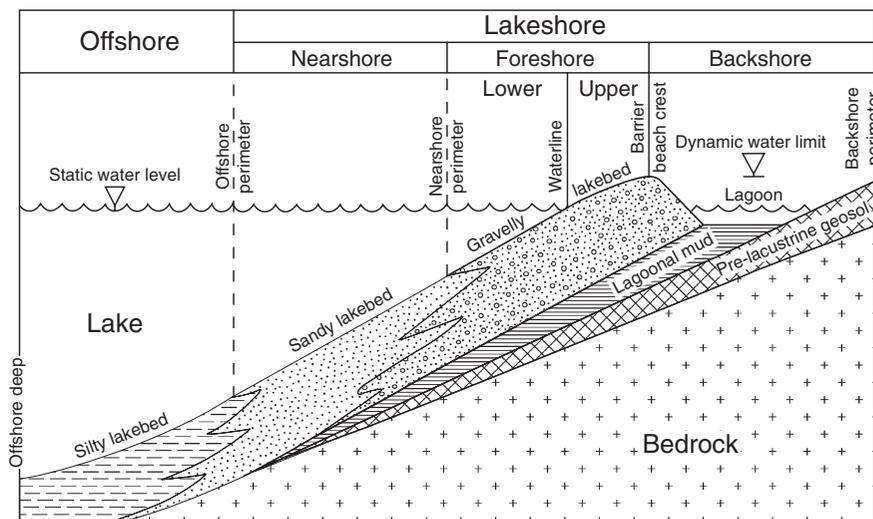
Fig. 16.2 Schematic cross section of a lakebed in a hemiarid lake basin, showing bathymetric environment zones in and near an idealized barrier beach lakeshore. See Table 16.1 for details

three types are commonly referred to as allogenic, endogenic, and authigenic, respectively, although the latter two are sometimes grouped together because of their common links to lake biochemistry (Jones and Bowser 1978). Here, sediments that have their origins on land are termed terrigenous, following usage in marine geology, and those that have their origins in and under lakes are termed limnogenous.

Terrigenous lacustrine sediments (Table 16.2) comprise all clastic materials that are transported into lakes by geomorphic agents, as well as those that lakes acquire by lakeshore erosion. Fluviolacustrine materials are commonly the dominant terrigenous sediments on the lakebeds of hemiarid basins with major streams. Away from the deltas of major streams and in hemiarid lake basins without major streams, alluviolacustrine materials are commonly the dominant terrigenous sediments, particularly in lakeshore deposits.

Limnogenous sediments (Table 16.3) comprise all materials that originate physicochemically or biochemically at the top of, within, at the bottom of, or under the water column in hemiarid lake basins, regardless of water depth. Of the lacustrine chemical sediments (Eugster and Kelts 1983), carbonates are the most ubiquitous in hemiarid lake basins, far exceeding organic matter and typically equalling or exceeding soluble salts. Micritic marls, with amounts and sizes of admixed terrigenous fines that reflect proximity to land-based sediment sources, are the most common offshore carbonate sediments (Galat and Jacobsen 1985, Oviatt et al. 1994). Various forms of tufa (Morrison 1964, Benson et al. 1995, Ku et al. 1998) and ooidal sands (Eardley 1966) are common carbonate sediments in lakeshore zones.

In many hemiarid lake basins algaloid tufas (Table 16.3, Fig. 16.3) are among the more intriguing and varied surficial materials. Algaloid tufas are laminated calcite, aragonite, and calcite-aragonite mixtures that form on algae-colonized substrates in sunlit, wave-agitated water saturated with calcium bicarbonate. Large algaloid tufa forms include mounds, domes, and pinnacles, as well as extensive mats (hardgrounds) on soft sediments. Smaller forms include cauliform discs and heads, radiating (dendritic) discs and heads, polyp clusters, smooth rinds and rippled rinds on bedrock and detached rocks, rinds enveloping metre-size pods of gravel, bun-shaped oncoids, and pearl-like pisolites.

Lakeshore Sediment Pathways

Most limnogenous sediments are deposited beneath or at their point of origin in the formative water column. Alternatively, most terrigenous sediments, as well as coarse limnogenous sediments such as ooidal sands, are transported significant distances before undergoing long-term deposition. The finer terrigenous sediments,

Table 16.2 Terrigenous lacustrine sediments of importance in hemiarid basins are supplied by lakeshore erosion (E) or by short- to long-distance transportation (T)

Sediment types	Sediment origins
Litholacustrine	(E) Clastic sediments that lakes acquire by eroding cliffs (free faces) in resistant bedrock and bluffs (straight slopes) in nonresistant bedrock; includes clasts acquired by rockfalls and rockslides from cliffs and bluffs
Colluviolacustrine	(E) Clastic sediments that lakes acquire by stripping unconsolidated colluvial materials off slopes that are underlain by bedrock and consolidated sediments
Alluviolacustrine	(E) Clastic sediments that lakes acquire by eroding bluffs in alluvial fans and bajadas; includes clasts acquired by mass wasting of bluffs
Retrolacustrine	(E) Clastic sediments (intraclasts) that lakes acquire by reworking and redepositing terrigenous and limnogenous sediments of earlier lakebeds
Fluviolacustrine	(T) Clastic sediments, including glacial outwash, that are introduced into lakes by drainage networks of many sizes; partly dispersed offshore and partly localized inshore (in low-gradient, suspended-load deltas, bedload fan deltas, sandy underflow fans, and aggraded-prograded estuaries)
Aerolacustrine	(T) Airborne mineral dusts (silts and clays), biodusts (palynomorphs and humic matter), organic ashes, volcanic ashes, and salts that settle out of the atmospheric column onto lake surfaces; insoluble dusts settle out of the water column onto lakebeds
Cryolacustrine	(T) Ice-rafted dropstones (commonly pebbles and cobbles) that are released during spring breakup of shore-fast lake and river ice; ice-shoved beach deposits
Anthropolacustrine	(T) Materials (structures and refuse) that are placed in lakes by people
Glaciolacustrine	Sediments that are carried into lakes by glacier ice are rare or nonexistent in hemiarid lake basins

Table 16.3 Limnogenous sediments of importance in hemiarid lake basins

Sediment types	Sediment origins
Micrites	Silt-size carbonate crystals that form in calcium-bicarbonate-saturated surface waters, and settle out as marl in the summer, when CO_2 is depleted by phytoplankton (mainly algal) photosynthesis and thermal degassing; calcite micrites (and tufas) tend to precipitate in low-salinity hard waters, and aragonite micrites (and tufas) tend to precipitate at higher salinities
Plankton residues	Organic matter (sapropel or proto-kerogen) that results from anaerobic decay of settled-out plankton (mainly algae); common in fine-grained sediments on poorly oxygenated lakebeds
Microfossils*	Opaline frustules of diatoms can be particularly abundant, with sediments ranging from diatomaceous muds and marls to pure diatomites; pollen grains are commonly preserved in water-saturated sediments
Macrofossils*	Mollusca shells are common in the deposits of fresh-to-brackish shallow waters; charaliths (diminutive straw-like calcified filaments of macrophyte algae, particularly of the genus *Chara*) are commonly washed into nearshore deposits from foreshore substrates; ostracod shells are common in fine-grained sediments on well-oxygenated lakebeds; fish bones and scales are less common, but occur widely in the deposits of fresh-to-brackish waters
Ooids	Spheroidal ooids (aragonite-encapsulated sand grains) and cylindrical ooids (aragonite-encapsulated fecal pellets, e.g. of the brine shrimp *Artemia*) that form in gently shoaling calcium-bicarbonate-saturated nearshore waters; commonly wash onshore to form beaches and dunes
Algaloid[†] tufas	Phycolites (general name for all algaloid structures) comprise (a) spongiostromes (laminated structures formed by algae growing in smooth mats), including stromatolites (attached to substrate) and oncolites (unattached, free to roll), and (b) dendrolites (arborescent or near-arborescent structures formed by algae growing in tufted mats), including dendritic, cellular, and 'coralline' tufa
Tufacretes	Conglomerate- or concrete-like, calcite- and aragonite-cemented gravels and coarse sands that form in shallow, calcium-bicarbonate-saturated waters where moderate (not copious) supplies of coarse clasts are available and where breaking waves accelerate warm-season degassing of CO_2; tufacrete landforms include platform pavements and ledges, slope-draping slabs, and foreshore beachrock
Salt beds	Offshore and nearshore beds of soluble salts that settle out after crystallizing in seasonally supersaturated surface waters, e.g. halite (NaCl) when evaporation is high and mirabilite ($Na_2SO_4 \cdot 10H_2O$) when temperatures are low; foreshore salt beds include mirabilite that washes onshore and is preserved in the interstices of more stable beach materials; backshore salt beds include halite that precipitates on lake-fringing saltflats

*Including subfossils of late Quaternary age.
[†]Richard Rezak's classification (Morrison 1964, p. 48).

mainly fluviolacustrine clays, silts, and fine sands, are commonly transported by runoff that discharges directly into offshore waters by hypopycnal flow as near-surface suspensions of clays and silts, and by hyperpycnal underflow in near-bottom density currents laden with mixtures of clay, silt, and fine sand. The coarser terrigenous sediments, consisting mainly of alluviolacustrine and litholacustrine gravels and coarse sands (Table 16.2), and coarse limnogenous sediments occur mostly in lakeshore (nearshore, foreshore, and backshore) zones. There they are reworked and redeposited many times as they move from sediment sources to sediment traps along lakeshore pathways.

The four basic lakeshore sediment pathways (Fig. 16.4) in hemiarid lake basins trend (a) landward from the foreshore zone to the backshore zone and sometimes beyond, (b) landward from the nearshore zone to the foreshore zone, (c) basinward from the foreshore zone to the nearshore or offshore zone, and (d) in the direction of net littoral drift within the foreshore and nearshore zones. These pathways are known as inland transport, onshore transport, offshore transport, and longshore transport, respectively.

It is common for lakeshore sediment pathways in hemiarid lake basins to be well defined geomorphically. In inland transport, foreshore medium sands are carried into lagoons by overwash and onto accreting foredunes by saltation. In onshore transport, nearshore ooids and fragments of tufa and beachrock commonly are carried onto foreshore beach faces by the onshore component of breaking waves (swash). In offshore transport, foreshore fines are winnowed into deeper water by breaking waves, and foreshore sands and gravels pass into deeper water on the updrift sides of groin-like headlands and at the ends of spits and cuspate barriers. In longshore transport, foreshore sands and gravels can be carried several kilometres by the longshore component of breaking waves (littoral drift),

Fig. 16.3 Dense, coral-like tufa in the Lake Bonneville basin deposited on what was a steep, subaqueous slope of lacustrine gravel

without benefit of topographic gradient. Longshore transport has moved large (128–256 mm) cobbles at least 2 km on high-energy beaches in the Great Basin.

It is also common for geomorphic conditions to vary greatly from one lakeshore sector to another. In all but the smallest hemiarid lake basins, this produces distinctive basinwide and local patterns of lakeshore segmentation (Fig. 16.5). Lakeshore segments are distinguished by two criteria, their longshore transport directions and longshore sediment budgets. Lakeshore segments join at segment boundaries, called nodes, which are points where (a) longshore transport directions reverse, or (b) longshore sediment budgets change algebraic sign (from net erosion to net deposition or vice versa). Erosional lakeshore segments have deficit longshore sediment budgets in which total longshore outputs exceed total longshore inputs, with the difference equal to sediments entrained by lakeshore erosion. Depositional lakeshore segments have surplus longshore sediment budgets in which total sediment inputs exceed total longshore outputs, with
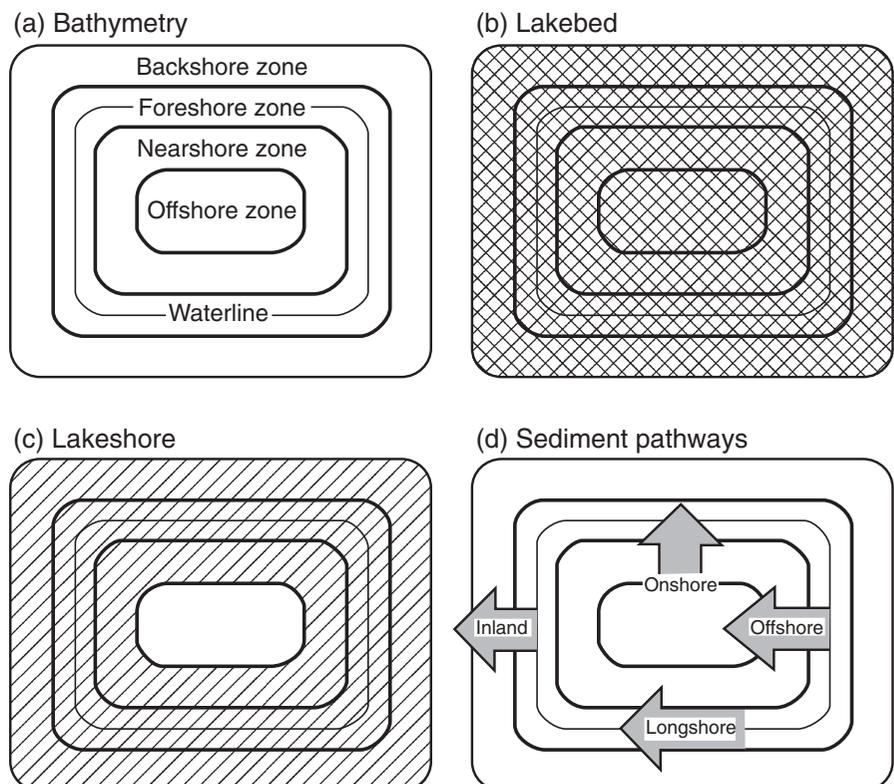

Fig. 16.4 Schematic plans of (**a**) bathymetric zones (Table 16.1 and Fig. 16.2), showing (**b**) lakebed and (**c**) lakeshore areas of (**d**) inland, onshore, offshore, and longshore sediment movement

Fig. 16.5 Map of hypothetical lakeshore showing longshore pathways from sediment sources to depositional sites. L = lagoon and B = barrier beach. Longshore vector polygon and resultant longshore vector are plotted within lake area. N = number of lakeshore segments (= number of longshore vectors), ΣL = total length of longshore vectors, L_R = length of resultant longshore vector, S_R = strength of resultant longshore vector (L_R as fraction of ΣL), and θ_R = azimuth of resultant longshore vector. Symbols indicating erosional segments project landward; those marking depositional segments project lakeward
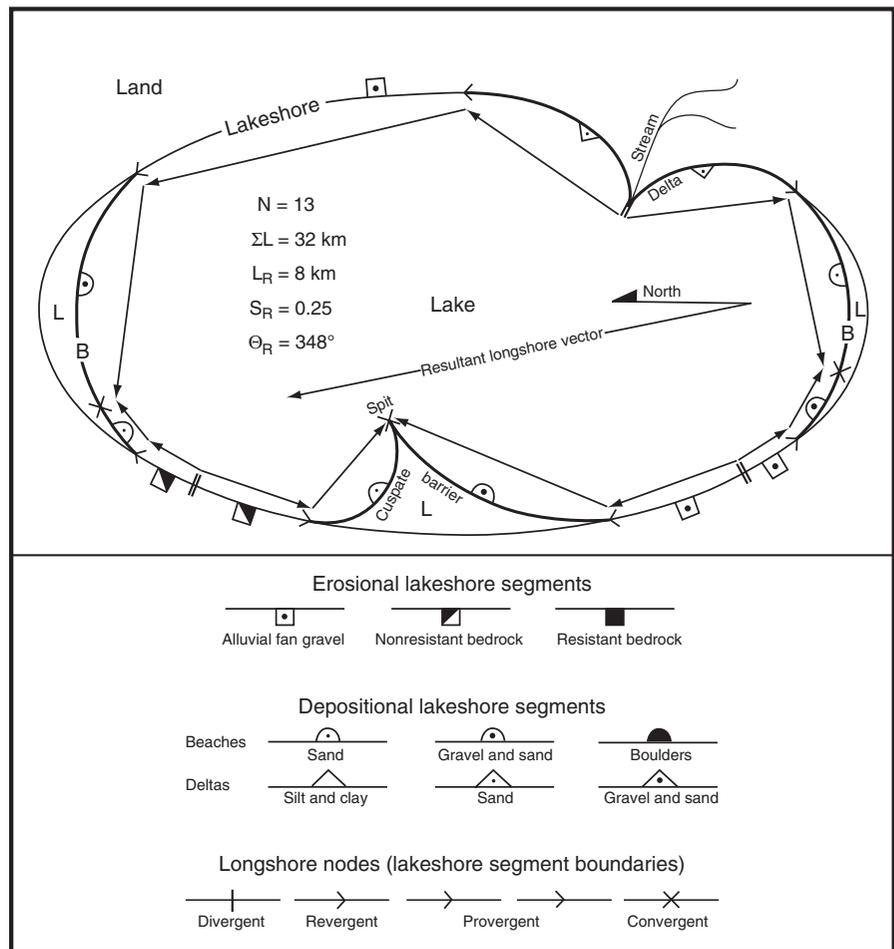
the difference equal to sediments stored in beaches and deltas.

Lakeshore segment boundaries (Fig. 16.5, longshore nodes) occur where longshore transport directions diverge or converge (divergent and convergent nodes), where longshore transport budgets change from deposition to erosion (revergent nodes), and where longshore transport budgets change from erosion or steady state to deposition (provergent nodes). In addition to the longshore criteria that are used to define lakeshore segmentation, features such as lithology and geomorphic expression (original geomorphic development together with subsequent geomorphic preservation) can be noteworthy features of lakeshore segments and subsegments (Wilkins and Currey 1997, Adams and Wesnousky 1999, Carter et al. 2006).

Lakebed Sediment Sinks

The marine geomorphic literature sometimes distinguishes among coastal sediments that reside in (a) stores, such as temporary sediment storage in active beaches, (b) traps, which constitute long-term sediment storage as in beaches at reentrants, and (c) sinks, representing permanent sediment losses from beaches onto land and into deep water (Davies 1980). Similar distinctions can sometimes be made in hemiarid lake basins, although relatively steep stream and slopewash geomorphic gradients tend to limit postlacustrine residence times of lake sediments in beaches and, most notably, in blanket deposits above basin floors. However, the corollary, that the residence times of lake sediments, including the ubiquitous reworked

sediments, in basin-floor sinks are essentially unlimited, does not necessarily follow. This stems from the fact that the floors of many hemiarid lake basins (a) are prone to vigorous subaqueous and aeolian scour during lowstands (Magee et al. 1995, Nanson et al. 1998), and (b) eventually undergo tectonic rejuvenation by tilting and/or faulting (Amit et al. 1999).

Sediment sinks in hemiarid lake basins can be viewed from several perspectives. For example, physiography may be used as a basis for identifying and differentiating depositional subenvironments. Alluvial fans, fan-toe sandflats, dry mudflats, saline mudflats, salt pans, perennial saline lakes, aeolian dunes, perennial streams, ephemeral streams, springs, spring-fed ponds, and shorelines represent major depositional environments in saline lake basins (Hardie et al. 1978, Eugster and Kelts 1983). Distributary-channel deltoids (Mabbutt 1977) are important in some desert lowlands, such as where the terminal reach of the Amargosa River intermittently aggrades Badwater Basin on the floor of Death Valley, California (Hunt et al. 1966). Two spatial perspectives that focus on lakebed sediment sinks are outlined here, the zone-sector-polygon model and the bubble model.

The zone-sector-polygon subenvironment model (Table 16.4 and Fig. 16.6) describes the continuum of lakebed sediment sinks in terms of two orthogonal spatial patterns: (a) topologically concentric bathymetric zones, and (b) topologically radial sediment budget sectors. In this model, the four bathymetric environment zones outlined previously (Fig. 16.2 and Table 16.1) intersect 12 (or more) longshore sediment budget sectors to define 48 (or more) depositional subenvironment polygons. The structure of this model lends itself to GIS applications, including geomorphic mapping, in hemiarid lake basins.

'Bubble models' of depocentres represent another approach for highlighting major patterns of lakebed sediment sinks. Models (e) through (k) in Fig. 16.7 derive specifically from observations in North American hemiarid lake basins. Underflow depocentres (Fig. 16.7e) occur offshore from river mouths with sediment-laden hyperpycnal flow (e.g. Oviatt 1987, Oviatt et al. 2003). Fringing-beach depocentres (Fig. 16.7f) are found mainly in small basins with easily eroded piedmont gravels. Depocentres fed by wind-driven longshore drift (Fig. 16.7g,j) occur in almost every hemiarid lake basin, often as major beaches at gravel-dominated sites and beach-fed dunes at sandy

sites. Bidirectional longshore drifting (Fig. 16.7h) has formed major beaches at the north and south ends of many Great Basin lakes due to orographically channelled southerly and northerly winds (e.g. Sack 1990, plate 1). A major dune field was constructed of sand from the front of a windward-projecting late Pleistocene delta (Fig. 16.7i) inland from at least one Great Basin palaeolake (Sack 1987). Ooidal beaches and beach-fed dunes of Holocene age are widespread in gently shelving, mainly west-facing sectors of Great Salt Lake (Fig. 16.7k) (Dean 1978, Currey 1980).

In many hemiarid basins, lakebed landforms and sediments are regionally mantled and locally buried by subsequent aeolian, colluvial, and pedogenic surficial materials. Aeolian deposits, including loess (ubiquitous in at least minor quantities), mud-pellet dunettes (often anchored aerodynamically to shrubs), and lunettes (around downwind margins of playas), and secondary sand dunes and sand sheets reworked from beach-fed primary dunes (Davies 1980), commonly date from lake regressions and lowstands. Colluvial deposits, including coverhead that accumulates on erosional shorelines (Sharp 1978) and coverbeds that accrete around the basin during waning-ice-age intervals (Kleber 1990), are poorly sorted, loess-enriched surficial materials emplaced by creep and slopewash. Colluvial surficial deposits commonly contain pedogenic carbonates and translocated clays (e.g. Birkeland et al. 1991), particularly where steppe vegetation has restricted geomorphic activity and contributed to pedogenesis.

Lakebed Landforms

Sediment sources, pathways, and sinks in hemiarid lake basins are embodied in landforms that record pre-lacustrine, co-lacustrine, and postlacustrine geomorphic history. Lakebed landforms can be viewed in many ways; here they are presented as modules in planimetric and stratigraphic patterns, and as indicators of postlacustrine change.

Lacustrine geomorphic information is recorded mainly in lakeshore landforms, particularly depositional landforms. Geomorphic resolution of lake history tends to increase with increasing supplies of lakeshore terrigenous sediments (and ooidal sands) and increasing depth of lakeshore embayments (Fig. 16.8).

Table 16.4 Zone-sector-polygon model of lacustrine depositional subenvironments, in which 48 subenvironment polygons (Fig. 16.6) are defined by the intersections of four bathymetric environment zones (Fig. 16.2 and Table 16.1) and 12 longshore environment (sediment dynamics) sectors. Paired upper case letters denote typically strong linkages between depositional subenvironments and longshore sediment dynamics; lower case letters denote typically weak linkages

Longshore environment (sediment dynamics) sectors	Bathymetric environment zones			
	Offshore (O)	Nearshore (N)	Foreshore (F)	Backshore (B)
	Depositional subenvironment polygons			
Sediment source (net output) sectors:				
nonresistant bedrock (N)	on	NN	FN	BN
earlier lakebeds (E)	oe	NE	FE	BE
alluvial fan gravels (A)	oa	NA	FA	BA
stream mouth gravels (S)	OS	NS	FS	BS
river mouth sands and silts (R)	OR	NR	FR	BR
ooid-supplied shore (O)	oo	NO	FO	BO
Sediment transfer (steady state) sector:				
longshore transport (L)	ol	NL	FL	BL
Sediment sink (net input) sectors:				
beach accretion sink (B)	ob	NB	FB	BB
inland aeolian sink (I)	oi	NI	FI	BI
deep water sink (D)	OD	ND	FD	bd
Energy- and sediment-starved sectors:				
wave-starved shallows (W)	ow	nw	FW	BW
clast-starved resistant bedrock (C)	oc	nc	FC	BC

Fig. 16.6 Zone-sector-polygon model of lacustrine depositional subenvironments arrayed in conceptual plan, with 48 subenvironment polygons defined by intersections of four concentric, bathymetric environment zones (offshore, nearshore, foreshore, backshore; Table 16.1 and Fig. 16.2) and 12 radial sectors (longshore sediment dynamics sectors). See Table 16.4 for explanation of symbols
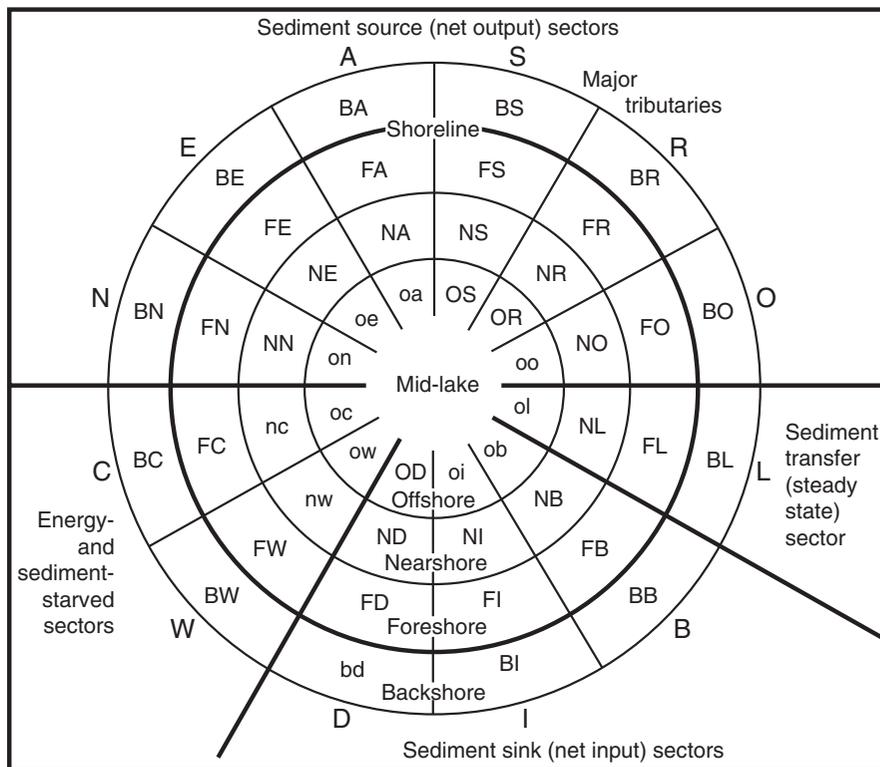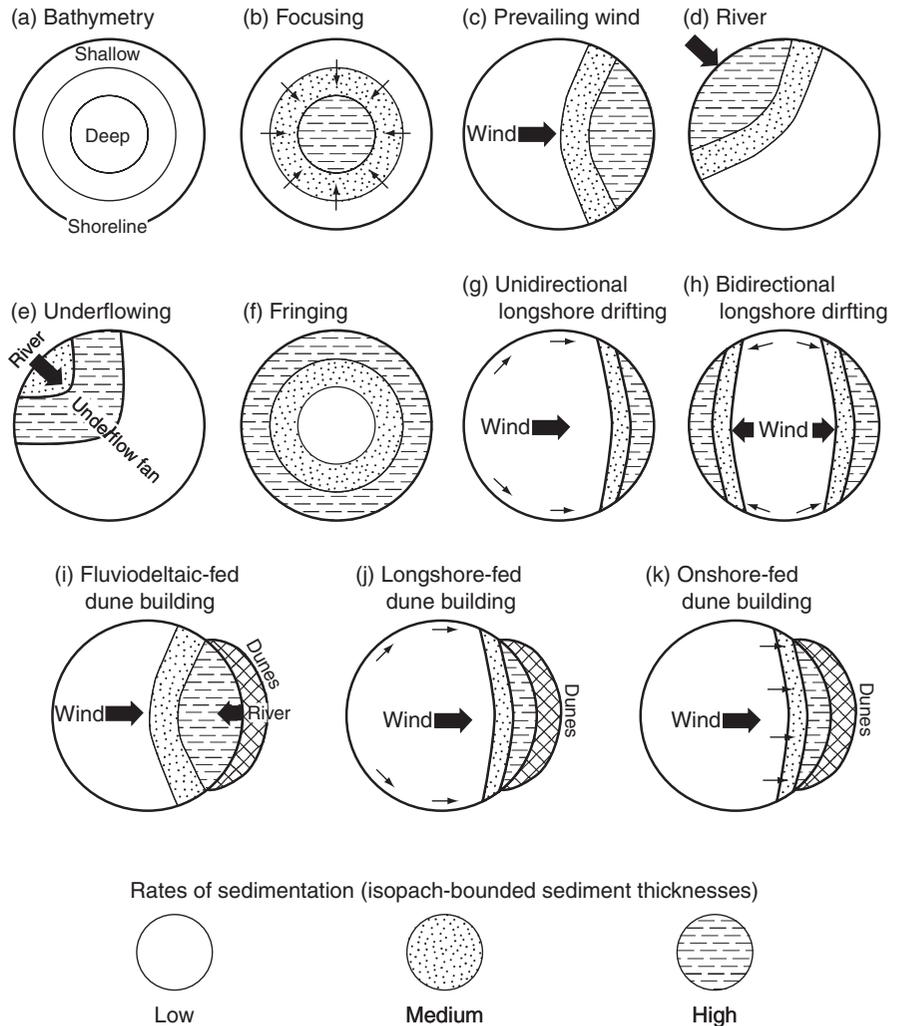
Fig. 16.7 'Bubble' models showing areal patterns of sediment redistribution in lacustrine depocentres; (**a–d**) are after Longmore (1986); (**e–k**) are additional patterns observed in western North America

(a) Bathymetry (b) Focusing (c) Prevailing wind (d) River

(e) Underflowing (f) Fringing (g) Unidirectional longshore drifting (h) Bidirectional longshore dirfting

(i) Fluviodeltaic-fed dune building (j) Longshore-fed dune building (k) Onshore-fed dune building

Rates of sedimentation (isopach-bounded sediment thicknesses)

Low   Medium   High

Straits are significant sites of geomorphic information (e.g. Burr and Currey 1992) in large hemiarid lake basins; major embayments, including the concave ends of elongate lakes, are important in most basins; corner bays, coves, and pockets with useful information occur in most basins and on islands (Fig. 16.9). Two exceptions to the geomorphic importance of lakeshore embayments and terrigenous sediment supply should be noted. It has long been recognized that (a) cuspate progradation (e.g. Gilbert 1885, Zenkovich 1967, Carter 1988) commonly produces detailed geomorphic records in lakeshore sectors that are straight or even convex lakeward, and (b) tufa accretion (e.g. Russell 1895, Morrison 1964, Benson et al. 1992, Benson et al. 1995, Ku et al. 1998) commonly produces detailed lakeshore geomorphic records during

intervals favourable to biogeochemical production of limnogenous sediments.

Stratigraphic sequences in hemiarid lake basins can be viewed as dominated by two geomorphic end members (Fig. 16.10) that alternate in basins with large lake-size variation. In the shallow water geomorphic pattern (Fig. 16.10a), basin floors undergo progressive enlargement and overall flattening by hydroaeolian planation, in which six phases of geomorphic activity occur repeatedly as conditions alternate between shallow (typically less than 2 m) inundation and subaerial exposure (Merola et al. 1989, Currey 1990): (1) wind-driven bodies of shallow standing water entrain suspended sediment by subaqueous and circumaqueous (lateral) scour; (2) deposition of suspended sediment occurs through the processes of settling in still water

Fig. 16.8 Forty-five common lakeshore geomorphic environments, arrayed *left to right* in order of increasing terrigenous sediment supply, and *bottom to top* in order of increasing embayment depth; uncommon or null sets are stippled. Geomorphic resolution of lakeshore history is largely a function of sediment supply and embayment depth. Lakeshore geomorphic environments merge laterally in many combinations. Headland environments, for example, are commonly flanked by hemi-embayment environments (see Fig. 16.9)

Lakeshore planimetric configuration (Embayment depth increases generally upward)	Lakeshore terrigenous sediment source (Sediment supply increases to right)				
	Litholacustrine or alluviolacustrine source			Fluviolacustrine source	
	Resistant bedrock	Nonresistant bedrock	Alluvial fan gravels	Stream-mouth gravels	Stream-mouth sands
Strait	fringing beaches	set of spits or cuspate barrier	set of spits or cuspate barrier		
Estuary				estuarine fan delta	estuarine delta and underflow fan
Major embayment (Bay)	bayhead beach	bayhead or baymouth beach ridges	bayhead or baymouth beach ridges	bayhead fan delta	bayhead delta and underflow fan
Hemi-embayment (Corner bay)	inner-corner beach	outer-corner spit, inner-corner barrier	outer-corner spit, inner-corner barrier	inner-corner fan delta	inner-corner delta
Minor embayment (Cove)	cove-head beach	cove-mouth barrier	cove-mouth barrier	cove-head fan delta	cove-head delta
Incipient embayment (Pocket)	pocket beach	pocket beach	pocket beach	pocket beach	
Broadly concave lakeshore	fringing beach	fringing beach ridge	fringing beach ridge	fringing beach ridges	beach-ridge plain
Straight lakeshore	fringing beach	cliff-base beach	bluff-base beach	fringing beach ridges	beach-ridge plain
Broadly convex lakeshore	wave-cut cliff and platform	wave-cut bluff and platform	wave-cut bluff and platform	arcuate fan delta or foreland	arcuate delta or foreland
Cuspate depositional lakeshore		cuspate barrier or double tombolo	cuspate barrier or double tombolo	cuspate fan delta or foreland	cuspate delta or foreland
Bold rocky headland	wave-cut cliff and platform	wave-cut bluff and platform	Geomorphic Record — Resolution High Low; Erosional; Depositional { Beach / Delta }		

and stranding in evaporating water; (3) desiccation reduces newly deposited suspended sediment to subaerial clasts of curled and cracked dry mud; (4) aeolian erosion deflates mud clasts and abrades desiccated surfaces; (5) aeolian deposition of mud clasts constructs foredunes as upwind-opening lunettes that partially encircle deflated areas, and as downwind-opening antilunettes that are largely surrounded by extensive deflated areas; and (6) post-aeolian diagenesis sinters and cements aeolian mud clasts. Materials in (5) and (6) are reworked by repetitions of (1)–(4). Draping lacustrine strata, especially lakeshore strata, are common in the deep water geomorphic pattern (Fig. 16.10b), where basin-floor planation is eclipsed by lakebed differentiation into offshore, nearshore, foreshore, and backshore bathymetric zones (Table 16.1 and Fig. 16.2).

After a lake cycle, portions of the lakebed geomorphic record in hemiarid lake basins may be (a) stratigraphically preserved but geomorphically obliterated through burial by nonlacustrine sediments, or (b) partially to wholly obliterated from geomorphic and stratigraphic preservation by erosion and by sediment reworking. Aeolian and alluvial fan processes are predominant obliterators in this

Fig. 16.9 Map of a
hypothetical island with one
hemi-embayment (corner
bay), two minor embayments
(coves), and three incipient
embayments with pocket
beaches
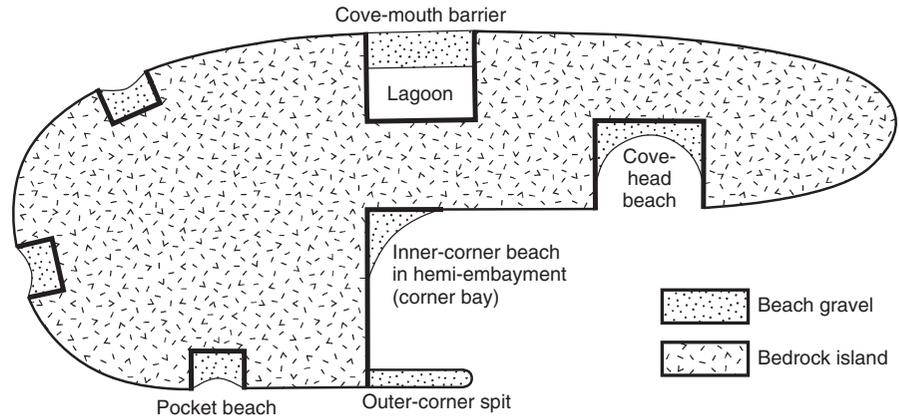
setting (Sack 1995). For example, lakeshore sand is commonly entrained and reworked into aeolian dunes (Hoelzmann et al. 2001). Mud pellets that accumulate as dunettes or lunettes and gypsum pellets that form dunes and sand sheets which bury lakebeds in one location are typically deflated from subaerially exposed fine-grained, basin-floor lakebeds upwind in the same lake basin (Fig. 16.11) (Sack 1994, Magee et al. 1995). In some basins, expanses of small yardangs mark substantial aeolian erosion of basin-floor lakebeds (Hoelzmann et al. 2001). When a lake cycle ends, ephemeral and intermittent streams as well as debris flows return to the highland-bordering alluvial fans that during the lake cycle were scored with shoreline bluffs and mined by waves and currents for downdrift coastal depositional landforms. Postlake alluvial fan processes may bury part of the shoreline record from the piedmont zone, but frequently breach and erode

lakeshore landforms, reworking the sediment into stream and alluvial fan deposits lower on the piedmont (Fig. 16.12).

This postlacustrine geomorphic change in co-lacustrine, as well as pre-lacustrine, lakeshore landforms is perceptible across a wide range of spatial scales. At the local end of the scale spectrum the change is revealed in surveyed profiles and cross sections, such as the erosional shoreline examples of Fig. 16.13. There, geomorphic modification is time-dependent change in which postlacustrine colluvial and alluvial wedges grow at the expense of buried mid-slopes and waning upper slopes. Regionally, in maps and imagery, landform decay is time-dependent plani-metric change in which postlacustrine geomorphic activity, commonly fluvial and mass wasting processes related to alluvial fan activity, gradually obliterates lateral segments of lakeshore, as in the generalized
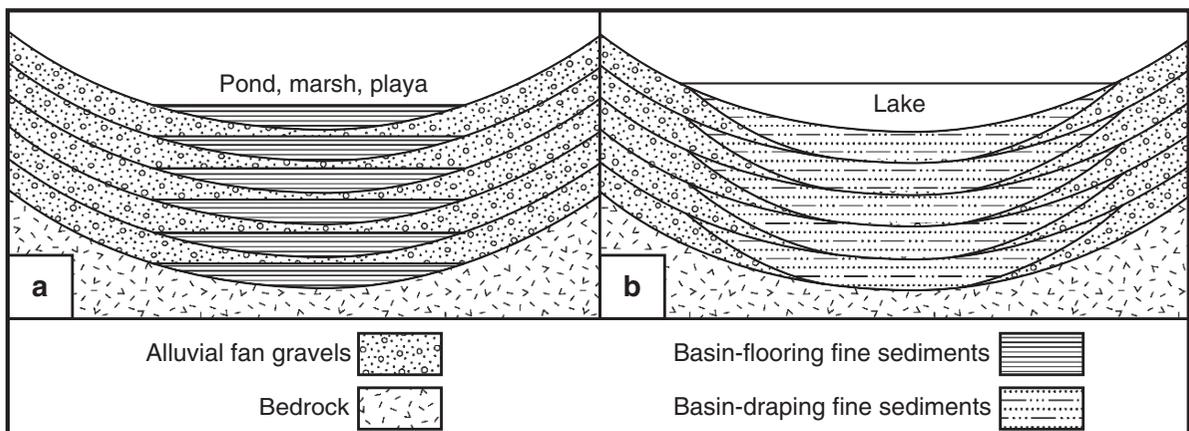

Fig. 16.10 Schematic cross sections of hemiarid lake basins with depositional sequences produced by recurring (**a**) shallow-water and (**b**) deep-lake cycles (after Currey 1990)

Fig. 16.11 Wind-blown clasts of sand-sized, carbonate-rich, mud pellets from a Lake Bonneville subbasin floor are deposited downwind in a source-bordering lunette
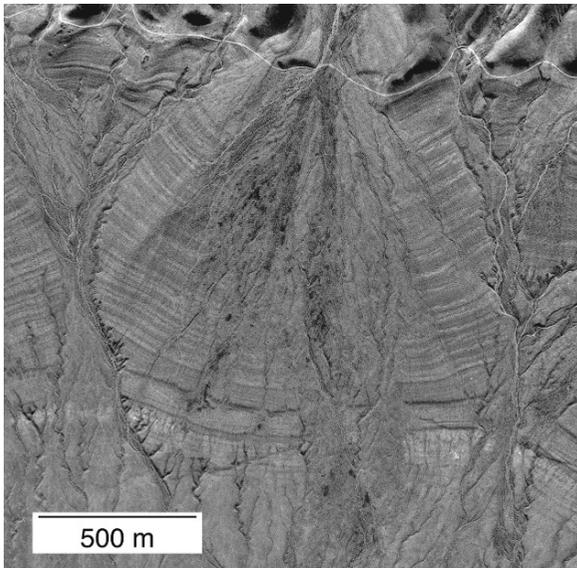

Fig. 16.12 On the highland-bordering piedmont zone of this hypertectonic hemiarid lake basin, postlake (Holocene) alluvial fan processes have obliterated segments of the Lake Bonneville shoreline geomorphic record

shoreline examples of Fig. 16.14. A useful gauge of geomorphic decay is given by the expression $1 - \pi_S$, where π_S is the shoreline preservation index, a dimensionless number from 0 to 1 that expresses visible shoreline length as a fraction of reconstructed total shoreline length (Sack 1995).

Palaeolake Studies

Despite postlacustrine subaerial processes, hemiarid lake basins commonly display considerable evidence of having contained standing water bodies in the late Pleistocene and Holocene. Studies of these palaeolakes draw on paradigms and techniques of the geosciences and biological sciences (e.g. Spencer et al. 1984, Benson et al. 1990, Oviatt et al. 1999, Last and Smol 2001, Balch et al. 2005) and have applications that relate to many science questions and public policy issues. The goals of palaeolake studies are to reconstruct palaeolake histories and to constrain reconstructions of regional and global environmental change. Selected aspects of palaeolake studies that are relevant to geomorphology are outlined here.

Palaeolake histories, and the histories of hemiarid lake basins, are reconstructed from lacustrine and non-lacustrine material evidence (bold rectangular boxes in Fig. 16.15). Much of this evidence is contained in depositional landforms, that is, in morphostratigraphic records. Morphostratigraphy, in which the methods of geomorphology and stratigraphy are employed interactively, is fundamental to successful research design in geomorphic studies of palaeolakes and their basins (Fig. 16.16). Morphostratigraphy is particularly useful in palaeolake studies that stress shoreline history as a basis for reconstructing hydrographic and tectonic history.

Spatial analysis of basinwide palaeolimnology, as illustrated by the idealized Great Basin palaeolake in Fig. 16.17, provides a unifying framework for reconstructing individual stages of palaeolake history. In qualitative terms, the proximal, medial, and distal reaches of compound palaeolakes tend to have distinctive patterns of hydrology, circulation, sedimentation, and lithofacies (Table 16.5) that help to explain geomorphic and stratigraphic patterns. In more quantitative terms, the proximal, medial, and distal reaches of many palaeolakes can be viewed as loci in ternary fields that depict relationships among

Fig. 16.13 Schematic cross sections showing postlacustrine modification of co-lacustrine slopes, with patterns that are typical of erosional shorelines in resistant bedrock (A-A′), nonresistant bedrock (B-B′), and alluvial fan gravels (C-C′). Colluvial wedge edge (large dot = upper limit of positive colluvium mass balance) migrates upslope toward middle of co-lacustrine cliff (i.e. in resistant bedrock) or bluff (i.e. in nonresistant bedrock and sediments) as a function of postlacustrine time
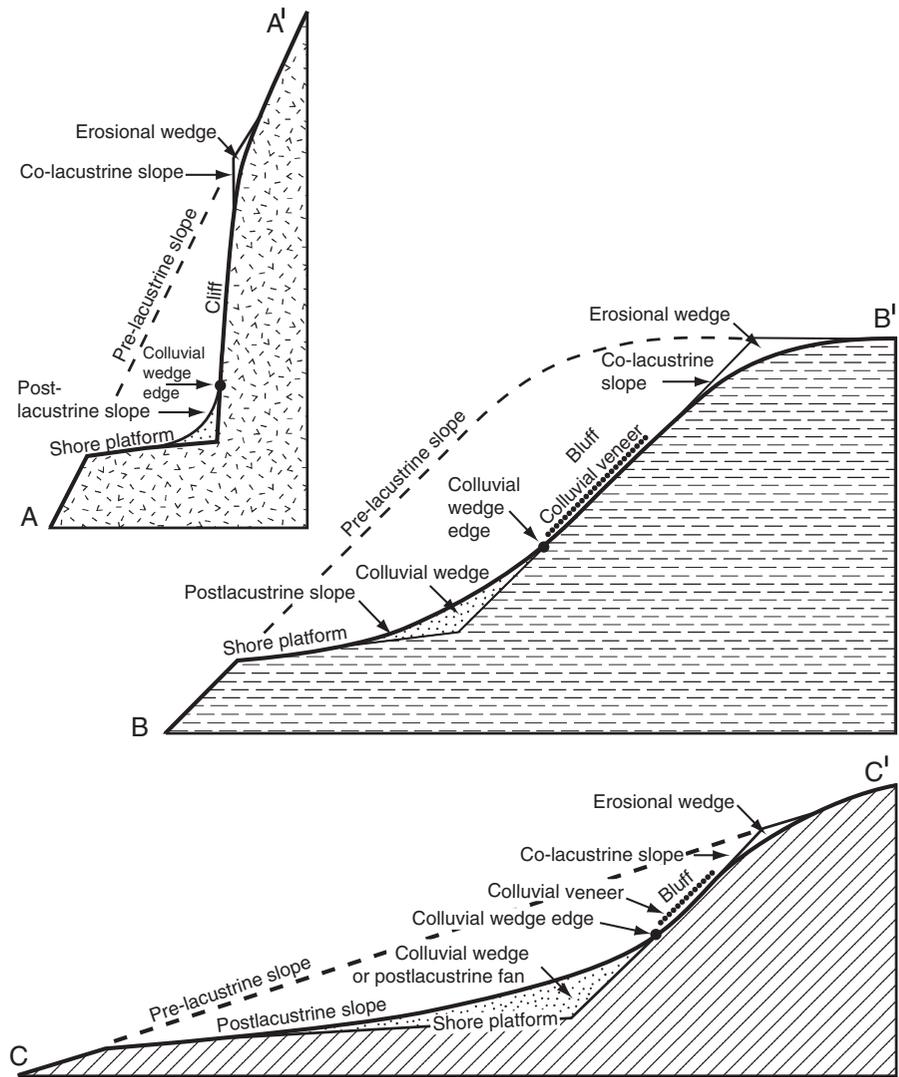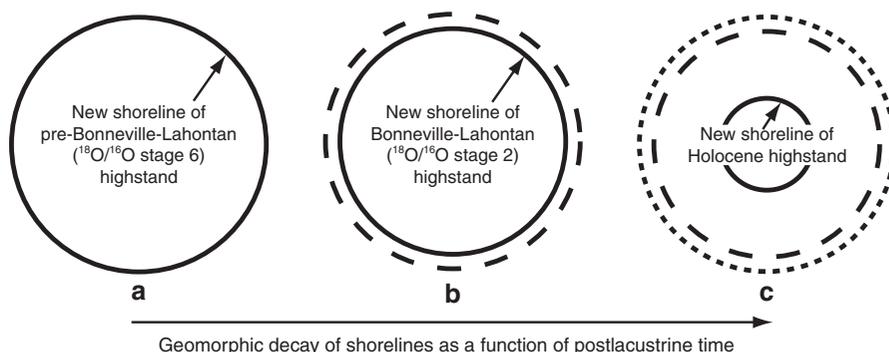
palaeolimnologic variables, including inputs to the lacustrine water balance (Fig. 16.18a), origins of net horizontal motion in the epilimnion (Fig. 16.18b), and origins of sediment at the bottom of the water column (Fig. 16.18c).

In contrast to basinwide palaeolimnology, basinwide (or subbasin-wide) stratigraphy, as illustrated by the idealized Great Basin graben in Fig. 16.19, provides the framework for reconstructing long intervals of palaeolake history. The large variations in water body size that are so characteristic of hemiarid lake basins result in depositional sequences with complex lateral and vertical changes of lithofacies, biofacies, and chemofacies. This complexity tends to be cyclical, which lends itself to what the *North American Strati-*

graphic Code (NACSN 2005) terms allostratigraphic classification. In Fig. 16.19, four allostratigraphic units of alloformation rank, each including two or three lithofacies, can be differentiated on the basis of laterally traceable discontinuities, in this case buried soils and disconformities (NACSN 2005). Stratigraphic markers, including regional discontinuities that generally date from palaeolake lowstands, assume great importance in hemiarid lake basins (e.g. Table 16.6) for two reasons: (a) in some cases they are the lower and upper boundaries of alloformations, and (b) in many other cases they are indispensable tools for correlating intra-alloformation events within individual basins and from one basin to another.

Fig. 16.14 Schematic plans showing postlacustrine decay of successively younger concentric shorelines. Patterned after late Quaternary shorelines in Nevada (e.g. Mifflin and Wheat 1979). Shoreline (**a**) probably formed about 140 ka, (**b**) about 15 ka, and (**c**) about 2.6 ka

New shoreline of pre-Bonneville-Lahontan ($^{18}O/^{16}O$ stage 6) highstand

a

New shoreline of Bonneville-Lahontan ($^{18}O/^{16}O$ stage 2) highstand

b

New shoreline of Holocene highstand

c

Geomorphic decay of shorelines as a function of postlacustrine time

Advances in palaeolake studies have closely paralleled refinements in geochronology (e.g. Easterbrook 1988, Forman 1989, Sack 1989, Birkeland et al. 1991, Noller et al. 2000, Björck and Wohlfarth 2001). In the last two decades, increasing spatiotemporal resolution has made hemiarid lake basins prime venues for studies of geomorphic kinematics (time rates of past landform changes) (Sack 1995), hydrographic kinematics (time rates of past waterbody changes), and crustal-upper mantle geodynamics (Bills and May 1987, Bills et al. 1994, 2002). Because radiocarbon dating has been such an important tool in late Quaternary palaeolake studies (e.g. Table 16.7), refinements and improved understanding of that technology are noteworthy (Benson 1993, Benson et al. 1995, Geyh et al. 1999, Fornari et al. 2001, Pigati et al. 2004). The shift from β-decay counting to accelerator mass spectrometry (AMS) measurement of ^{14}C has allowed ages of good precision to be obtained from samples containing milligram quantities of carbon. Applications include AMS ^{14}C dating of organic carbon traces in lake sediments (e.g. Thompson et al. 1990, Peck et al. 2002) and in lakeshore rock varnish (e.g. Dorn et al. 1990, Liu and Broecker 2007). As calendaric calibration of ^{14}C ages has improved (e.g. Bard et al. 1990, Stuiver and Reimer 1993, Stuiver and van der Plicht 1998), so has precision in studies of palaeolake kinematics and geodynamics.

Other geochronology advances that have proven useful for palaeolake studies include various types of luminescence dating (e.g. Smith et al. 1990, Kuzucuoglu et al. 1998, Oviatt et al. 2005, Stone 2006) dating, and geochronometry using cosmogenic isotopes other than ^{14}C. For example, cosmogenic helium (^3He) and chlorine (^{36}Cl) have seen successful experimental use in dating basalt erosion and halite deposition, respectively, in the Lake Bonneville region, but ^3He was recently unsuccessful in the study of another Great Basin palaeolake (Carter et al. 2006).

Within-basin and between-basin comparisons of isotopic ages of possibly synchronic (coeval) features are commonly of interest in palaeolake studies. A dimensionless basis for comparing paired ages, that is, the ages before present of two samples from one palaeolake basin or of one sample from each of two palaeolake basins, is the index of temporal accordance ι. This index ranges from 0 where paired ages are completely dissimilar (discordant) to 1 where paired ages are identical (accordant). In Table 16.8, $\iota = 1 - [(\text{older age} - \text{younger age})/(\text{older age} + \text{younger age})]$.

Beginning with the work of Russell (1885) and Gilbert (1890), late Quaternary hydrographic change in hemiarid lake basins has traditionally been portrayed by hydrographs in which surface elevation, maximum depth, average depth, area, volume, or mass of standing water is plotted as a function of relative or absolute time. With increasing spatiotemporal resolution of lakeshore morphostratigraphy have come increasingly detailed palaeolake histories, often with several temporal wavelengths and spatial amplitudes of hydrographic change appearing as cycles within cycles (Fig. 16.20). First- and second-order temporal wavelengths, sometimes termed episodes and phases (NACSN 2005), are measured in millennia. Third- and fourth-order temporal wavelengths, sometimes termed oscillations (e.g. Currey 1990) and stands, are mostly measured in centuries and decades (e.g. Currey and Burr 1988). 'Instantaneous' singularities in palaeolake history are commonly referred to as events, with some of the more notable being seismic, pyroclastic, and catastrophic flood (e.g. Jarrett and Malde 1987) events.

Fig. 16.15 Flowchart
showing elements of
palaeolake history (rounded
boxes), which are
reconstructed from the
geologic and geomorphic
records (bold rectangular
boxes) in lake basins and
surrounding regions by
response-process inference
that is essentially counter to
process → response causality
(after Currey 1990)
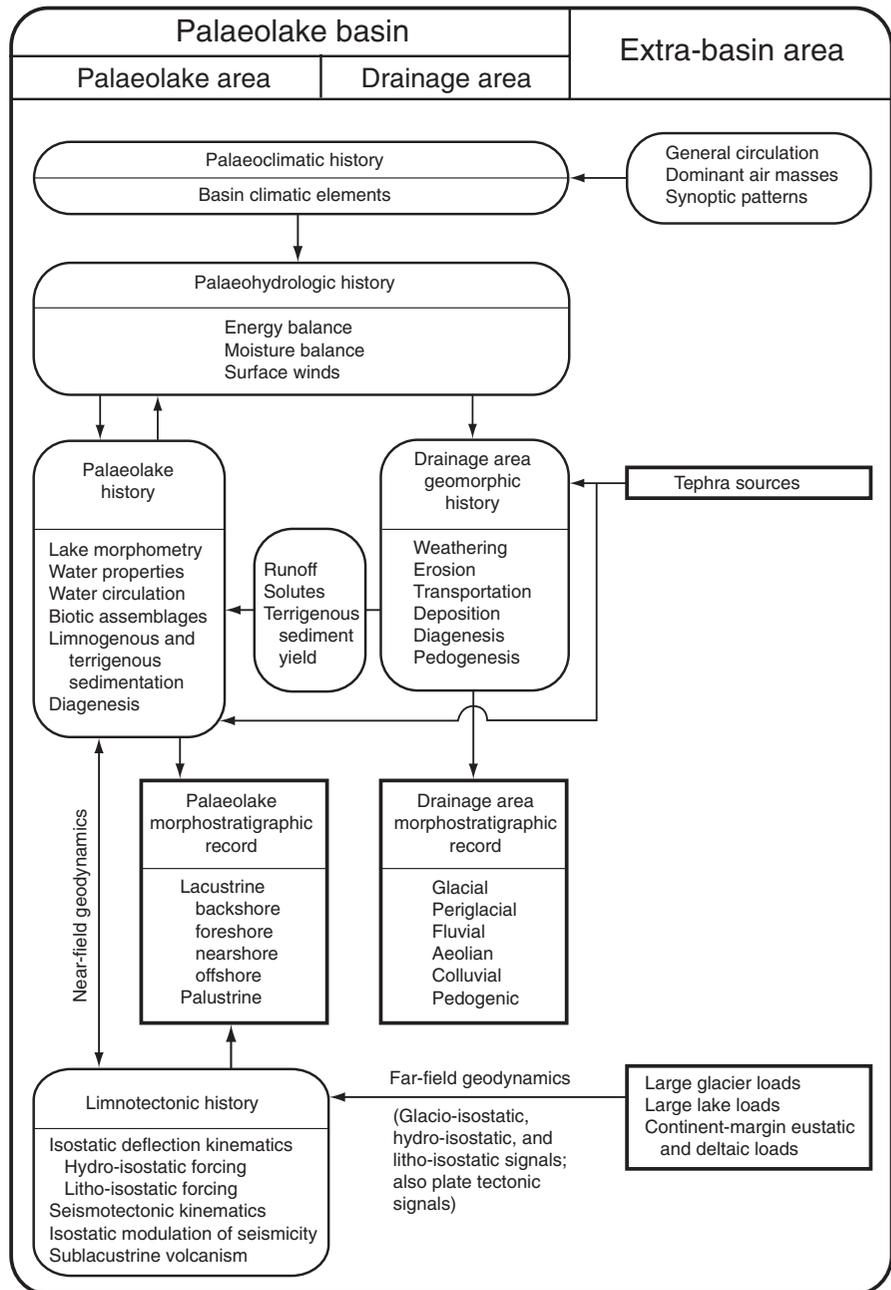
Geomorphic and palaeoenvironmental change that may not be evident in traditional hydrographs can often be represented explicitly in geomorphically annotated hydrographs. In Fig. 16.20, annotations highlight several hypothetical but plausible features. Ooid beaches indicate saline stages, possibly with brine shrimp. Prominent gravel beaches mark transgressive stages, when pre-lacustrine alluvial fans and colluvium-mantled slopes were initially worked into beaches. Tufa-cemented stonelines denote regressive stages, when water hardness increased and older beach gravels were locally reworked and cemented. Intrenched and prograded deltas indicate a falling local base level, that is, a regression. A salinity crisis near the close of the lacustral episode is represented by fetid, organic-rich sediments that accumulated offshore
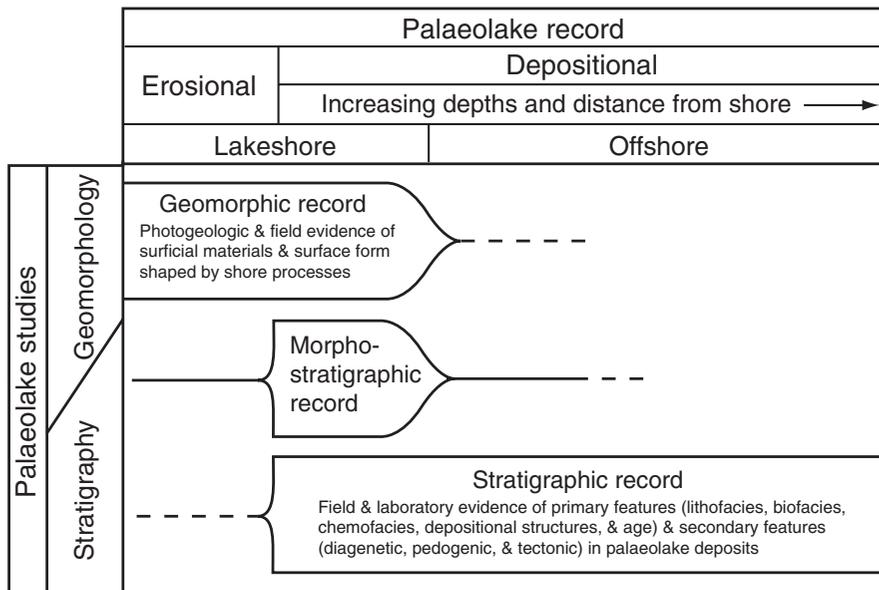
Fig. 16.16 Morphostratigraphy combines the methods of geomorphology and stratigraphy in studies of palaeolake depositional landforms (after Currey and Burr 1988)
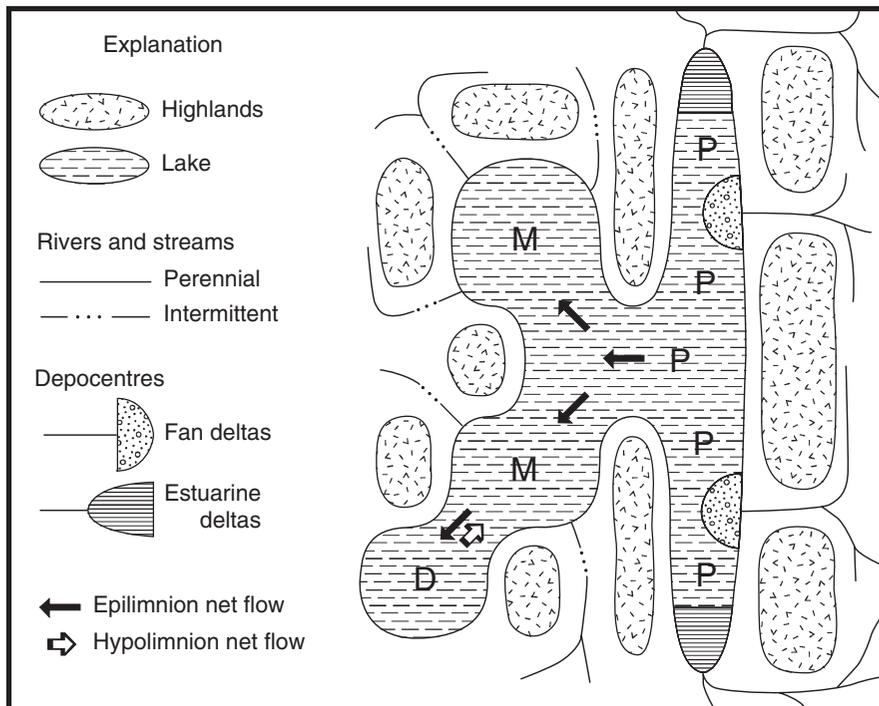

Fig. 16.17 Map of hypothetical palaeolake in hemiarid basin showing proximal (P), medial (M), and distal (D) reaches (after Currey 1990). Arrows show general directions of net flow (see Table 16.5 and Fig. 16.18)

Table 16.5 Conditions typical of proximal, medial, and distal reaches in closed-basin lakes*

	Proximal reach	Medial reach	Distal reach
Hydrology	Local runoff dominant source of water-balance input; epilimnion salinity relatively low	Transbasin flow important source of water-balance input	Transbasin flow dominant source of water-balance input; epilimnion salinity relatively high
Circulation	Water-balance-driven net outflow in epilimnion	Water-balance-driven net throughflow in epilimnion	Water-balance-driven net inflow in epilimnion
Sedimentation	High rates of terrigenous and very low rates of limnogenous sedimentation	Low rates of terrigenous and limnogenous sedimentation	Low rates of limnogenous and very low rates of terrigenous sedimentation
Lithofacies	Fluviodeltaic clastics prevalent	Offshore micrite (typically calcite) and lakeshore clastics	Offshore micrite (typically aragonite) and lakeshore carbonates

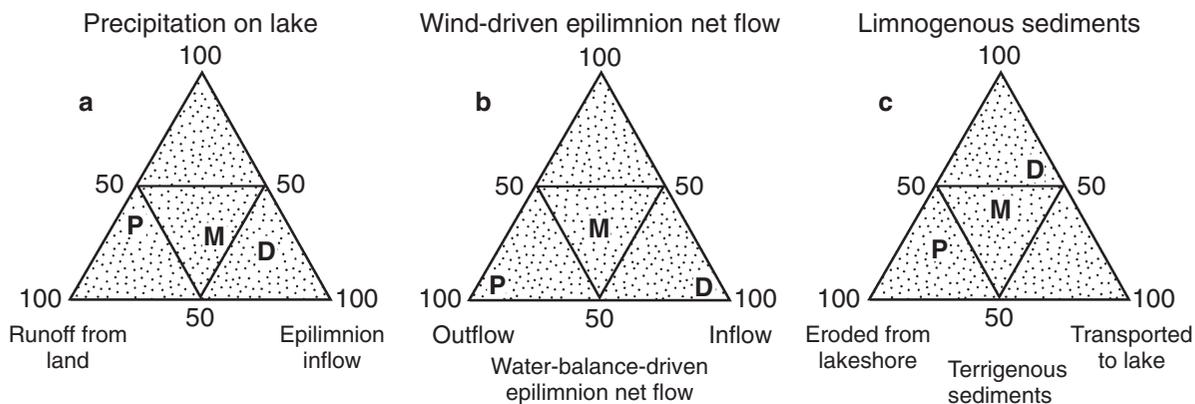*Adapted from Currey (1990). See Figs. 16.17 and 16.18.

Fig. 16.18 Loci of proximal (P), medial (M), and distal (D) reaches of hypothetical palaeolake (Fig. 16.17 and Table 16.5) in ternary fields depicting lake dynamics: (**a**) water balance inputs as a percentage of long-term receipts, (**b**) sources of net horizontal motion in epilimnion as a percentage of long-term net epilimnion flow, and (**c**) sources of sediments at bottom of water column as a percentage of long-term sedimentation (after Currey 1990)
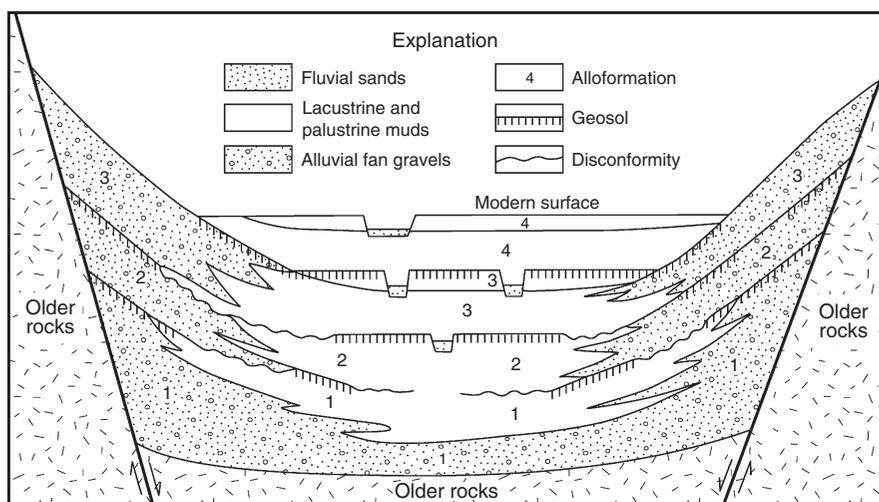

Fig. 16.19 Schematic cross section illustrating allostratigraphic classification of lacustrine muds and other sediments in a graben (after NACSN 2005). Patterned after Cache Valley, Utah, in the Lake Bonneville basin (Williams 1962)

Table 16.6 Stratigraphic markers of regional importance in Lake Bonneville studies: B = marker beds (distinctive sediment layers), H = marker horizons (distinctive surfaces between sedi- ment layers), and P = marker profiles (sediment layers imprinted by subaerial palaeoenvironments or palaeoseismicity)

Stratigraphic markers	B	H	P	Examples
Offshore micrites:				Oviatt et al. 1994
white marl	●			
with abundant dropstones	●			
Coquinas:				Oviatt 1987
gastropod	●			
ostracod	●			
Tephra:				Oviatt and Nash 1989
silicic	●			
basaltic	●			
Evaporites:				Eugster and Hardie 1978
mirabilite	●			Eardley 1962
halite	●			
Stonelines:				
foreshore	●			
fluviolacustrine	●			
buried desert pavement	●	●		Currey 1990
Tufa:				
tufacrete ledges	●	●	●	
heads and mounds	●	●		Carozzi 1962
beachrock and hardground	●			Spencer et al. 1984
Transgressive basal layers:				
gravels on truncated geosols	●	●	●	
basal organics (muck and wood)	●			Scott et al. 1983
Oolitic sand layers	●			Eardley et al. 1973
Buried aeolian deposits:				
loessal colluvium	●	●	●	
aeolian sand	●	●		
Discontinuities:				NACSN 2005
erosional unconformities		●		
nondepositional unconformities		●		
Red beds:				
in situ		●	●	
transported	●			Currey 1990
Soils:				Birkeland et al. 1991
buried soils (geosols)		●	●	Eardley et al. 1973
relict (residual) soils		●	●	
K horizons (caliche)		●	●	Machette 1985
natric horizons		●	●	
Root tubules (rhizoliths)		●	●	Eardley et al. 1973
Desiccation cracks		●	●	Currey 1990
Seismically convoluted bedding			●	

when freshwater plankton populations were annihilated by (and pickled in) increasingly concentrated brines. Red beds mark emergence of the basin floor at the close of the lacustral episode, when previously anoxic hypolimnion sediments were reddened by oxidation of Fe^{+2} sulphides to Fe^{+3} oxides. Lastly, salt beds are former dissolved solids forced from solution by volumetric reduction at the close of the lacustral episode.

Applied Palaeolake Studies

Palaeolake studies have applications in many fields, including climatology, hydrogeology, wetlands and shorelands management, mineral industries, and limneotectonics. Many of these applications are based on the principle of converse uniformitarianism (conformitarianism), which states that the past is the key to the
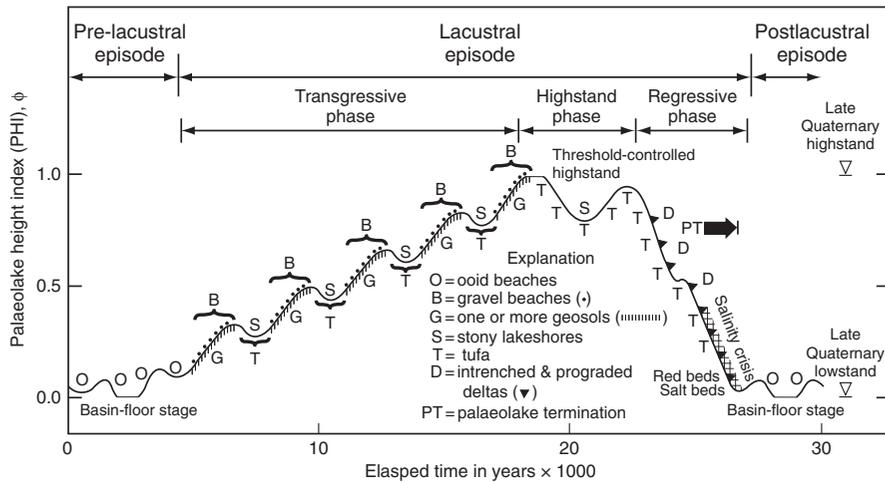
Fig. 16.20 Geomorphically annotated hydrograph (*heavy line*) of a hypothetical palaeolake cycle in a hydrographically closed basin. Patterned in part after Lake Bonneville (e.g. Currey et al. 1984). Hydrograph depicts decamillennium-scale change (lacustral episode and phases) and millennium-scale oscillations (subphases); century-scale fluctuations are not shown except as implied by beach dots; decade-scale variation lies within the hydrograph line width

present and future. The importance of palaeolakes as sources of proxy climate data in atmospheric research, including global change studies and general circulation models, is well documented (e.g. Street-Perrott and Harrison 1985, Benson et al. 1998, Broecker et al. 1998, Lin et al. 1998, Stager et al. 2002). In the western United States, studies of Quaternary lakes provide crucial information in hydrogeologic evaluations of potential sites for long-term storage of high-level nuclear waste and other sensitive projects (e.g. Williams and Bedinger 1984, Sargent and Bedinger 1985).

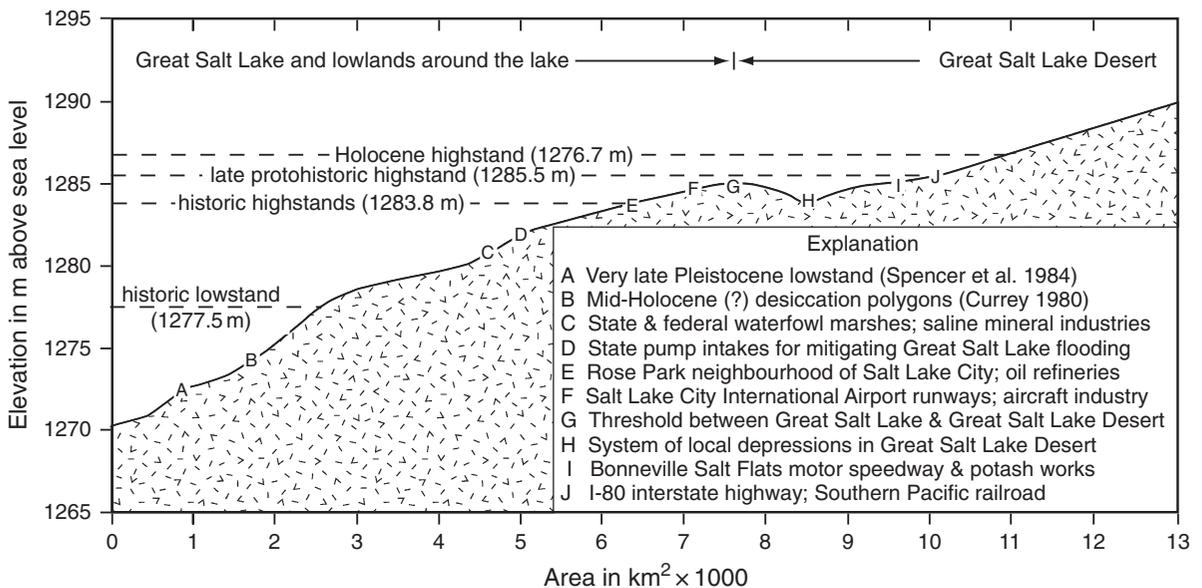Wetlands management in hemiarid lake basins seeks to minimize the adverse effects that hydrographic

Fig. 16.21 Geomorphically annotated hypsograph showing singular levels in the lowest part of the Great Salt Lake basin, Utah (after Currey 1990). Average gradient across area depicted is only 0.0002

Table 16.7 Organic carbon (O) and carbonate carbon (A = aragonite, C = calcite, D = dolomite) materials yielding radiocarbon ages of relevance to Lake Bonneville studies

Material	O	A	C	D
Wood fragments	●			
Charcoal flecks	●			
Spring bog peat	●			
Marsh muck	●			
Seeds	●			
Geosol humates	●			
Biodust in rock varnish	●			
Bone collagen	●			
Neotoma excreta	●			
Mollusca, shell proteins	●			
Mollusca, snail shells		●		
Mollusca, clam shells		●		
Ostracods, shells		●		
Ostracods, shell proteins	●			
Ooids		●		
Artemia faeces in ooids	●			
Marl, *Chara* phytoliths		●	●	
Marl, micrite		●	●	
Plankton residues in mud	●			
Tufa, algaloid		●	●	
Algal residues in tufa	●			
Tufacrete matrix		●	●	
Travertine, cave			●	
Travertine, spring			●	
Caliche			●	
Root tubule rhizoliths			●	
Saline mudflat carbonate				●

Table 16.8 Index of temporal accordance (IOTA)

Temporal accordance	IOTA (ι)
High (paired ages plausibly synchronous)	$1.00 \geq \iota > 0.99$
Problematic (paired ages possibly synchronous)	$0.99 > \iota > 0.90$
Low (paired ages doubtfully synchronous)	$0.90 > \iota \geq 0$

fluctuations can have on vital aquatic environments, including those that support waterfowl, recreation and tourism, and saline industries (e.g. Fig. 16.21). Shorelands management in hemiarid lake basins seeks to minimize, by measures such as planning, zoning, dyking, and pumping, the potential impacts of rising lake levels on transportation and communication networks, public utilities, industrial development, and urban sprawl. Increasingly, wetlands and shorelands management strategies are founded on baseline information from palaeolake studies.

Many hemiarid lake basins contain significant mineral resources, chiefly potash, soda ash, sodium chloride, borates, nitrates, magnesium, lithium, ura-

nium, sand and gravel, volcanics, zeolites, diatomite, and fossil fuels (e.g. Reeves 1978, Gwynn 2002). Palaeolake studies and mineral industries tend to be mutually supportive, with the former providing information that often is of value in assessing mineral reserves and development options, and the latter contributing to the corpus of palaeolake knowledge by making available subsurface information that frequently has been obtained at great expense (e.g. Smith 1979, Smith et al. 1983).

Limneotectonics (lacustrine neotectonics) is the use of palaeolake levels as long baseline tiltmeters and palaeolake beds as local slipmeters to measure co-lacustrine and postlacustrine rates of crustal motion, particularly vertical motion (Currey 1988, Bills et al. 1994, 2002). A palaeolake level is the originally horizontal upper bounding surface (atmosphere-lake interface) of a palaeolake stage of known age, as reconstructed from lakeshore morphostratigraphic evidence that is analogous to the raised shorelines (e.g. Rose 1981) of many sea coasts. A palaeolake bed is the lower bounding surface (lake-substrate interface) of a palaeolake stage of known age, as observed in the lakebed stratigraphic record.

In many hemiarid lake basins, total neotectonic vertical deformation is the algebraic sum of (a) seismotectonic vertical displacement caused by faulting, and (b) one or more (near-field, far-field, hydro-, glacio-, litho-) isostatic vertical deflection signals generated by crustal loading and/or unloading. An important goal of limneotectonics is to assess the contribution made by each of these sources of crustal motion (e.g. Fig. 16.22).

Palaeolakebeds that have been displaced by faulting are common in hemiarid lake basins that owe their existence to hypertectonism (Fig. 16.1), as does the basin of Lake Bonneville-Great Salt Lake. Beneath Great Salt Lake, seismic reflection surveys (Mikulich and Smith 1974) and many boreholes have helped to define the geometry of subbottom palaeolake beds and, thereby, the late Cenozoic kinematics of subbottom tectonic blocks (e.g. Pechmann et al. 1987). In backhoe trenches across postlacustrine fault scarps at many localities in the Lake Bonneville-Great Salt Lake region, detailed studies of offset palaeolake beds (and of scarp-burying colluvial wedges) have provided insights into the magnitudes and recurrence intervals of late Quaternary seismic events (e.g. Machette et al. 1991).
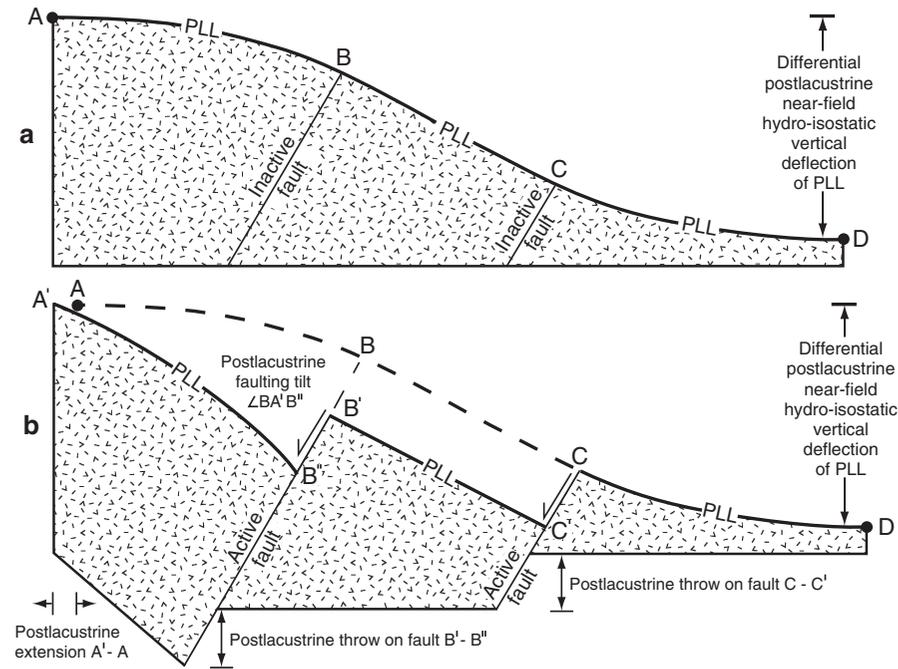
Fig. 16.22 Schematic profiles (not to scale) of regional and sub-regional deformation of an originally horizontal palaeolake level (PLL) of known age (after Currey 1990). A-D is regional trend of a hydro-isostatically deflected PLL. A and D are PLL localities of maximum and minimum observed isostatic rebound, that is, A is the isostatic deflection centroid and D is a distal point on an isostatic deflection radius. (**a**) Total postlacustrine neotectonic deformation comprises only near-field hydro-isostatic deflection. (**b**) Total postlacustrine neotectonic deformation comprises regional isostatic deflection (dashed) overprinted with subregional seismotectonic displacement, including rotational displacement of tectonic block A′-B″ and translational displacement of tectonic block B′-C′

At several sites in the Lake Bonneville-Great Salt region, maximum late Quaternary seismicity and maximum late Quaternary isostatic rebound seem to have coincided in time, particularly where the orientation of seismotectonic extension corresponded with the orientation of isostatic deflection radii (Fig. 16.22b). This suggests a pattern in which the tempo of seismotectonic displacement is modulated by the vertical direction and tempo of hydro-isostatic deflection. Specifically, where the traces of active extensional (normal) faults are tangent to isolines (isobases) of near-field hydro-isostatic deflection, seismicity may be (a) suppressed during times of sustained isostatic subsidence, and (b) enhanced during subsequent times of maximum isostatic rebound.

Palaeolake levels that have undergone near-field hydro-isostatic deflection occur in hemiarid lake basins with histories of large water load changes, as in the Lake Lahontan (Mifflin and Wheat 1971) and Lake Bonneville (Crittenden 1963, Currey 1982, Bills

et al. 2002) regions of the Great Basin. Subsequent to Lake Bonneville's highstand about 15 ka, when the lake had a depth of over 370 m and a volume of almost $10,000 \, \mathrm{km}^3$, about 74 m of differential uplift occurred within the near-field area ($52,000 \, \mathrm{km}^2$) enclosed by the highest shoreline (Currey 1990). About 16 m of additional differential uplift can be detected as far-field effects in small lake basins up to 120 km beyond the highest Bonneville shoreline (e.g. Bills and Currey 1998, May et al. 1991). Post-Bonneville rebound has totalled less than 1 m since 2.6 ka, as gauged by the essentially horizontal shoreline that marks the Holocene highstand of Great Salt Lake.

The maximum rate of hydro-isostatic vertical deflection in the Bonneville basin is estimated to have been $-7.3 \, \mathrm{cm \, y}^{-1}$ at about 15 ka (Currey and Burr 1988). This is somewhat less than maximum rates of glacio-isostatic rebound in Fennoscandia and Canada, where regional crustal uplift exceeded $10 \, \mathrm{cm \, y}^{-1}$ in very late Pleistocene and early Holocene

time (Lajoie 1986). Where (a) known water loading and unloading histories have acted on (b) unknown Earth rheologies to produce (c) known hydro-isostatic deflection histories, limneotectonics can be a powerful tool in Earth rheology modelling (Bills and May 1987), that is, limneotectonics can be a rich source of insight into the thickness and flexural rigidity of the Earth's crust and the viscosity layering of the upper mantle.

Geomorphic patterns of palaeolake evidence in hemiarid lake basins direct researchers to many important applications. As the embodiment of sediment sources, pathways, and sinks, depositional lacustrine landforms are especially noteworthy sources of information on the palaeohydrography, and underlying palaeohydrology, palaeoclimatology, and tectonics, of hypertectonic hemiarid terrain. As the appreciation of the relevance to the present and future of the record of past environments continues to grow, so should the research opportunities for scientists studying hemiarid lake basins.

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