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SEDIMENTOLOGY OF ACID SALINE LAKES IN SOUTHERN WESTERN AUSTRALIA: NEWLY DESCRIBED PROCESSES AND PRODUCTS OF AN EXTREME ENVIRONMENT

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ABSTRACT: **Naturally acid saline systems with pH values between 1.7 and 4 are common on the Yilgarn Craton of southern Western Australia. A combination of physical and chemical processes here yield a previously undescribed type of modern sedimentary environment. Flooding, evapoconcentration, desiccation, and eolian transport at the surface, as well as influx of acid saline groundwaters, strongly influence these lakes. Halite, gypsum, kaolinite, and iron oxides precipitate from acid hypersaline lake waters. Shallow acid saline groundwaters affect the sediments of the lakes and associated mudflats, sandflats, channels, and dunes by precipitating early diagenetic halite, gypsum, iron oxides, clays, jarosite, and alunite. These modern environments would likely yield a rock record composed mostly of bedded red siliciclastic and reworked gypsum sand, alternating with less common beds of bottom-growth gypsum and halite, with alteration by early diagenetic features diagnostic of acid saline waters. This documentation of sedimentary processes and products of modern acid saline environments is an addition to the comparative sedimentology knowledge base and an expansion of the traditional models for classifying brines. Implications include better interpretations of terrestrial redbeds and lithified martian strata, improved acid remediation methods, new models for the formation and occlusion of pores, and the new setting for finding previously undescribed extremophiles.**

INTRODUCTION

Hundreds of ephemeral saline lakes exist in southern Western Australia. These lakes are shallow and deposit siliciclastic and chemical sediments. Our studies show that a notable characteristic of this region is the great diversity of pH in lakes in close proximity (Fig. 1). Approximately 40% of these lakes have pH less than 4 (we call these extremely acid), while nearby lakes are moderately acid (pH 4–6), neutral (pH 6–8), or even moderately alkaline (pH greater than 8). Flooding, evaporation, desiccation, winds, and groundwater-contributed acidity determine the sedimentary characteristics of all of these lakes. These acid saline lake waters and groundwaters do not fit the traditional classifications for brines. The combination of physical and chemical processes yield a previously undescribed type of modern sedimentary system. Here, we document the surface processes and resulting sedimentary facies of extremely acid saline lake systems.

Implications of the sedimentology of acid saline lakes are varied and abundant. First, these natural acid saline lakes and groundwaters in Western Australia are an environmental hazard, necessitating the piping of desalinized seawater hundreds of kilometers inland for residential and industrial use. Clearing vegetation for cropland has caused the recent rising of acid saline groundwaters, resulting in poor farming and ranching conditions. Elsewhere in the world, man-made or man-influenced acid waters, such as acid-mine drainage streams, also present a challenging environmental problem. Abandoned sulfide pit mines in the western U.S., for example, are filled with sulfuric acid and pose a threat to migratory birds. A better understanding of the various types of natural acid waters may lead to improved remediation methods. Secondly, acid waters cause dissolution and/or precipitation in host rocks, possibly leading to models for secondary pore formation and occlusion of interest to the petroleum, environmental, and mining industries. Thirdly, natural acid saline lakes host unique microorganisms and, thus, can help in the study of the diversity of life, biogeochemical processes, and bioremediation techniques (Hong et al. 2006). Finally, mineralogical and geochemical data from lithified martian strata suggest that acid saline waters may have once acted there (Squyres et al. 2004). Thus, terrestrial acid saline lakes may be analogs for past martian environments, as well as for some ancient terrestrial red beds (Benison 2006; Benison and Bowen 2006; Benison and Goldstein 2002; Benison and LaClair 2003). Although some intriguing geochemical processes occur in the groundwaters to produce acidity and yield dynamic early diagenesis, this paper focuses on the sedimentary facies and the surface processes that produced them.

BACKGROUND

Acid Saline Lakes

Acid saline lakes have been recognized in both Western Australia (Alpers et al. 1992; Mann 1988; McArthur et al. 1991) and northwestern

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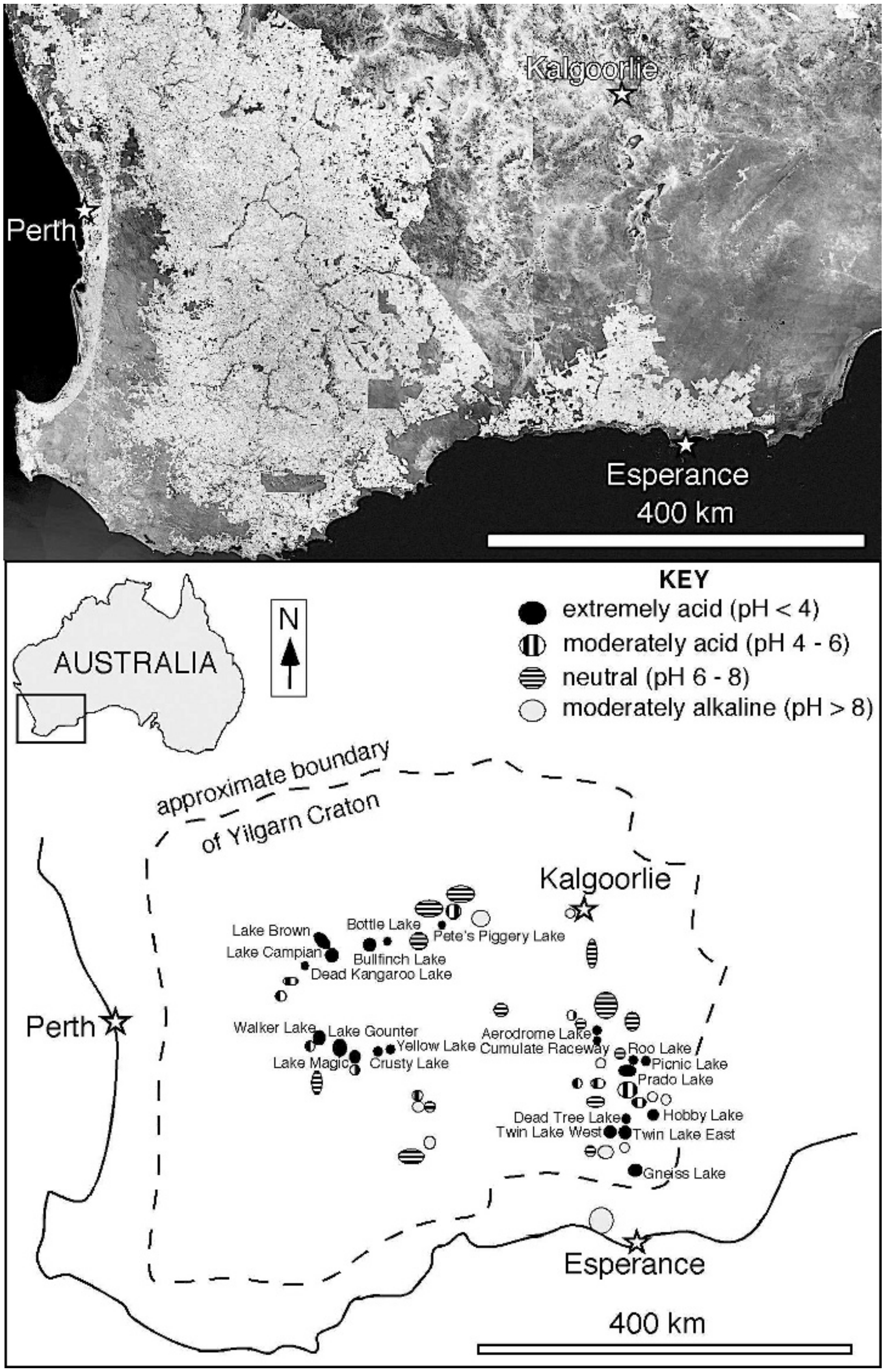

FIG. 1.—Approximate locations and relative sizes of saline lakes in southern Western Australia. Top: Landsat image. Bottom: Map of 58 lakes studied during austral winters of 2001 and 2005 and austral summer of 2006. Key shows lake types based on pH range. Names of only 21 extremely acid lakes are labeled here (names are for closest black dot) and only Lake Brown, Lake Campian, Lake Gounter, Lake Magic, and Walker Lake are formal names.

Victoria (Long et al. 1992a; Macumber 1992), as well as in Chile (Risacher et al. 2002). Published work has focused on specific mineralogical and chemical characteristics of these waters and their adjacent groundwaters. However, the sedimentology of these lake systems has not been described. Surface processes and resulting sediments are important in terms of understanding these extreme environments and identifying other acid saline lakes in the geologic record.

The acid saline lakes in northwestern Victoria have received the most detailed study of the three known natural acid saline lake settings. Detailed studies of the geochemistry and hydrogeology of the Lake Tyrrell and adjacent groundwaters have been published (e.g., Long et al. 1992a; Long e al. 1992b; Macumber 1992). We have also conducted field work at Lake Tyrrell and six other saline lakes in northwestern Victoria in August 2001 and July 2005. We found all the lake waters to be in the neutral range (pH 5.3–8.0), with only very localized acidity (pH 3.5–6.1) in the shallow groundwaters adjacent to Lake Tyrrell. For this reason, we consider the acid lakes in southern Western Australia, with lake-water pH values of 1.7–4, to be better examples of acid sedimentary systems.

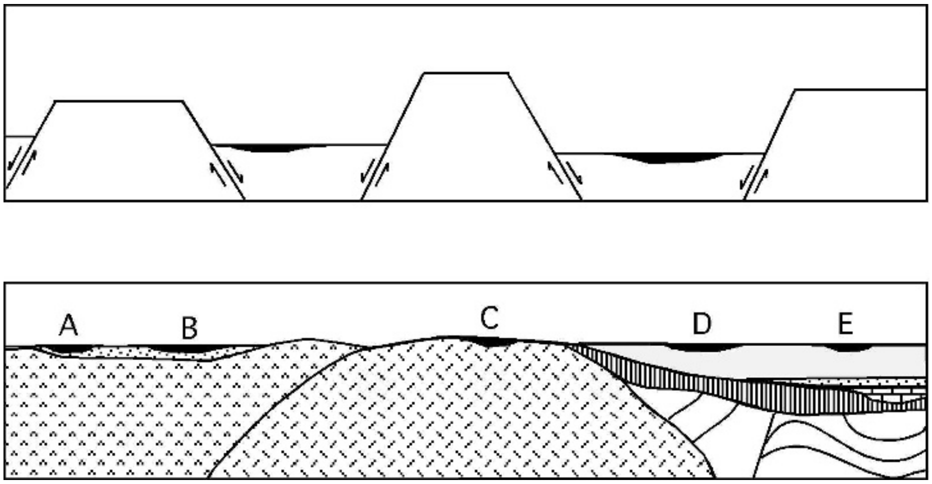

FIG. 2.—Schematic cross sections of geologic settings for saline lakes. Top: Common closed basins formed in fault block valleys. Bottom: Yilgarn Craton setting on deformed, faulted Archean metamorphic rocks and igneous intrusions with varying amounts of regolith (highly weathered bedrock; vertical stripes pattern). **A, B)** Some lakes are hosted by thin, laterally-discontinuous Tertiary sandstones. **C)** Some lakes are situated directly on Archean bedrock. **D, E)** Other lakes are hosted by loose sediment. Highly localized limestones in the subsurface (as under lake E) may locally neutralize regional acid groundwaters to result in the neutral and moderately alkaline lakes.

Geological Setting of the Yilgarn Craton

The Yilgarn Craton comprises a large (~ 1.78 million km^2), tectonically stable area of southern Western Australia (Figs. 1, 2). It is composed of highly weathered Archean rocks with little or no sedimentary cover (Anand and Paine 2002). Granites and gneisses dominate the bedrock, but anorthosites, quartzites, and ironstones are found here as well. In and near some lakes, we have observed highly weathered basement regolith at shallow depths (0.5 m or less) below the surface. This regolith grades stratigraphically upward into clastic sediments. This makes it difficult to distinguish between the regolith and overlying fine-grained clastic sediments. At some other lakes, the clastic sediments may be up to 100 m thick (Clarke 1994; Gray 2001; Salama 1997). Some lakes are hosted by Archean bedrock outcrops. Although no Paleozoic or Mesozoic rocks have been found on the Yilgarn Craton, there are some localized, relatively thin Tertiary sedimentary units, including lignites, siltstones, sandstones, and marine limestones, all interpreted as having been deposited by two marine transgressions in the Eocene (Clarke et al. 1996).

Although most of the lakes have not been cored or studied for age determination, Salama (1994) described 10 m of bedded halite, gypsum, sand, and mud in a core taken from Lake Deborah West, a neutral lake at present (shown in Fig. 1 as northernmost lake studied). Palynological data from this core suggest a Quaternary age for lake sediments to a 2 m depth, below which palynomorphs may be late Tertiary in age (Salama 1994). Our preliminary data from extremely acid lakes are similar, with only Recent palynomorphs identified in shallow mid-lake cores to 50 cm depth and AMS radiocarbon age of 2913 ± 48 years for sediments at ~ 30 cm depth (Story et al. 2006).

The terrain is relatively flat with elevations ranging from ~ 250 to ~ 365 m above sea level. The modern climate is arid and warm. Air temperatures average ~ 10–27°C, but can reach the extremes of −5°C to 50°C (Australia Bureau of Meteorology home page). Average rainfall is between ~ 26 cm/yr and ~ 34 cm/yr, with the western and southwestern parts of the Yilgarn Craton receiving the higher precipitation amounts. Relative humidity averages ~ 25% during austral summers and ~ 70% during austral winters. Average annual evaporation ranges from ~ 1800–2800 mm/yr for the Yilgarn Craton. Multidirectional winds have an average velocity of ~ 30 km/hr year round in southern Western Australia (with gusts up to ~ 120 km/hr), but are strongest from the east and southeast during austral summers and from the west and northwest during austral winters (Australia Bureau of Meteorology home page).

Land use includes some cropland in the "wheatbelt" (southern and western part of this region), as well as localized gold and salt mining. However, sparse eucalyptus, wattle, and saltbush forests ("malee"-type vegetation) and salt lakes cover most of the Yilgarn Craton. The lakes are common and range in size and shape from tiny round lakes only ~ 0.4 hectares in area to large, elongated lakes that are ~ 81,000 hectares in area. Although the lake depths fluctuate (Figs. 3, 4), we observed no lake waters deeper than 48 cm. More typically, we observed lake waters from 2 to 14 cm deep. A regional view from an airplane or satellite shows that many of the lakes are aligned along the remains of a dendritic branching drainage system, suggesting that they occupy abandoned early Tertiary river channels (Fig. 1; Clarke 1994; deBroekert and Sandiford 2005; Salama 1994, 1997).

METHODS

This study is the product of three field trips to 58 ephemeral saline lakes in Western Australia, 21 of which had lake water pH less than 4. Mapping of sedimentary facies was conducted with detailed attention paid to sedimentary textures, sedimentary structures, authigenic minerals, and environmental conditions such as basic lake and shallow ground water chemistry (pH, temperature, and salinity), water depths, and climate and weather conditions. Sediments and water samples, as well as water depth and chemistry and GPS measurements, were collected along transects across sandflats and lakes and around lake perimeters. To test for lake stratification, an eye dropper was used to sample water from both the bottom and the top of water columns in lakes and then the water samples were tested in the field for salinity and pH. No differences in salinity or pH were found for specific depths within the same water column at individual lakes, showing that lake water was not stratified. Shallow groundwaters were studied in the field by digging into the sandflats/mudflats and immediately measuring groundwater pH, salinity, and

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FIG. 3.—Photographs of acid saline lakes at different stages. A1, A2) Cumulate Raceway, part of Lake Cowan basin, near Norseman. **A1)** July 2001, at end of evapoconcentration stage and beginning of desiccation stage. Note dry lake in middle of photo with thin white halite crust and shallow lake water (~ 2 cm deep) in background, actively precipitating halite and gypsum. **A2)** January 2006 in flooding stage (~ 1 hour after heavy rainstorm). Lake water is 5–6 cm deep. B1, B2) Dead Kangaroo Lake, part of the Bandee Lakes system, near Kellerberrin. **B1)** June 2005, during flooding stage. Water depth ~ 20 cm deep. **B2)** January 2006 during desiccation stage. C1, C2) Lake Brown, north of Merredin. **C1)** June 2005, during flooding stage. **C2)** January 2006, during evapoconcentration stage. D1, D2) Lake Aerodrome, part of Lake Cowan basin, near Norseman. **D1)** During rainstorm in January 2006. **D2)** ~ 1 hour after rainstorm.


A1
B1
A2
B2
C1
D1
C2
D2

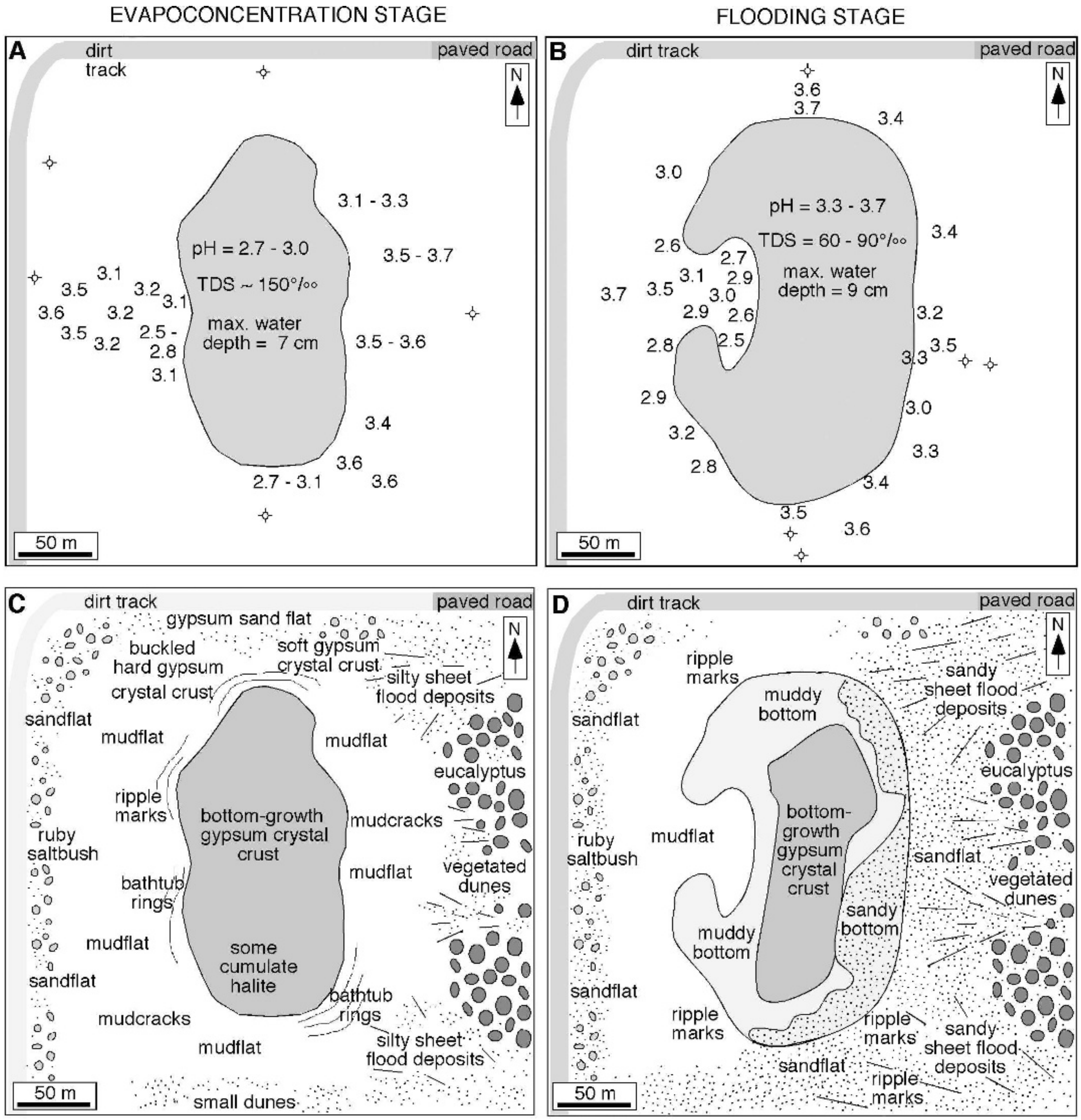

FIG. 4.—Maps of Aerodrome Lake, part of Lake Cowan basin, illustrating changes in water chemistry and sedimentary features over time. A and C show the lake system based on field work conducted from July 27–30, 2001 at the end of a three-year drought. B and D show the lake system on June 26, 2005, after a particularly wet season. Numbers in A and B represent groundwater pH. Note that lake water pH, salinity, and depth changed over time, but groundwater pH stayed relatively constant. C and D show major sedimentary facies, sedimentary structures, and plants. During evapoconcentration stages, evapoconcentration, desiccation, and winds are the dominant sedimentary processes. During flooding stages, sediment transport by water and dissolution of evaporites are common processes.

temperature. Any bedrock observed was also noted and sampled. Shovels and trowels were used to expose shallow sedimentary cross sections (up to 50 cm deep) and PVC pipes, metal cans, and a box corer were used to take shallow (up to 30 cm deep) core samples. Field instruments included pH meters and pH strips, optical salinity refractometers, thermometers, and a GPS unit. Digital cameras and a videocamcorder were used to document field observations.

Field work was conducted in July and August of 2001, in June and July of 2005, and in January of 2006 (Table 1). We observed the lakes during a three-year drought and just as the drought ended (austral winter of 2001) and after the wettest season in ~ 30 years (austral winter, 2005), as well as during an austral summer (2006). Because specific sedimentary processes and products in these environments are greatly influenced by climate and weather conditions, we noted time of day we sampled and

TABLE 1.—*Summary of field data for 21 extremely acid saline lakes (with lake water pHs less than 4) in southern Western Australia. Columns labeled "01," "05," and "06" denote year that lakes were visited. "F," "E," and "D" represent flooding, evapoconcentration, and desiccation stages, respectively. "LW pH" is range measured for lake waters. "LW TDS" is range of measured salinities as total dissolved solids in parts per thousand. "GW pH" and "GW TDS" are the pHs and salinities for shallow groundwaters near the lakes.*

Lake Name	01	05	06	F	E	D	LW pH	LW TDS	GW pH	GW TDS
Aerodrome	X	X	X	X	X		2.7–3.7	60–150	2.5–3.7	60–240
Bottle			X	X	X		2.9	200	3	110
Brown		X	X	X	X		3.9–4.5	130–250	3.1–3.7	150–160
Bullfinch			X		X		3.5	70		
Campian		X	X	X	X		3.7–5.1	150–250		
Crusty			X		X	X	3	270		
Cum. Raceway	X	X	X	X	X	X	3.1–3.7	90–100	3.0–3.3	100–200
Dead Kangaroo		X	X	X		X	3.3–4.3	40–130		
Dead Tree	X		X	X			2.9–3.5			
Gneiss	X	X		X	X		2.7–3.3	80–83	3.3–3.7	75–90
Gounter			X		X		2.5	280	4.1	115
Hobby			X	X			3.9	140	5.9	150
Magic		X	X	X	X		1.7–2.5	240–280	3.3	70–150
Pete's Piggery			X	X			3.8	150		
Picnic			X	X			3.5	55		
Prado	X	X	X	X	X		2.5–3.9	100–240	3.2–3.7	65–225
Roo			X	X			3.9	52		
Twin Lake East	X	X	X	X	X		2.7–3.6	100–215	2.9–3.3	60–200
Twin Lake West	X	X	X	X	X		2.7–3.8	115–210	2.4–5.4	50–240
Walker		X	X	X			3.5–4.1	10–30	3.1	50–60
Yellow			X		X		2.6	280	2.8–2.9	230

made repeated visits to some of the lakes on several consecutive days, at night time, and before, during, and after rainstorms. Evidence of previous conditions could occasionally be seen during some field trips. For example, lake beds composed of polygon-cracked subaqueous halite crusts suggested previous desiccation periods. In addition, anecdotal data from other scientists who visited the lakes or region at other times supplement our observations (David Gray, Sarah Stewart Johnson, Fiona Takulis, Bob Whittam, personal communications).

Laboratory work included cutting cores and making thin and thick sections. Additional descriptions of sedimentary textures and structures were made in the laboratory by examination of cores, thin sections, and loose sediments. Identification of minerals was conducted by optical petrography, X-ray powder diffraction, and reflectance spectroscopy.

Samples of loose sand from nine acid lakes (namely lakes Aerodrome, Cumulate Raceway, Brown, Bullfinch, Gneiss, Magic, Prado, Twin East, Twin West) were examined petrographically. Depositional environment, sample depth, minerals, grain size, sorting, grain shape, color, and any other distinctive features were noted. Over fifty sediment samples were examined from the various facies in acid-saline-lake systems (including dunes, channels, outwash sheet deposits, sandflats, mudflats, and lakes). The samples included surface sediments from each of these environments, and samples from individual beds down to 35 cm below the surface.

LAKE TYPES

We studied 58 lakes in Western Australia. Fifty-seven of these lakes are continental and one is a marginal marine lake, separated from the ocean only by sand dunes (Fig. 1). Twelve lakes in southern Western Australia were visited in 2001, 22 in 2005, and 47 in 2006. Six of these lakes were visited in all three field seasons, and 16 were visited in two field seasons. Based on our field observations, we identified four lake types defined by pH. These are: (1) extremely acid lakes, with pH values less than 4; (2) moderately acid lakes, with pH between 4 and 6; (3) neutral lakes, with pH between 6 and 8; and (4) moderately alkaline lakes, with pH greater than 8 (Fig. 1). Of the 58 lakes we studied, 21 are extremely acid (see Table 1 for summary of field data for these lakes). Regardless of lake water pH, shallow groundwaters tend to be acid throughout the region. Some lakes were in contact with outcrops of older rocks (including Archean felsic–ultramafic igneous and metamorphic rocks and Tertiary sandstone; Fig. 5). However, all the lakes we visited contained evaporites and were hosted by at least some siliciclastic component (Figs. 6, 7). The same general physical sedimentary processes and evaporative products exist in all these lakes, regardless of pH. However, because the sedimentology of modern acid saline systems has not before been described in detail and have unusual geochemical processes that contribute to the sedimentological and mineralogical features, the extremely acid lakes are the focus of this paper.

GEOCHEMICAL CHARACTERISTICS OF EXTREMELY ACID SALINE LAKES IN WESTERN AUSTRALIA

Lake and ground waters range in salinity from 10 to $>$ 280 ppth (more commonly 100–280 ppth; Table 1) and are typically Na–Mg–Cl–SO_4 brines with variable yet locally high amounts of Ca, K, Al, Fe, Si, and Br (Bowen and Benison 2006). The fluid compositions are unusual, complex, and variable through space and time. For example, in some waters, the amount of Al $>>$ Ca, the amount of Br $>$ K, and comparison of total S to SO_4^{2-} values suggest the presence of uncommon S-bearing species. Bicarbonate is not detected in any of the waters with pH less than $\sim$ 5. These waters are enriched in ^{18}O and D, suggesting that they are highly evaporated (Bowen and Benison 2006).

Element concentrations are variable in both lake water and groundwater. For example, K ranges from 61 to 4516 ppm in lake waters and from 89 to 1559 ppm in groundwaters at these 21 extremely acid lakes. Aluminum ranges from 105 to 3057 ppm in acid lake waters and from 234 to 8017 ppm in acid groundwaters. Iron ranges from 0 to 403 ppm in acid lake waters and 0 to 459 ppm in acid groundwaters (Bowen and Benison 2006). There are greater temporal variations in the lake waters, but greater spatial variations in the groundwaters (see Fig. 4A and B for pH variations; elemental constituents of waters have similar temporal variation for lake waters and spatial variations for groundwaters). This suggests to us that flooding and evapoconcentration have a greater effect on the lake waters and localized interaction with host rocks may have

FIG. 5.—Photographs showing geologic settings of acid saline lakes in southern Western Australia. **A)** Air photo showing lakes west of Kalgoorlie in July 2001; various colors represent salt crusts, red mud, and/or shallow water in lakes in close proximity. **B)** Outcrops of ironstone and sandstone along shore of Twin Lake West. **C)** Vertical exposure of regolith and overlying sediment at Royal North mine, Croesus gold mine, near Norseman. **D)** Lake Magic, with halite and yellow water, hosted by coarse sand composed of quartz and granite clasts. **E)** Warrachuppen Rock, an Archean granite dome. Drainage waters here had pH 2.8 in January 2006. **F)** Outcrop of black amphibolite at Twin Lake West. **G)** Tertiary (?) sandstone outcrop at Prado Lake. **H)** Archean metamorphic outcrop in lake water at Twin Lake East. **I)** Archean gneiss outcrop at Gneiss Lake.

a greater effect on the groundwaters. Lack of NO_3^-, NO_2^-, and PO_4^{3-} in the lake waters and groundwaters, along with their geographic distribution, has allowed us to rule out geochemical input from agriculture or mining. The compositions of these fluids suggest an extensive and spatially diverse history of brine evolution. Influences of host-rock mineralogy and weathering, and possible microbiological activity on water geochemistry are as yet not completely understood.

Models of brine evolution have been established based upon globally prevalent geochemical conditions (Hardie and Eugster 1970). Most evaporite systems that have been studied are alkaline and neutral, have HCO_3^- as an important component, precipitate some carbonate minerals, and do not have high Fe and Al. Therefore, evaporative systems are commonly described in terms of chemical divides based on the high solubility of salt minerals relative to the moderate solubility of calcium sulfate and low solubility of calcium carbonate minerals (e.g., Hardie and Eugster 1970; Lowenstein et al. 1989; Li et al. 1997). In Western Australia, acid saline lake waters and groundwaters do not fit these traditional brine classifications.

FIG. 6.— Sediments from acid saline lake systems in Western Australia. All scale bars = 1 mm. **A)** Lake Aerodrome sandflat sediment sampled from 13 to 15 cm below surface; composed of quartz, gypsum, and hematite; reflected light. **B)** Lake Cowan West basin dune sediment sampled from surface; composed of reworked gypsum sand and gravel; crossed polars. **C)** Gneiss Lake sandflat sediment sampled from surface; composed of very fine quartz sand grains coated with hematite; crossed polars. **D)** Lake Magic sandflat sediment sampled from surface; composed of quartz and coarse granite sand; reflected light.

FACIES

Individual facies at acid saline lakes in Western Australia include lake, mudflat/sandflat, ephemeral channel, and dune facies. These facies change spatial position and character over relatively short time periods (Figs. 3, 4). For example, during flooding, a lake facies has its greatest areal extent, but during desiccation, the facies is essentially absent at the surface and simply becomes an extension of the dry sandflat facies. At times of great drought, when lakes are dry and wind processes dominate, sandflats and sand dunes migrate across the former lake facies. Because the positions of facies migrate over short periods of time, we describe the facies here in terms of the three major sedimentological stages: flooding, evapoconcentration, and desiccation.

Lake Facies

The lake facies here is described as the subenvironment that is, at times, subaqueous. Although it might be technically considered a "saline pan"

FIG. 7.—Photographs of acid-saline-lake facies in Western Australia. **A)** Halite cumulate rafts at Lake Brown. White rafts with shadows are floating on surface of water ~ 6 cm deep. White rafts without shadows have sunk to lake bottom. **B)** Subaqueous halite crystal crust growing in lake water 8 cm deep at Twin Lake West. Trowel for scale. **C)** Cross-sectional view of halite crust taken from triangular hole shown in photograph B. Smaller bottom crystals are cumulates. Larger crystals at top are chevron crystals, which grew upward from lake bed. **D)** Partially dissolved subaqueous halite crust in Twin Lake East in lake water 20 cm deep. Field of view is approximately 0.75 m. **E)** Thin-section view of halite chevron crystal from Twin Lake West. Dark growth bands are composed of high concentrations of primary fluid inclusions. Note truncation of growth bands at top of photo by dissolution surface. **F)** Lake halite (white) and Gypsum (orange) crystals with red-brown mud on trowel from bottom Cumulate Raceway. **G)** Subaqueous crust of halite (white) and clear needle-shaped gypsum crystals from Lake Brown. **H)** Subaqueous gypsum crust growing in lake water 7 cm deep in Lake Aerodrome. **I)** Cross-sectional view of shallow core sample taken at photograph H location. Note large gypsum crystals underlain by red mud. **J)** Partially dissolved subaqueous gypsum crust in Lake Aerodrome in lake water 9 cm deep. Field of view is approximately 0.75 m. **K)** Cross-sectional view of single gypsum crystal. Red bands are composed of hematite mud. **L)** Ripples in subaqueous sand in Lake Brown in lake water 3 cm deep. Trowel for scale.

(Lowenstein and Hardie 1985), we have chosen to call it "lake" to reflect the fact that, over the course of three field trips, we have seen these lakes wet more often than dry. The lake facies changes dramatically over time, depending upon whether the lake is undergoing flooding, evaporative concentration, or desiccation (Figs. 3, 4).

Lake Facies at Flooding Stage

During and soon after any precipitation on the Yilgarn Craton, rainwaters run off the surface and towards the lowest topography: shallow circular and oval depressions that serve as lake basins. The soil of the Yilgarn Craton is thin, composed mostly of siliciclastic sand and little organic matter, mostly eucalyptus debris. Therefore, rains promote flash floods (Fig. 3D1).

Flooding causes lake levels to rise by several centimeters. However, the lakes are still considered shallow; the deepest water depths we recorded are 48 cm. Lake shape and areal extent change during flooding because of the low relief of the lake basins. Coarse-grained sediments, mostly sand and some localized gravel weathered from Archean outcrops, are transported short distances by flood waters in the form of sheet floods and are eventually deposited in the lakes (Fig. 6). These siliciclastics leave planar laminae, thin beds, and cross-laminae on the sandflats and in the lakes (Fig. 8E, G, H, I).

The floodwaters carry fresh water into the lakes, diluting the lake water and resulting in initially lower salinities and slightly higher pHs (Fig. 4). Evaporite crystals formed previously in the lakes begin to dissolve, making the halite and gypsum crusts thinner, less laterally extensive, and pockmarked with both lateral and vertical holes ("dissolution pipes;" Fig. 7D). The extent of this evaporite dissolution depends upon the dominant type of evaporite mineral at the specific lake (halite is dissolved more readily than gypsum), the amount of flood water (more flood water causes more dissolution), and the previous lake depth (shallower lakes are more easily affected by flooding). This dissolution of evaporite minerals greatly affects the lake-water chemistry. Some of the most saline waters we observed (~ 240 ppth total dissolved solids [TDS]) were at the end of a flooding stage in the austral winter of 2005 when water was relatively deep and halite crusts had partially to completely dissolved, adding to the total dissolved salinity of the lake water. pH rose only slightly, by ~ 1 pH unit, as a result of flooding.

Flooding stages of various magnitudes may occur at different temporal scales. The greatest flooding on a regional scale may occur during times of exceptionally wet weather (~ 10–100 years; for example, the austral winter of 2005 was the wettest season in 30 years in southern Western Australia). Flooding may occur depending upon seasonal precipitation variations. In addition, an individual heavy rainstorm, regardless of the season, may yield efficient flash floods at a local scale, as we witnessed during July 2001 and January 2006 (Fig. 3D1), while nearby lakes remained dry.

In these lake facies, the grain size ranges from clay (relatively rare) to coarse sand. Individual beds are moderately to poorly sorted. The coarse-grained samples tend to be more poorly sorted and angular and the fine-grained samples tend to be well sorted, indicating an overall greater maturity. Coarse-grained minerals tend to directly reflect the proximal host-rock environment and tend to be dominated by a specific mineralogy (quartz or gypsum), while finer grains tend to be a more even mix of quartz and gypsum (Fig. 6). We also noted that lakes surrounded by sandflats with outcrops had coarse grains trapped on the sandflats and, therefore, tended to have finer-grained lake facies (Fig. 5F, G). During late stages of flooding and early stages of evapoconcentration, small-scale wave ripples form where lake water is shallow and wind-produced water waves move silt- and fine sand-size grains (Fig. 7L).

Lake Facies at Evapoconcentration Stage

Evapoconcentration is the process of surface water evaporating due to arid conditions, promoting higher salinity and the precipitation of evaporite minerals such as halite and gypsum. The arid climate of Western Australia results in evapoconcentration of lake waters throughout much of the year.

All extremely acid lakes of the Yilgarn Craton precipitate both halite and gypsum, although lakes tend to be dominated by one evaporite mineral over the other. That is, some lakes are halite-rich, with only small amounts of gypsum, while gypsum is the primary precipitate in other lakes with minor halite.

Halite grows several different ways in the lakes. Some halite crystals precipitate from lake water along the shoreline, making a white "bathtub ring" (Fig. 9E). Initial halite growth, especially, seems to be at the air–water interface, where tiny cubic halite crystals grow. Eventually, they either sink to the lake bottom as they become larger or several crystals grow together into a "raft" which floats on the water surface until it eventually sinks as well (Fig. 7A; Arthurton 1973; Shearman 1970). Most of these rafts are approximately 1–2 cm in diameter, but we observed some as large as 32 cm across. Rafts may be pushed along the lake water surface by winds and accumulate at the leeward shore. The sunken surface-grown cumulate crystals, either individually or as rafts, make beds of cumulate halite. Halite growth continues at the bottom of the lake, where chevron crystals grow upward, often using the cumulate crystals as growth nuclei (Fig. 7C; Arthurton 1973; Shearman 1970). Chevron crystal growth is competitive; larger crystals incorporate smaller ones as they grow upward. Eventually, the halite forms hard crusts, some up to ~ 40 cm thick, on the lake floors (Fig. 7B, C, D, E). These halite crusts can accumulate quickly in the lakes. For example, in July 2005, we visited Lake Magic and observed no halite in the lake. Six months later, in January 2006, the same lake had a halite crust 45 cm-thick (Fig. 5D).

Gypsum-dominated extremely acid saline lakes also form hard, subaqueous, evaporite crusts during the evapoconcentration stage (Fig. 7H). We observed two such lakes actively precipitating bottom-growth gypsum: Aerodrome Lake and Walker Lake. Bottom-growth gypsum crystals also display a competitive crystal growth, with individual crystals enlarging as they grow upward (Fig. 7I). Twinned "swallow-tail" crystals are common (Fig. 7I). We have observed gypsum crystal crusts up to 15 cm thick. Individual crystals up to 12 cm long are not uncommon.

These bottom-growth gypsum crystals have alternating clear and orange growth bands (Fig. 7K). The orange bands are rich in pure iron oxide mud (mostly hematite, but some goethite has been detected as well). It is possible that this iron oxide mud may have been transported into the lakes by wind or by floods. However, these iron oxide bands in gypsum crystals are not associated with grains that are coarser or of a different composition, as might be expected if flooding or wind had been the transporting agent. The iron oxide bands are not associated with any dissolution features within the gypsum crystals that would suggest flooding. We hypothesize that the iron oxides were trapped in the gypsum crystals at times when hematite, as well as gypsum, was precipitating directly from the lake waters. Our field work during the austral winter of 2001 coincided with an evapoconcentration stage, interrupted by flooding induced by a heavy rainstorm at Lake Aerodrome, one of these gypsum-dominated acid lakes. During evapoconcentration, the lake water pH was 2.7–2.9, had 150 ppth TDS, and was red and almost opaque, presumably due to active precipitation of iron oxide mud. During flooding, the water cleared and salinity dropped to 65 ppth TDS, but the pH rose only to 3.0. Later laboratory filtering of the lake water sampled during evapoconcentration resulted in abundant hematite mud. However, the flood-water filter residue consisted of only a small amount of quartz sand and silt and no hematite mud. The hematite mud grains are found in the gypsum lakes

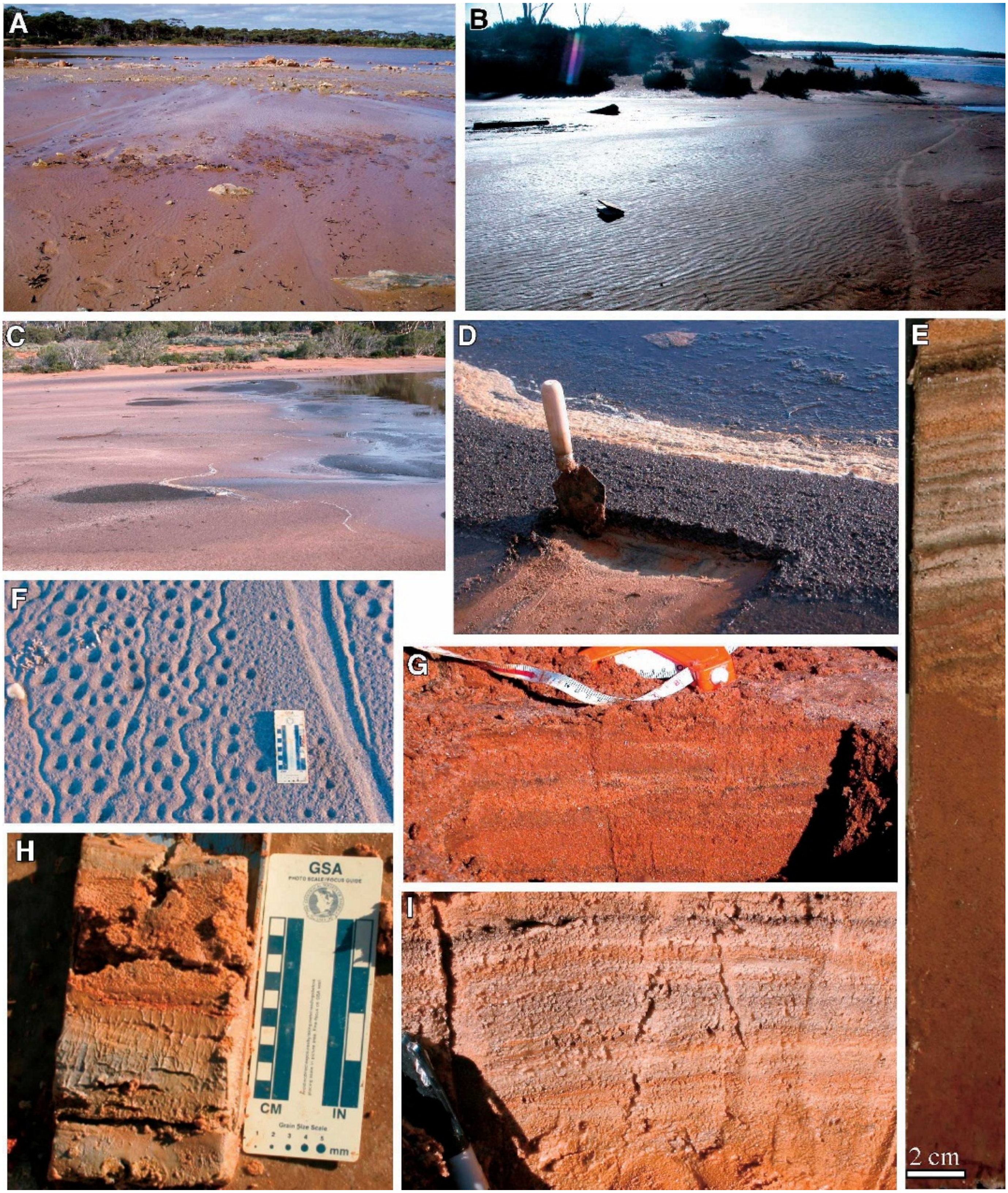

FIG. 8.—Photographs of sandflats/mudflats after flooding. **A)** Sandflat at Twin Lake East with a sheet-flood deposit with a wet surface and outcrops of Archean rocks. **B)** Sandflat at Lake Aerodrome showing ripples in wet sand. **C)** Sandflat at Cumulate Raceway ~ 2 hours after rainstorm. Note accumulations of black plant debris carried by floodwaters from vegetated dunes toward lake. **D)** Close-up view of thin, laterally-discontinuous bed of plant debris from photo C. **E)** Shallow core from sandflat at Lake Aerodrome. Black laminae are rich in decayed plant material, such as that in photos C and D. **F)** Highly-altered interference ripples, raindrop imprints, and small ephemeral streams at Twin Lake West sandflat. **G)** Cross section of sandflat at Lake Aerodrome. **H)** Box core from Lake Brown sandflat. **I)** Cross-section of sandflat at Lake Aerodrome.

FIG. 9.—Photographs of sandflats/mudflats during dry times. **A)** Peak Charles Road dry lake. Flood lag in foreground is composed of quartzite cobbles and quartz sand coated on the bottom with hematite. White in background is thin halite crust of desiccated lake. **B)** Lake Aerodrome mudflat. **C)** Sheet-flood deposit on sandflat at Lake Aerodrome. **D)** Mudcracks and root remnants on mudflat at Lake Campian. Lateral field of view is ~ 0.75 m. **E)** ''Bathtub ring'' of halite around former shoreline of Lake Aerodrome. **F)** Halite crystals growing on Lake Aerodrome sandflat. **G)** Gypsum crystal crust with polygonal expansion ridges on Lake Aerodrome sandflat. **H)** Wind ripples composed of quartz grains and gypsum clasts and truncated by expansion cracks at Cumulate Raceway. **I)** Close-up of photograph H showing efflourescent gypsum crystals growing from evaporating groundwater. **J)** Wind lineation formed in reworked gypsum clasts on desiccated lake bed at Dead Kangaroo Lake. Although this is technically lake facies, sandflat processes have taken over after desiccation. **K)** Reworked gypsum crystals that have been blown by wind to partially bury ruby salt bush at Lake Aerodrome. **L)** White gypsum crystals form hard crust over loose hematite-coated quartz grains and reworked gypsum clasts at Lake Aerodrome.

only in direct contact with bottom-growth gypsum crystals. These Lake Aerodrome waters had relatively low dissolved Fe concentrations (15–32 ppm; at lower end of range during flooding and at higher end during evapoconcentration) compared to waters at other lakes without any red muds (lakes Gounter, Magic, and Yellow have 127–403 ppm Fe; Bowen and Benison, 2006). The pH of 2.7 to 3.0 at Lake Aerodrome puts these highly oxidized lake waters on the boundary between the stability fields for dissolved Fe^{2+} (and Fe^{3+} at higher Eh) and hematite precipitation (Drever 1988; Garrels and Christ 1965). We hypothesize that the increase in aqueous Fe during evaporation and the decrease in aqueous Fe during flooding drive the iron oxide precipitation–dissolution reactions back and forth across the boundary between the stability fields, resulting in periods of direct precipitation of hematite from lake water.

Another direct precipitate of lake waters during evapoconcentration may be kaolinite. We find localized white kaolinite layers along the beds of at least two lakes, Lake Aerodrome and Twin Lake West. It has a soft, sticky texture similar to that of wet toothpaste. Kaolinite is not found in the surface sediments of the sandflats/mudflats, ephemeral channels, or sand dunes, suggesting that it is not being transported into the lakes by flooding. The dissolved Al measured in these lake waters ranges from 105 to 242 ppm at Lake Aerodrome and from 242 to 1903 ppm at Twin Lake West (the range of Al in other extremely acid lake waters ranges from 169 to 2516 ppm Al). Dissolved Si is also variable and sometimes of very high concentrations (44–3730 ppm) in these extremely acid lakes. The aqueous geochemistry of these lakes, including dissolved Al and Si and pH of ~ 3, seems to satisfy the conditions required for direct kaolinite precipitation from water (Drever 1988).

Lake Facies at Desiccation Stage

The lakes dry up at different time scales. During the austral winter of 2001, at the end of a drought 2–3 years-long, some of the extremely acid lakes we visited were dry, while others nearby contained surface water but were shallow (less than ~ 15 cm) and actively precipitating evaporite crystals. Some of the largest lake basins in the region, such as Lake Lefroy (just south of Kalgoorlie), Lake Cowan (near Norseman), and Lake Gilmore (near Salmon Gums), were mostly dry, with small shallow lakes (such as Lake Aerodrome and Cumulate Raceway in Lake Cowan basin) in isolated spots. Similar observations were made in the austral summer of 2006 when dry, highly evaporated, and flooded lakes were in close proximity. Highly localized rainstorms may have been responsible for this selective flooding in a season that had been dry with a predominance of dry lakes before the rainstorms. Additionally, some lakes may have greater groundwater input than others.

During periods of desiccation, lake-water-precipitated evaporite crystals are exposed to the air. In addition, during early stages of desiccation, shallow groundwater just below (1–8 cm depth) the dry lake bed still is undergoing evaporation, causing millimeter-scale efflorescent evaporite halite and gypsum crystals to coat the lake bed surface. Many efflorescent halite crystals have a popcorn texture, forming a thin, white, crinkly surface crust (Fig. 9G). Efflorescent gypsum is composed of randomly oriented, needle-like crystals (Fig. 9I). During more extensive desiccation events, groundwater below the lakes is deeper (at least 15 cm below the surface) and wind processes play a larger role on the surface sediments of the dry lake bed.

Wind subaerially reworks the lake facies sediments, including any siliciclastics remaining from previous flooding events and any bottom-growth and efflorescent evaporites formed during evapoconcentration and desiccation, respectively (Smoot and Castens-Seidell 1994). The effect of wind on siliciclastic sediments (mostly quartz here) is likely constrained mainly to sorting by grain size, redeposition on the dry lake bed, and transportation to adjacent subenvironments, such as sand flats and dunes. Lake evaporite crystals likely are more vulnerable than siliciclastic grains to reworking by wind. Halite and gypsum are soft minerals of low density, so they may easily be broken up into smaller clasts and entrained (Figs. 6B, 9K). Linear accumulations of detrital gypsum crystals have been observed forming at a dry lake facies as reworked gypsum crystals are blown along the dry lake bed (Fig. 9J). These evaporites then act as siliciclastics and may be transported easily as fine sand and silt and redeposited on the dry lake bed, in adjacent environments, or even in different lakes.

Sandflat/Mudflat Facies

Sandflats and mudflats are the relatively flat, vegetation-free areas around the lakes (Smoot and Lowenstein 1991). GPS resolution was not high enough to give accurate slope angles in this relatively flat region, but we estimate slope angles of 0–5°. Traditionally, as the names imply, a sandflat is composed of sand and a mudflat is composed of mud; mudflats are typically closer to the lake. However, we observed that these subenvironments encircling the acid saline lakes on the Yilgarn Craton change sediment grain size temporally, depending upon lake stage and the associated physical processes. Therefore, we use the "sandflat/mudflat" term here.

The sandflats/mudflats encircling the extremely acid lakes vary in width, depending upon the individual lake and the sedimentological stage. At the narrowest, there is only ~ 1–2 meters of sandflat/mudflat between the lakeshore and dune facies. But, at some lakes, we measured sandflats/mudflats up to ~ 40 meters wide. During flooding, when lake levels rise, sandflats/mudflats are narrowest; they are wider upon lake lowering due to evaporation, and essentially override lake facies during desiccation.

Most sandflat/mudflat deposits range in composition from entirely quartz to entirely gypsum to a gypsum-quartz mix, and commonly these grains are coated with orange hematite (Fig. 6C). At Lake Brown, several different surface sediments from sandflats have a consistent mineralogy and commonly are composed of ~ 50% quartz and ~ 50% gypsum. Localized outwash sands sourced from soils rich in iron oxide concretions (as at some sandflat localities at Lake Brown) or diverse lithology outcrops (as at Twin Lake West) may contain up to 40% of grains composed of other materials (such as ironstone or granite). At Aerodrome and Cumulate Raceway, certain sandflat areas contain up to 10% of a black, opaque, slightly magnetic mineral (likely, hematite; Fig. 6A). Grain size ranges from very fine to coarse sand and sorting ranges from well sorted to very poorly sorted, suggesting a variety of grain transport histories for these now-similar environments. Several lakes have sandflat areas with rounded, well-sorted grains with bimodal very fine to fine sand size distributions, suggesting an eolian input.

At lakes with onshore outcrops, the coarse-grained sands tend to become trapped in the crevices of the outcrops of Archean and Tertiary bedrock, preventing the formation of sandy channels and sand-sheet outwash deposits along the lake margin. These lakes tend to have fine-grained shore sediments (silty mudflats versus sandflats) and more mixed-lithology sediments, depending on the type of outcrop (sandstone, ironstone, gneiss, granite, etc.).

Sandflat/Mudflat Facies at Flooding Stage

Sands dominate on the surface of a sandflat/mudflat during and after flooding. Fan-shaped sheet-flood deposits can be seen covering most of the sandflat (Fig. 8A). Some have discernible small distributary channels. Flooding-stage sandflats are commonly covered with medium- to large-scale (up to 8 cm wavelength) interference ripples, raindrop impressions, and some plant debris, including eucalyptus woody parts left stranded on the sandflat, and black decaying eucalyptus leaves accumulated along the shoreline (Fig. 8). Few, if any evaporites are found on the surface. During and after flooding, sandflats typically have a tan or brown color. During flooding, the groundwater table is at or just below the sandflat/mudflat surface (~ 1 cm depth). Approximately 1–2 hours after flooding, groundwater is found at depths of ~ 1–10 cm below the sandflat surface.

Sandflat/Mudflat Facies at Evapoconcentration Stage

During the evapoconcentration stage, the sandflat/mudflat has more of a silty than a sandy texture (Fig. 4). Its color is orange, likely due to iron oxide precipitation. Some mudcracks have been observed crosscutting wave ripples. Some evaporite minerals are found on the surface. These include both millimeter- to centimeter-scale, isolated white halite cubic crystals and millimeter-scale needle-shaped gypsum crystals (Fig. 9F). Some halite and gypsum crystals encrust roots and sticks on the sandflat/mudflat. Dead snakes and frogs have been observed on sandflat/mudflats, especially during evapoconcentration stages. The groundwater is a bit deeper below the surface, at 10+ cm depth.

Sandflat/Mudflat Facies at Desiccation Stage

During the desiccation stage, sandflat/mudflat and lake facies merge, causing these two facies to be more similar sedimentologically than in flooding and evapoconcentration stages. Loose surface sediments are mostly of a silt size. Evaporites are common on the surface and include efflorescent crusts (Fig. 9G, H, I) and reworked crystals of gypsum and halite (Fig. 9J, K). Some coarse sand lag from previous sheet floods remains after finer grains are deflated. There are some orange iron oxide coatings on the undersides of the lag sand (Fig. 9A). This combination of siliciclastic grains with iron oxide coatings and evaporite crystals give the sandflats/mudflats pale orange and white colors during the desiccation stage. Eolian processes form asymmetrical ripples and parting lineations. Mudcracked polygons formed by expansion of effluorescent evaporite crust growth are common. Groundwater is deeper below surface (~ 40+ cm depth and sometimes not reachable by shovel).

Channel Facies

Several ephemeral channels are found at each of the acid saline lakes. They are typically shallow (~ 1–15 cm deep), short (~ 1–20 meters long), and relatively straight, and they crosscut siliciclastic sediment at the transitional areas between dunes and sandflat/mudflats (Fig. 10). It is presumed that these are dry at most times and that water flows in them only during and immediately after a heavy rainfall, as rainwater runs off bedrock, dunes, desert soils, agricultural fields, and roads. Most of these ephemeral channels end in fan-shaped sheet-flood deposits on the sandflats. They, along with sheet-flood runoff and rain, are the only ways freshwater is transported to the lakes.

Channel Facies at Flooding Stage

The channels carry water only during the flooding stage. Some channels are shallow, but they have steep sides, suggesting high-energy flow and that more erosion than deposition occurs here (Fig. 10B). Grains deposited are typically of medium–coarse sand size. Medium-scale asymmetrical ripples form here (Fig. 10D).

Channel Facies at Evapoconcentration and Desiccation Stages

Channels are dry and inactive during the evapoconcentration and desiccation stages, when no runoff water is available. Some channels may become partially buried or eroded by eolian deposition during this time. In addition, gravity may cause avalanching of dry channel walls.

Dune Facies

A variety of sand dunes are found near all of the acid saline lakes (Fig. 11). We might call the lakes "interdune lakes" because of this relationship. Dunes are adjacent to sandflat facies, and the margin between the two facies types is easily distinguished by a break in slope and change in vegetation (Fig. 11A, B). Whereas sandflats are fairly flat, the dune facies are characterized by gentle slopes. Whereas sandflats are fairly free of vegetation (or may only contain sparse salt bush), most dunes are vegetated.

Dunes are composed mainly of medium sand-size quartz and/or gypsum grains, typically coated with a thin layer of iron oxide. Digging into the dunes to expose a vertical profile shows either massive, well-sorted sand or faintly defined cross bedding (Fig. 11C, D).

Some dunes are free of vegetation, but most are vegetated with the sparse "malee." This results in a litter of dry eucalyptus trunks, branches, and leaves on the dune surface. Ant hills and snake and spider burrows are common here (Hudson 2005).

We estimate that approximately half of the lakes are surrounded by inactive dunes, recognized as such by their abundant vegetation and patches of microbial crusts.

In some places, there are patches of a centimeter-thick layer of desert soil, composed mostly of sand and a microbial crust. Some microbial crusts contain polygonal desiccation cracks. Associated with some sand dunes and sandy soils are thin calcretes, silcretes, gypcretes, or ferricretes, both on the surface and at shallow depths (up to ~ 0.5 m below the surface). Many of these duricrusts have a nodular or columnar ped texture. Although the surface crusts seem to be relatively recent, subsurface crusts may be older (early Quaternary? late Tertiary?).

NEAR-SURFACE STRATIGRAPHY OF LAKE AND ASSOCIATED FACIES

Although surface dynamics are driven by flooding, evaporation, and desiccation (F–E–D) cycles (Fig. 12), features distinctive to individual cycles are not always preserved in the strata observed in short cores and shallow holes. Mid-lake facies preserve the best record of past F–E–D cycles. Beds of bottom-growth halite and/or gypsum indicate evapoconcentration stages, whereas sand beds and thin black organic laminae, as well as dissolution features in evaporites, represent past flooding. Detrital gypsum, mudcracks, and rare buried efflorescent halite crusts, are preserved from past desiccation events. For example, the mid-lake facies of Lake Brown has distinct beds of halite chevron crystals and gypsum bottom-growth crystals separated by beds of sand, silt, and organics. At some other lakes, we see no halite beds under the lake facies (within ~ 40 cm depth from the lake beds). Evaporites, especially halite, are vulnerable to dissolution, and we have observed dissolution of halite and gypsum during flood events. It seems most likely that this "missing" halite was later dissolved and consequently is not preserved in the subsurface strata.

Sandflat/mudflat facies show little evidence of past F–E–D cycles. The strata here are thick laminae and thin beds of sand, defined mainly by color variations (Fig. 8). Lighter colored (tan, orange, white) strata are composed mostly of sand grains. Black silty laminae are composed of decayed plant material, most likely deposited at past shorelines during flooding events (Fig. 8). In addition, early diagenetic features, especially at depths below ~ 15 cm, mask some depositional features, making many earlier F–E–D stages difficult to interpret (Figs. 8E, 13).

These observations suggest that acid-lake environments would yield a rock record composed mostly of bedded siliciclastic and reworked gypsum sand, alternating with less common beds of bottom-growth gypsum and halite, with some alteration by early diagenetic features diagnostic of acid-saline-water environments.

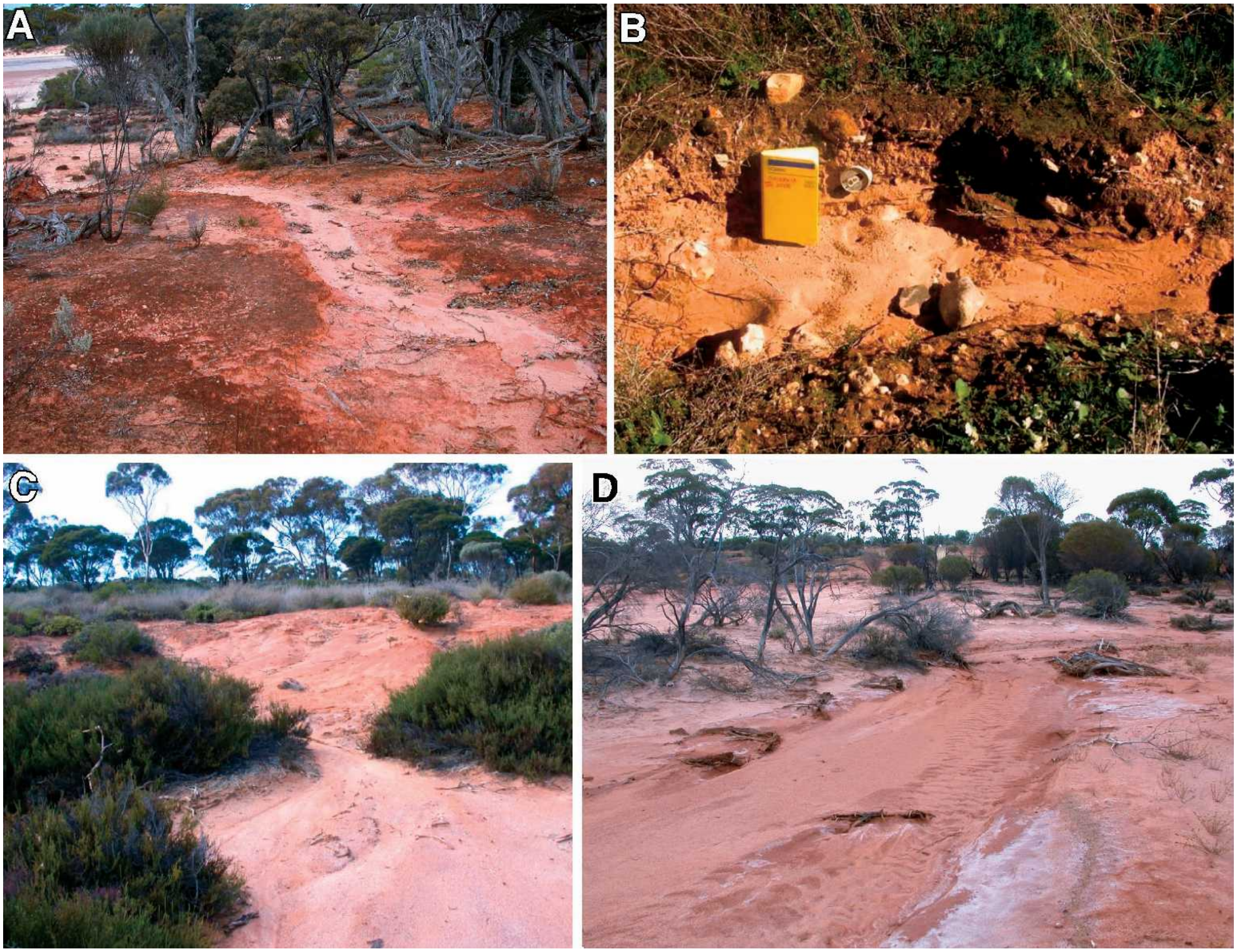

FIG. 10.—Photographs of ephemeral channels leading to acid saline lakes. **A)** Prado Lake, looking downstream (lake is in upper left of photo). **B)** Cross-sectional view of dry channel at Twin Lake East. Note embedded beer can to right of field book for relative age of channel. **C)** Shallow channel at Lake Aerodrome, looking upstream toward vegetated sand dune. **D)** Relatively large dry channel at Bullfinch Lake.

EARLY DIAGENETIC FEATURES

The unusual geochemistry of the lake and shallow ground waters in southern Western Australia make these sedimentary environments unlike other complexes of ephemeral-saline-lakes. Because the groundwaters are shallow and influenced by surface processes such as flooding and evaporation, they promote early diagenesis here. The sedimentology cannot be fully characterized without including a description of these early diagenetic minerals and textures.

Many of the same minerals precipitated from acid lake waters are also precipitated from acid groundwaters. Halite and gypsum, and likely hematite and kaolinite as well, precipitate directly from lake waters. Acid saline groundwaters in intergranular pore spaces in the sediment of the lakes and the sandflats/mudflats precipitate these same minerals, as well as goethite, illite, jarosite ($(K, Na)Fe_3(OH)_6(SO_4)_2$) and alunite ($(K, Na)Al_3(OH)_6(SO_4)_2$; Figs. 13, 14).

Early diagenetic minerals take several forms. Halite and gypsum grow displacively from groundwater, producing randomly oriented cubic halite crystals and needle-, lath-, or rosette-shaped gypsum crystals in sand and mud (Fig. 13A, B; Casas and Lowenstein 1989). Hematite, goethite, jarosite, alunite, kaolinite, and illite grow from shallow acid groundwaters to make a variety of features. All grow in pore spaces in sand and silt in patches or "blebs," causing preferential early cementation of grains and color changes. Red blebs are caused by hematite and goethite cements, bright yellow-orange blebs are formed by jarosite and goethite cements, pale gray-blue blebs are made by alunite cements, and white blebs are composed of kaolinite cements (Fig. 13). A complex mixture of these colors (red, orange-yellow, gray-blue, and white) is common (Fig. 13E). Many of these minerals also coat grains. Hematite coatings are common on quartz and gypsum grains throughout the different facies. "Stringers" or veins of hematite, goethite, jarosite, and alunite have been observed in the subsurface just below lake and sandflat/mudflat facies (Fig. 13H).

Nearly all of the acid lakes exhibited some form of iron oxide precipitate within the shallow subsurface. Ferric iron in solution may be precipitated as ferric hydroxide (ferrihydrite) and then converted to more stable iron oxides such as goethite and hematite. Jarosite is also commonly precipitated within the pore spaces, and could also, much later, be converted to goethite and gypsum. Besides features such as grain coatings and pore-filling cements in bleb- and stringer-shaped patches, iron oxides also form concretions.

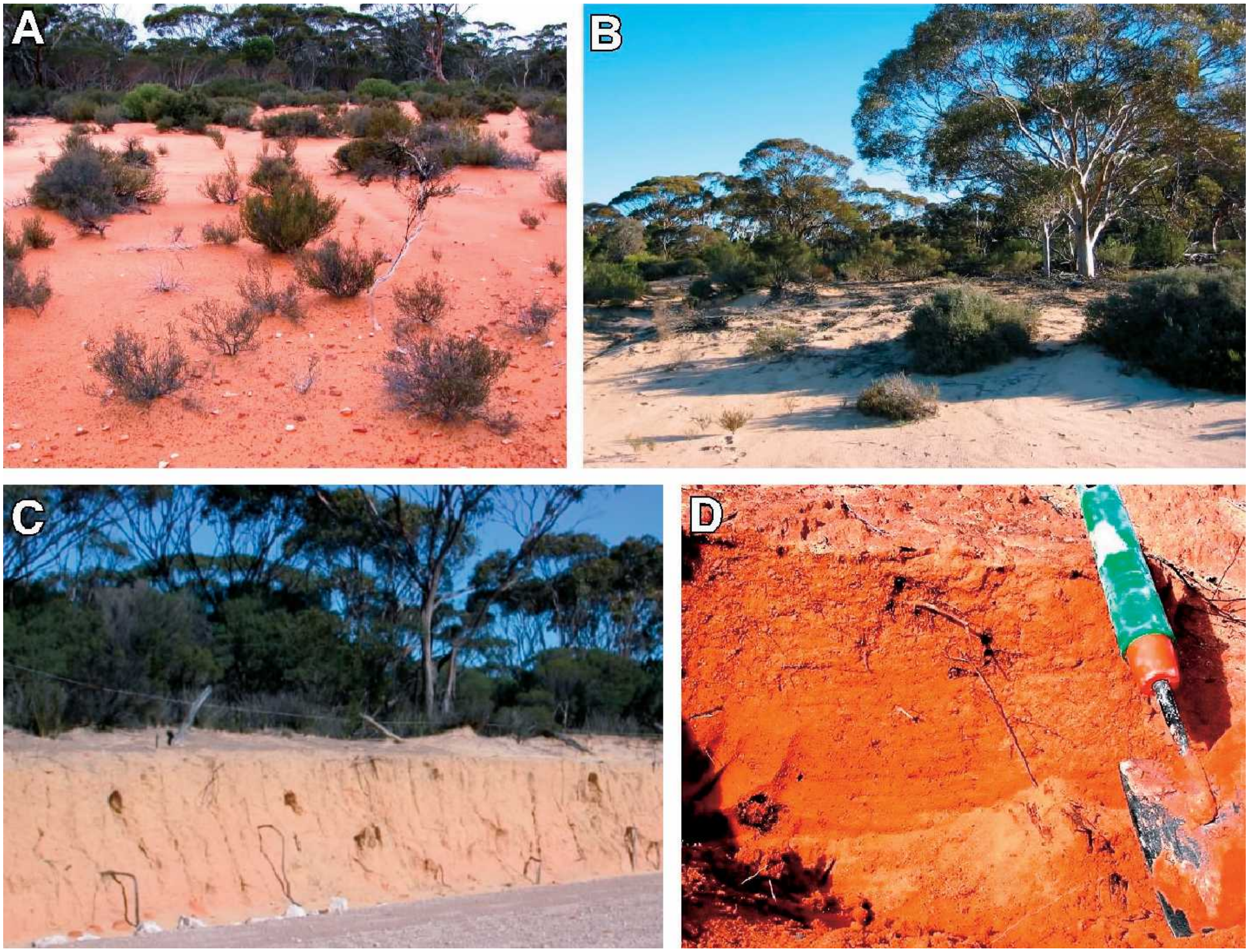

FIG. 11.—Photographs of eolian dunes in the vicinity of acid saline lakes. **A)** Dunes at Gneiss Lake. **B)** Vegetated dunes at Prado Lake. **C)** Cross section of dune sand with roots near Gneiss Lake. **D)** Cross section of dune near Lake Aerodrome. Grains are hematite-coated quartz and gypsum eolian sand grains.

Well-developed spheroidal iron oxide concretions have been found forming *in situ* in sediments below one acid lake and in shallow sandflat sediment at another, and are abundant in the ferruginous soils regionally (Fig. 14). At a depth of ~ 20 cm below Lake Brown, concretions were actively precipitating in an ~ 10 cm thick bed of coarse-grained quartz sand and gypsum and halite ooids (Fig. 14C, D). The concretions appear to form as smaller (millimeter-scale) blebs of pore-filling iron oxides and consolidate from isolated zones into a larger concretion. Unlike most other sands in the acid-lake facies, the host grains in this concretion-rich bed did not have iron oxide grain coatings, suggesting that all of the available iron had been mobilized and consolidated as part of the concretionary precipitates. AMS radiocarbon dates of organic-rich mud beds several centimeters above and below the concretion bed constrain its age to between 2,913 ± 48 years and 1,410 ± 100 years.

The spatial relationship of most of these minerals within the sediments and the young AMS radiocarbon dates indicate that diagenetic processes occur early. Diagenetic minerals precipitate after clastic sediment deposition in areas where sediments are saturated with hypersaline acid groundwaters in the top portion of the water table (which fluctuates over time from ~ 0.1 to ~ 0.5 m below the surface). Evapoconcentration, which decreases water pH and increases water salinity, likely promotes this precipitation from shallow groundwaters. However, floodwaters affect the lakes much more than they do the already acid saline regional groundwaters (see Figure 4A, B). Therefore, much of this early diagenesis likely continues during flooding, but perhaps at a slower rate than during periods of high evaporation.

DISCUSSION

Summary of Sedimentary Processes at Various Temporal and Spatial Scales

Acid-saline-lake systems are the result of a rare combination of physical and chemical processes that act on different time scales. Saline-pan processes, as described by Lowenstein and Hardie (1985), occur here. However, winds and acidity also contribute greatly to the sedimentary features in these Western Australian lakes. Although the saline-pan stages (flooding, evapoconcentration, and desiccation) are asynchronous in each lake, there is a continuous, but slow, input to the lake systems by the shallow acid saline groundwater.

Our visits to specific lakes during different years, seasons, and times of day have allowed us to see the dynamic aspects of both physical and chemical processes operating in these environments. For example, Lake Aerodrome, a very small gypsum-dominated lake in Lake Cowan basin

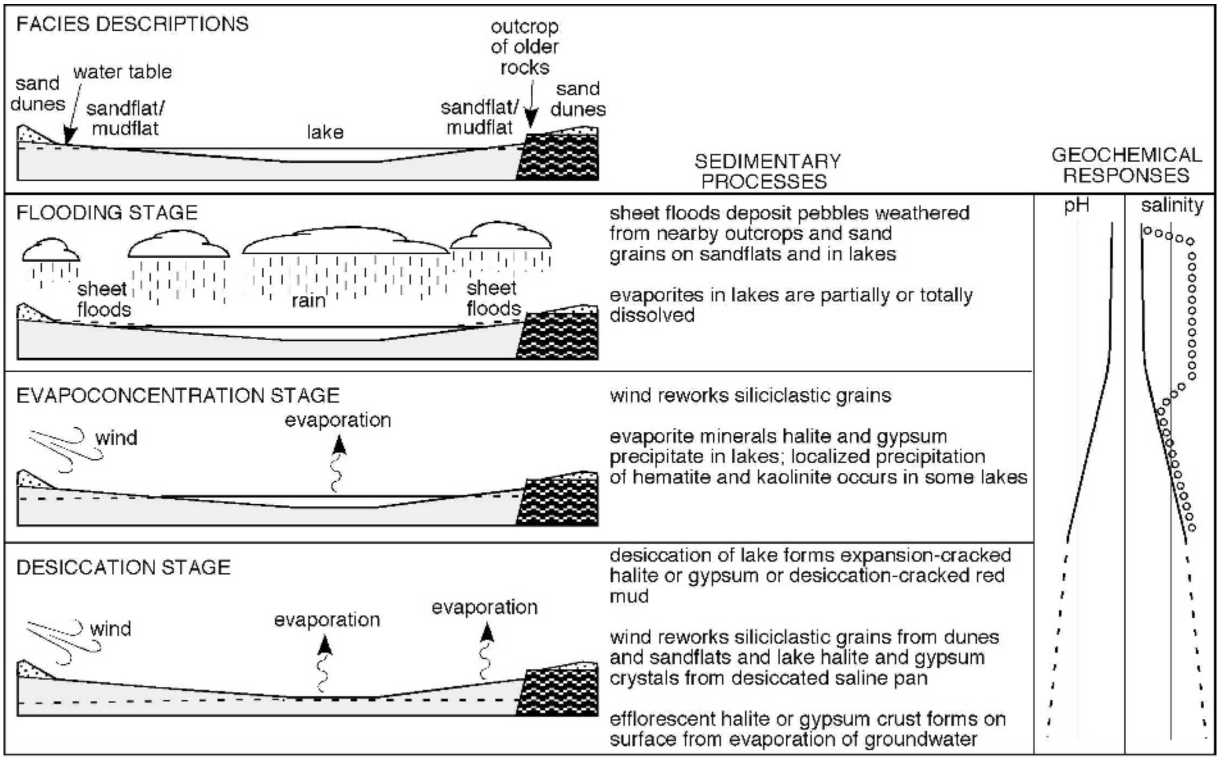

FIG. 12.— Schematic diagrams showing idealized cross sections for acid saline lakes in Western Australia and summarizing major sedimentary processes during flooding, evapoconcentration, and desiccation stages. Sedimentary processes and geochemical responses are shown to the right and correspond with the saline-lake stages. The pH range represents ~ 1 pH unit decrease from the flooding to desiccation stage, and the salinity range represents up to 140 ppth TDS increase from flooding to desiccation. These changes in pH and salinity affect the lake water more so than the groundwater. The bold lines under pH and salinity show the typical changes in lake water. During desiccation stages of the lakes, when there is no lake water, evaporation causes changes in pH and salinity of shallow groundwaters. These changes pH and salinity in shallow groundwater are represented with dashed lines. Under salinity, the circled pathway shows an alternate salinity curve that occurs in lakes that have a thick halite bed at the lake bottom when flooding occurs. In this case, the flooding actually causes an increase in salinity (but no similar change in pH) as the more dilute fresh waters dissolve the halite. When these brines start to evaporate, halite is precipitated rapidly, causing a sharp decrease in lake-water salinity before a gradual salinity increase occurs with further evaporation.

on the southwestern outskirts of the town of Norseman, was visited during July 2001, June 2005, and January 2006. During all three trips, we made multiple visits to assess any daily changes. We found no discernible changes based upon time of day or night, except for variations in air and surface water temperatures. On two of the three field trips, we observed the lake before, during, and after rainstorms (Fig. 3D1, D2). Individual rainstorms affected the surface temporarily. During a rainstorm, the entire sandflat/mudflat surface floods and the lake appears larger in area. Water runs into the lake from all directions. Only approximately one hour after a rainstorm, the size and shape of the sandflat/mudflat and lake look the same as they did before the storm began. However, a close inspection shows that some sedimentary and geochemical characteristics differ. For example, new ripples and raindrop imprints were seen after the rain in places on the sandflat previously covered with wind-blown, partially broken gypsum crystals. Lake waters were only slightly less saline and less acidic immediately after a single rainstorm.

More obvious differences in sedimentology and geochemistry were observed when contrasting Lake Aerodrome and other lakes from one year to another. Our July 2001 field work took place at the end of a three-year-long drought. We noted evapoconcentration at the lakes during much of that trip, with localized flooding due to a rainstorm at the end of that field trip. Our June 2005 trip coincided with the wettest year in three decades. We saw flooding stages at all lakes during this time. By the time of our January 2006 field trip, there had been several dry months followed by rainy days during our field work.

Lake Brown, north of Merredin, was very different at the times of our 2005 and 2006 trips, although only six months separated these visits (Fig. 3C1, C2). In June 2005, Lake Brown was in a flooding stage. Lake

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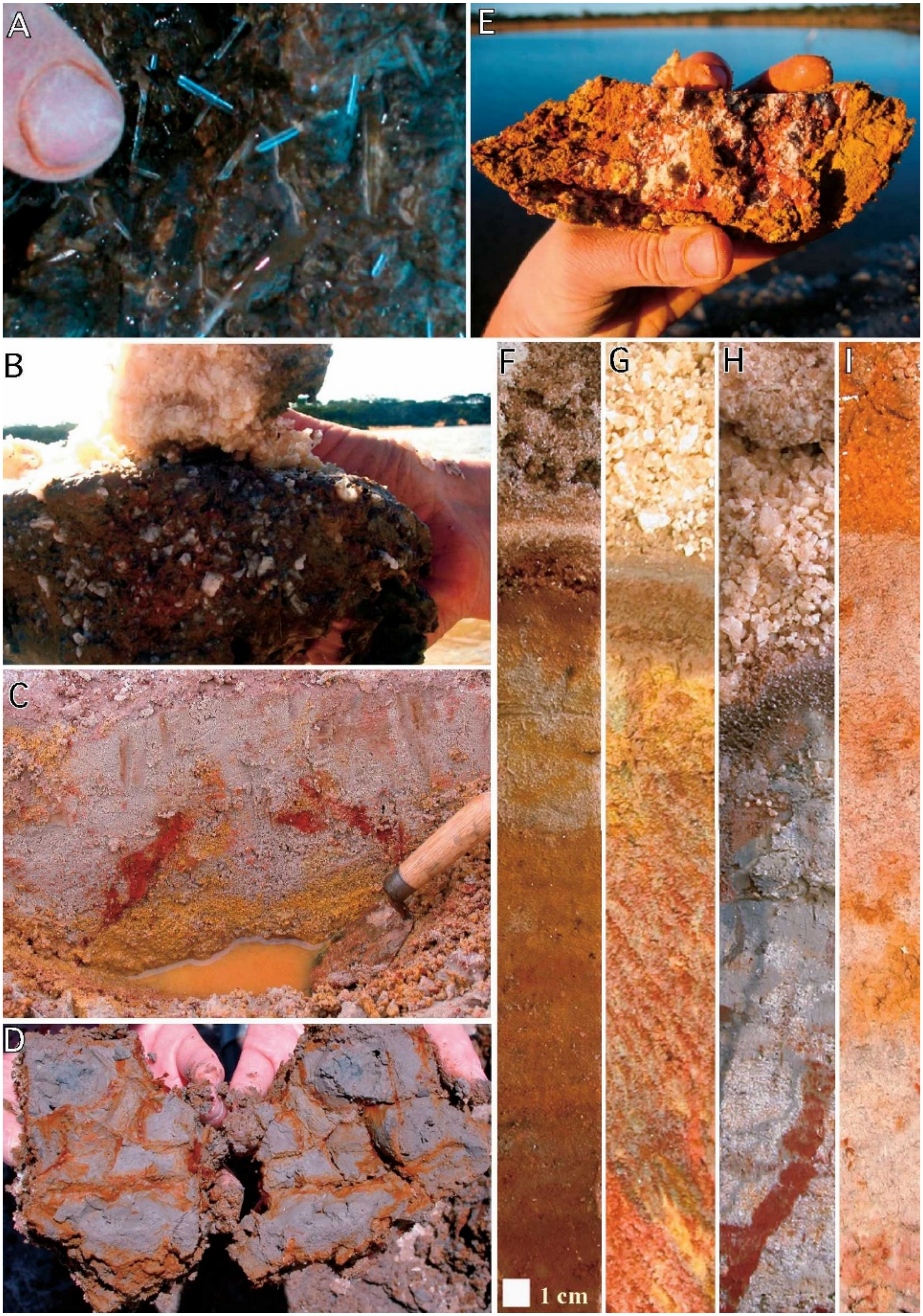
FIG. 13.—Early diagenetic features from acid-saline-lake systems in Western Australia. **A)** Displacive gypsum needle crystals from silt bed below Twin lake West. Fingertip for scale. **B)** Displacive halite crystals in brown silt below bottom-growth halite bed; Twin Lake East. Hand for scale. **C)** Cross-sectional view of Twin Lake West sandflat sediment and orange acid groundwater. Red blebs are hematite and yellow blebs are jarosite. Trowel for scale. **D)** Iron oxides line mudcracks just below surface of desiccated lake facies of Dead Kangaroo Lake. Hands for scale. **E)** Hematite and goethite (red), jarosite (orange/yellow), and alunite (white) from ~ 15–20 cm below the surface of Twin Lake West sandflat. Hand for scale. F–I) Shallow cores. Top of each core represents surface. **F)** Lake Aerodrome sandflat core, showing siliciclastic sand that has been diagenetically altered by iron oxide precipitation from shallow groundwaters. **G)** Twin Lake West mid-lake core, halite bed at top (crumbled by coring) overlying thin brown siliciclastic sediment and regolith (highly weathered bedrock; note metamorphic foliation; now containing jaosite and iron oxides). **H)** Twin Lake East mid-lake core, halite bed at top (crumbled by coring) overlying thin brown siliciclastic sediment that grades into regolith with iron oxide "stringer." **I)** Prado sandflat core composed entirely of siliciclastic sediments with patches of diagenetic iron oxide and jarosite.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water was up to 30 cm deep, temperature was 12–22 °C, and pH was 4.5. A halite crystal bed, containing both vertical and horizontal dissolution pipes, constituted the floor of the lake. Although the lake was in a flooding stage due to a season of heavy rainfall, the lake-water salinity was still rather high, with 130 ppth TDS, including 548 ppm Al, 55 ppm Fe, and 544 pm Si (Bowen and Benison 2006). During this flooding stage, groundwater was just below the surface of the sandflat and had pH values down to 3 and salinity of 150–160 ppth TDS. In contrast, we saw Lake Brown in an evapoconcentration stage in January 2006, with shallower lake water (5–7 cm), warmer lake-water temperatures (47°C), lower pH (3.9), and higher salinity (250 ppth TDS, including 1815 ppm Al, 291 ppm Fe, and 2640 ppm Si; Bowen and Benison 2006). There was a halite crust on the lake floor, composed of a bed, 5–6 mm-thick, of new halite cumulate crystals and rafts overlying an older halite cumulate and chevron halite crust with some dissolution features. A lamina (~ 2 mm thick) of red mud separated these two halite beds. There were also rafts of cumulate halite floating on the lake surface halite (Fig. 7A) and halite on the sandflat surface (Fig. 3C2). Groundwaters were also deeper below the sandflat surface, yet still had pH values down to 3 and salinities of 150–160 ppth TDS.

Lake Magic, near Hyden, was also observed at different stages. In June 2005, it was 15–20 cm deep, and was siliciclastic-rich, but it also contained a thin (~ 5 cm thick) crust of alternating halite and gypsum at its shoreline. Lake waters were clear and had pH 2.5, temperature of ~ 4 °C, and salinity of 230 ppth TDS, including 927 ppm Al, 127 ppm Fe, and 74 ppm Si (Bowen and Benison 2006). Sampled groundwaters had pH of 3.2–3.4 and salinity of 150 ppth TDS. In January 2006, Lake Magic was only 1–3 cm deep, had bright yellow water, and was underlain by a thick (at least 45 cm thick) bed of halite, with gypsum along the shoreline. These yellow lake waters had a pH of 1.7, temperature of ~ 24°C, and salinity of 280 ppth TDS, including 1774 ppm Al, 331 ppm Fe, and 510 ppm Si (Bowen and Benison 2006). Groundwaters had pH of 3.3 and salinity of 70–75 ppth TDS.

The above data from Lake Brown and Lake Magic suggest that seasons play a role in the sedimentology and geochemistry at the lakes. However, seasons are clearly not the driving influence in F–E–D cycles. An examination of Lake Aerodrome shows that, during the same season (austral winter) but different years, F–E–D stages were different. Figure 4 shows both facies maps and water-chemistry maps made during the austral winters of 2001 (evapoconcentration) and 2005 (flooding). Comparison of lake waters show that, during evapoconcentration, the lake had lower pH, by approximately 1 pH unit, higher salinity, and slightly shallower water (only 2 cm difference). Alternately, groundwater pH values were the same during the two times (Fig. 4A, B). In addition, sedimentary characteristics differed. During evapoconcentration, the lake was completely underlain by a bottom-growth gypsum crystal crust, and the sandflat/mudflat was finer grained and contained mudcracks, wind-blown gypsum crystal clasts, and efflorescent gypsum crusts (Fig. 4C). During flooding, Lake Aerodrome's bottom-growth gypsum crust only covered approximately half of the lake floor (Fig. 4D) and showed signs of dissolution (Fig. 7J). Much of the surface of the sandflat was covered with sandy sheet-flood deposits (Fig. 4D). These observations at Lake Aerodrome show that: (1) the specific saline-pan stage is not dictated solely by season; (2) groundwater acidity remains consistent, regardless of saline pan stage; and (3) multiple field trips undertaken at different times are necessary for understanding the sedimentology, as well as the geochemistry, of these acid-saline-lake systems.

We also noted contemporaneous diversity in saline-pan stages in lakes in close proximity, showing that local conditions must play some role in processes. We observed two saline-pan stages at different lakes within individual days during both July 2001 and January 2006. At the same time that Lake Brown was evaporating in January 2006, Dead Kangaroo Lake (one of the Bandee Lakes east of Kellerberrin and only approximately 50 km from Lake Brown) was dry. In July 2001, Lake Aerodrome was in an evapoconcentration stage while the greater part of Cumulate Raceway, in approximately the same size basin and only several hundred meters to the south, was dry. We also observed all three saline-pan stages in different lakes within only two days. In these cases, local rain, or lack of it, played the dominant role in determining lake stage.

The specific geochemistry of the waters, besides yielding evaporite minerals and early diagenetic features, also affects the sedimentary facies and how they fluctuate temporally and spatially. For example, at the times of our field work, gypsum was the dominant evaporite mineral in only two of the 21 extremely acid saline lakes studied. However, some halite-dominant lakes we observed have bottom-growth gypsum beds in the shallow subsurface, indicating past gypsum dominance. The lakes dominated by halite are most vulnerable to dissolution during flooding. Therefore, their salinities have a much wider range through time than do the gypsum lakes. In the halite lakes, some of the highest salinities occur just after flooding, when halite has dissolved to enrich the flood waters in sodium and chloride. Halite and gypsum lakes can be quite close together, as in the case of gypsum-rich Lake Aerodrome and its neighbor, halite-rich Cumulate Raceway.

HOW ARE THESE SYSTEMS DIFFERENT FROM OTHER NON-ACID, MODERN, CONTINENTAL EVAPORITIC ENVIRONMENTS?

Comparison with Nearby Neutral Saline Lakes on the Yilgarn Craton

Although this paper has focused on the sedimentology of the extremely acid saline lakes of the Yilgarn Craton, we have also studied moderately acid (pH 4–6), neutral (pH 6–8), and moderately alkaline (pH 8+) saline lakes in the same region (Fig. 1). Although there is a great range of lake water pH, shallow groundwater near the lakes tends to be acid (average pH ~ 3–3.5), due to a regional acid saline groundwater body throughout the Yilgarn.

The sedimentary processes are very similar among the different-pH lakes. The main difference is in the assemblage of minerals produced, both as lake water precipitates and as early diagenetic features. Acid-lake systems tend to have a red sediment color, due to iron oxide coatings on grains in the lakes and on the sandflats/mudflats. In general, the neutral and less common moderately alkaline lake settings have a tan or brown surface because siliciclastics are not coated by iron oxides. Some neutral lakes have white sediments, composed of uncoated gypsum. Gypsum is also commonly found in abundance in lake, sandflat, and dune sediments at acid lakes, but most acid lake-associated gypsum is orange due to hematite that coats gypsum grains and/or is incorporated as solid inclusions along the growth bands of the crystals.

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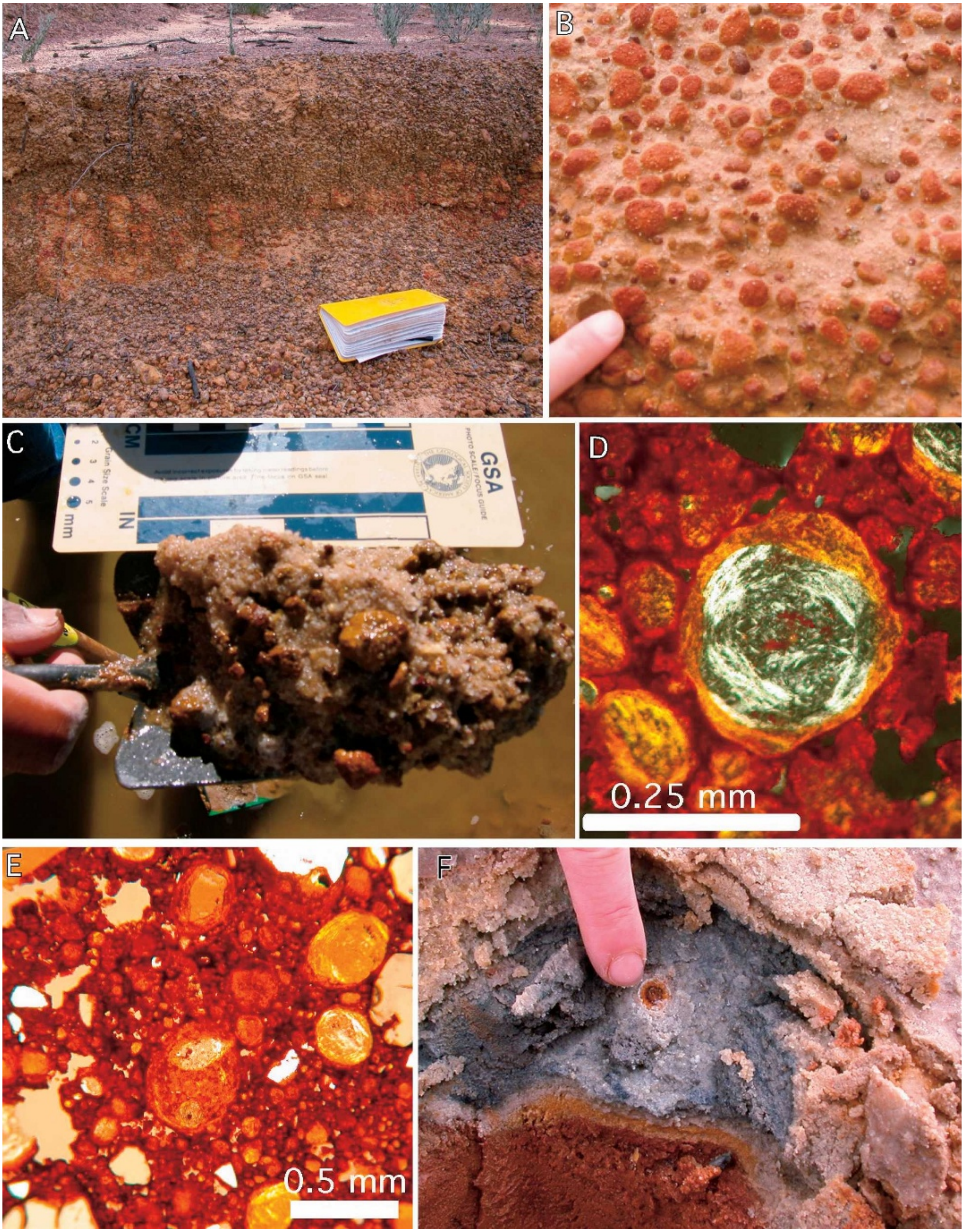
FIG. 14.—Iron oxide concretions in southern Western Australia. **A)** High concentration of iron oxide concretions in desert soil ~ 100 km west of Hyden. Field book for scale. **B)** Iron oxide concretions in young tan quartz sandstone near Kelleberrin. Finger for scale. **C)** On trowel, semi-soft and hard concretions from tan sand bed under Lake Brown. **D)** Photomicrograph of interior of single Lake Brown concretion, showing that the concretion is composed of quartz grains and gypsum and halite ooids coated with and cemented by iron oxides. Large grain in center of photo is an ooid with a halite subcubic (edges were rounded) crystal core that has been mostly replaced by gypsum; transmitted, polarized light. **E)** Photomicrograph of interior of single Lake Brown concretion, showing iron oxide ooids with cores of quartz grains, halite cubes, and gypsum clumps. Ooids are cemented by iron oxide meniscus cements; transmitted, polarized light. **F)** Concretion in Lake Aerodrome sandflat sediment ~ 4 cm below surface. Finger for scale.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Early diagenetic features characteristic of acid saline lakes are also found at some neutral saline lakes, due to the acid groundwater. However, below the sandflats of neutral lakes, these "acid" diagenetic features, including jarosite and iron oxide blebs, are far less abundant and more localized than at the acid lakes.

Another question that arises is: why the great range of pH among lakes? Although the distribution of acid lakes and neutral lakes seems random on the Yilgarn Craton (Fig. 1), we have noted that the lakes with larger lake surface areas and drainage basins are more likely to have neutral pH. We note this cautiously, though, because we have recorded extremely acid lake waters at some large lakes such as Lake Brown, as well as some neutral and moderately alkaline lake waters at small lakes such as the Gastropod Lakes, less than three kilometers south of extremely acid Twin Lake East and West. We hypothesize that the larger lakes have a greater input from rainwater and runoff, making their lake waters more neutral and diminishing the influence of regional acid groundwaters. In addition, some neutral lakes seem to be perched aquifers, in which the lake water is underlain by impermeable mud that keeps the acid groundwater from seeping into the lake. These two explanations may account for the many neutral lakes that have acid groundwaters, but a few neutral lakes do have neutral groundwaters. At specific lakes, the pH may be neutralized by varying amounts of buffers in subsurface host rocks, including isolated Eocene limestones (Clarke et al. 1996; see Fig. 2B, lake E). We have observed focused zones of neutral surface and shallow water in the central and northern parts of the Lake Cowan basin that are directly above cores containing limestone. However, other parts of Lake Cowan basin have extremely acid lake waters and groundwaters.

Comparison with "Closed" Basins Elsewhere in the World

Many traditionally-named "closed basins," such as those in the western U.S. (e.g. Death Valley and Great Salt Lake), east Africa (e.g. Lake Magadi), and China (e.g. Qaidam Basin), host ephemeral saline lakes and may be among the closest sedimentological relatives to the acid-saline-lake systems (e.g., Lowenstein and Hardie 1985). However, there are some major differences that lead to questions about how to define a true closed basin and whether the acid saline lakes in Western Australia are closed or semi-closed basins.

The AGI Glossary of Geology (Jackson 1997) defines a closed basin as an "enclosed area having no drainage outlet, from which water escapes only by evaporation." The classic closed basins are tectonically produced basins with mountains that separate them from one another (e.g. Handford 1982; Lowenstein and Hardie 1985; Schubel and Lowenstein 1997). In such lakes, springs and ephemeral channels transport waters into the basin. These closed basins are further isolated because wind does not blow sediments efficiently from one basin to another and there is no shallow groundwater table connecting the individual closed basins.

The acid saline lakes in Western Australia are closed basins in one sense; they have no surface drainage outlets by which water can escape. However, their geologic setting in a low-relief, tectonically stable region may actually allow these lakes to exchange materials with one another. Sediments, including mineral grains, plant debris, and even microscopic organisms, may be carried from one lake system to another by winds (Pelletier and Cook 2005). The shallow regional acid groundwater may be another connection between two or more lakes. Although the groundwaters seem to flow very slowly here (D. Gray, personal communication), it is still possible for groundwater chemistry produced in one basin to be transferred to another by regional groundwater flow. It has also been hypothesized that rains contribute salts to the lakes of the Yilgarn Craton (Hingston and Gailitis 1976; Alpers et al. 1992). It is possible that local evaporation of one lake produces some salt aerosols that later rain out over another lake. For these reasons, although there is no surface water outflow, these acid saline lakes may be more accurately called "semi-closed" basins.

How Are These Systems Different from other Acid Water Environments?

The lowest pH values on Earth have been recorded in volcanic acid waters and in acid mine drainage. Many of these two acid water types have the same pH range as the acid lakes in Western Australia. However, the Australian acid lakes are somewhat different in mineralogy and very different in sedimentology. In fact, the sedimentology of these acid systems is rarely studied in detail.

Comparison with Volcanic Acid Lakes

Volcanic acid lakes have been relatively well studied (e.g., Sriwana et al. 2000; Varekamp et al. 2001) and differ dramatically, geologically, from the acid saline lakes in Western Australia. Volcanic crater lakes can be extremely acid and highly saline, but, unlike the Western Australian lakes, they are hosted by young volcanic rocks. In addition, since their geochemistry does not tend to be rich in Na, Cl, and Ca, they do not form bedded halite and gypsum, which are so common in the Australian settings. Some acid crater-lake waters do flow down volcanoes in streams, springs, and, sometimes, into lakes at the foot of the volcanoes (Varekamp et al. 2001). However, some so-called "acid saline" lakes are closer to fresh water than to brines. For example, Lake Caviahue, which is fed by acid water from the crater lake atop Volcan Copahue on the Argentina–Chile border, has a salinity of 3 ppth TDS and pH of 4. As a result, this lake does not precipitate saline minerals. Most importantly, no F–E–D cycles have been documented at any volcanic acid lakes, as they are on the Yilgarn Craton. Therefore, the Australian acid saline lakes and volcanic acid lakes differ in both mineralogy and sedimentology.

Comparison with Acid Mine Drainage

Negative pH values have been recorded in acid mine drainage (AMD; Nordstrom et al. 2003). AMD tends to flow as streams from sites where sulfide ores at the earth's surface are oxidized and yield sulfuric acid solutions. Commonly, AMD sites have been influenced heavily by human mining activity (e.g., Nordstrom et al. 2003; Fernandez-Remolar et al. 2005). Some of the minerals produced at these sites, such as iron oxides and jarosite, are the same as those at the Western Australian lakes. However, AMD sites only rarely precipitate halite or abundant gypsum. In addition, their deposits tend to show fluvial sedimentary features and not ephemeral-lake and associated facies.

How Will These Sediments Be Preserved in the Rock Record?

The Yilgarn Craton provides an ideal setting for making a significant deposit of acid saline sediments now and into the future, due to a combination of: (1) the continued weathering of bedrock containing few buffers (Long and Lyons 1992); (2) the arid climate appropriate for chemical precipitates by evapoconcentration; (3) the relative longevity of reworked gypsum due to iron oxide coatings (which protect them from dissolution); and (4) the large-scale regional setting. We suggest that, over time, the saline lake systems of the Yilgarn Craton will produce a regionally extensive deposit of red beds composed of mixed siliciclastics and evaporites.

Recognizing ancient acid-saline-lake deposits may be challenging. Dissolution and wind often rework and destroy some original facies, especially bedded halite and gypsum of the lake facies. Ephemeral lake deposits, whether acid, neutral, or alkaline, look very different from the traditional black shale or carbonate mudstone lake facies of many perennial-lake deposits. Acid-lake systems are dominated by sandy sediments lacking in carbonate minerals. In addition, early diagenetic features obliterate some sedimentary structures and textures. However, the early diagenetic minerals may be part of the key to recognizing past acid-lake deposits (Benison and Goldstein 2002).

Are other red bed/evaporite deposits made by acid waters? The mid Permian Nippewalla Group and Opeche Shale of the mid-continent, U.S.A., serve as two documented ancient acid lake deposits (Benison et al. 1998). They are composed primarily of red bed sandstones and siltstones with some laterally discontinuous thin beds of halite and thin and medium beds of gypsum (Benison and Goldstein 2000, 2001). Recent data on the sedimentology and mineralogy of lithified strata on Mars are strikingly similar to the Western Australian acid-saline-lake systems, suggesting that acid saline surface waters and shallow groundwaters once existed there (Benison and Bowen 2006). Many other ancient terrestrial red beds contain evaporite minerals and should be investigated as possible acid-lake deposits.

CONCLUSIONS

A combination of physical and chemical processes, including flooding, evapoconcentration, desiccation, and winds, determine the sedimentary characteristics of the extremely acid saline lakes and surrounding mudflats, sandflats, channels, and dunes in southern Western Australia. Although surface processes are similar to those of some other hypersaline lakes elsewhere in the world, acidity contributed from groundwater results in some unusual processes, such as direct precipitation of hematite from lake water, and a rare assemblage of depositional and early diagenetic products. This knowledge of natural acid saline lakes expands our understanding of the range of terrestrial extreme environments and serves as a foundation for identifying acid lake deposits elsewhere on the earth and in the Solar System.

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