SEDIMENTOLOGY the journal of the International Association of Sedimentologists

Sedimentology (2012) **59,** 1237–1256 doi: 10.1111/j.1365-3091.2011.01304.x

Playa-lake sedimentation and organic matter accumulation in an Andean piggyback basin: the recent record from the Cuenca de Pozuelos, North-west Argentina

MICHAEL M. MCGLUE*, GEOFFREY S. ELLIS†, ANDREW S. COHEN* and PETER W. SWARZENSKI‡

**Department of Geosciences, The University of Arizona, 85721 Tucson, AZ, USA (E-mail: mmmcglue@email.arizona.edu)*

†Energy Resources Program, US Geological Survey, 80225 Denver, CO, USA

‡Pacific Coastal and Marine Science Center, US Geological Survey, 95060 Santa Cruz, CA, USA

Associate Editor – Daniel Ariztegui

ABSTRACT

Expansive playa-lake systems situated in high-altitude piggyback basins are important and conspicuous components of both modern and ancient cordilleran orogenic systems. Extant playa lakes provide vital habitat for numerous endemic species, whereas sediments from these deposystems may record signals of climate change or develop natural resources over geological time. Laguna de los Pozuelos (North-west Argentina) provides the opportunity for an actualistic sedimentological and geochemical assessment of a piggyback basin playa lake in an area of critical interest for understanding Quaternary palaeoclimate dynamics. Silty clays and diatom ooze are the dominant playa-lake centre microfacies, with concentrations of total organic carbon and biogenic silica commonly exceeding 1·5 wt% in this sub-environment. Elemental and stable isotopic analyses point to a mixed organic matter composition in the playa-lake centre, with substantial contributions from algae and transported aquatic macrophytes. Bulk sediment and organic mass accumulation rates in the southern playa-lake centre approach 0·22 g cm^{-2} $year^{-1}$ and 2·89 mg cm^{-2} $year^{-1}$, respectively, indicating moderately rapid deposition with negligible deflation over historic time. Playa margin facies contain higher percentages of fragmented biogenic carbonate (ostracods and charophytes) and inorganically precipitated aragonite crusts due to seasonal pumping and evaporation of ground water. Organic matter accumulation is limited along these heavily bioturbated wet and dry mud flats. Fluvial–lacustrine transitional environments, which are key waterbird habitats, are either silty terminal splay (northern axis) or sandy deltas (southern axis) containing highly oxidized and partially allochthonous organic matter. Modern analogue data from Laguna de los Pozuelos provide key insights for: (i) environmental reconstructions of ancient lake sequences; and (ii) improving facies models for piggyback basins.

Keywords Laguna de los Pozuelos, piggyback basin, playa lake, Puna, sedimentary organic matter.

INTRODUCTION

Cordilleran orogenic systems, typified by eastward subduction of oceanic crust and the development of contractional mountain belts, produce a number of different basin types in which thick packages of sediment have accumulated (Jordan, 1995; DeCelles & Giles, 1996). Whereas

© 2011 The Authors. Journal compilation © 2011 International Association of Sedimentologists

continental scale, partitioned foreland basins typify lowland retro-arc positions, smaller thrust fault-bounded basins commonly develop high atop the orogenic wedge itself ('piggyback basins'; Ori & Friend, 1984; Beer *et al.*, 1990; Talling *et al.*, 1995; Horton & DeCelles, 1997). The environmental conditions that prevail in these small, high-altitude basins typically are extreme, with low effective precipitation and wide temperature fluctuations. Yet a number of striking terrestrial ecosystems mark these basins, including large lakes and wetlands. In the central Andes, for example, playa lakes and their associated environments provide essential habitat and food resources for a variety of endemic fauna, including camelids (for example, *Vicugna vicugna*), flamingos (for example, *Phoenicoparrus andinus* and *Phoenicoparrus jamesi*) and shorebirds (for example, *Recurvirostra andina* and *Fulica cornuta)*. Additionally, playa-lake deposits are of considerable interest to geologists, sedimentologists and palaeolimnologists (Teller & Last, 1990; Rosen, 1994; Nicoll, 2004; Cupper, 2006). Throughout the Americas, playa-lake sediments have been used: (i) to reconstruct local and regional palaeohydrology (Eugster & Hardie, 1975, 1978; Dargam & Depetris, 1996; González & Maidana, 1998); (ii) to investigate ancient environments and their peoples (Markgraf *et al.*, 1984; Waters, 1989; Castiglia & Fawcett, 2006); and (iii) for economic purposes, such as in the development of lithium, trona and oil shale (Dyni, 2006).

The purpose of the present study is to explore sedimentation and organic matter (OM) accumulation in the Cuenca de Pozuelos, an internally drained piggyback basin in the Jujuy Province of north-west Argentina (*ca* 22° S; Fig. 1). The most striking hydrological feature of the basin is Laguna de los Pozuelos (LP), a shallow, polymictic playa lake situated near the centre of the basin. Aside from the studies of Igarzábal (1978) and Gangui (1998), there are no prior published geological studies of the late Quaternary record of LP, which is surprising considering: (i) the lake's reputation as a RAMSAR wetland of international importance and its role as an environmentally sensitive wintering site for Andean and Nearctic waterbirds; and (ii) the growing recognition of the importance of small lakes to the global carbon budget (Dean & Gorham, 1998; Duarte *et al.*, 2008). As one of the largest lacustrine ecosystems in the Andean Puna, LP provides a unique opportunity to investigate the patterns and provenance of organic sedimentation in a high-altitude piggyback basin where climate and tectonic conditions are relatively well-constrained. The motivation for this research stems from the dearth of realistic modern analogues for compressional basin lake deposits. Historically, modern alluvial fan and fluvial megafans in foreland basins have received significant scientific attention (DeCelles & Hertel, 1989; Sinha & Friend, 1994; Leier *et al.*, 2005; Assine & Silva, 2009). These actualistic studies have strongly aided in the interpretation of tectonic

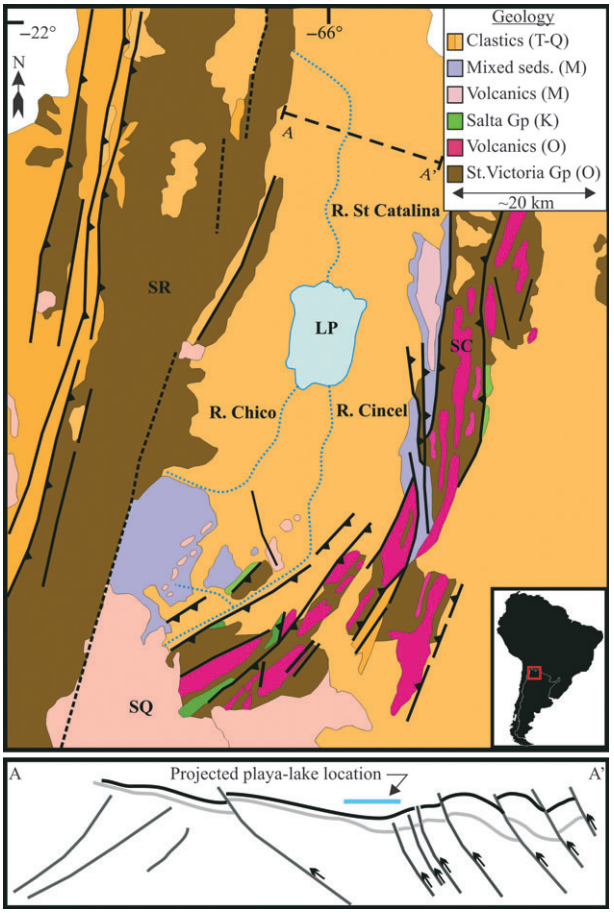

Fig. 1. Geological map of the Cuenca de Pozuelos (simplified from Page, 1996). Cross-section A–A′ (simplified from Gangui, 1998) illustrates the subsurface structure of the basin and the uppermost syn-orogenic stratigraphic packages (black and grey horizons). Westward-verging thrust faults control subsidence in the basin and provide accommodation space for Quaternary deposits. Laguna de los Pozuelos occupies a central location in the basin, and is seasonally fed by three rivers. Mixed Miocene-aged sediments are dominantly interbedded volcaniclastics, sandstones, conglomerates, gypsiferous beds and continental carbonates. (LP = Laguna de los Pozuelos; SR = Sierras de Rinconada; SC = Sierras de Cochinoca; SQ = Sierras de Quichagua; T = Tertiary; Q = Quaternary; M = Miocene; K = Cretaceous; O = Ordovician.)

processes and climate from the Phanerozoic rock record (Horton & DeCelles, 2001; Gierlowski-Kordesch *et al.*, 2008; Uba *et al.*, 2009). In contrast, extant lakes and wetlands in basins associated with 'thin-skinned' fold–thrust belts have received far less study from the perspective of basin analysis. As a result, accurate interpretations of equivalent ancient strata remain a challenge. Thus, the data presented herein have implications for improving facies models for intracontinental foreland basins, where natural resource exploration has traditionally been viewed as complex and high risk (Katz, 2001). Additionally, a number of active and vigorous debates centre on the late Quaternary climate history of the high Andes (Baker *et al.*, 2001; Placzek *et al.*, 2006; Fritz *et al.*, 2007; Quade *et al.*, 2008). Teller & Last (1990) note that closed basin lakes are highly sensitive to changes in hydrology, and a pronounced set of palaeoshorelines at the southern edge of the basin suggest that LP is no exception. As base-level fluctuations commonly impact the stratigraphic record in lake basins, long sediment cores from LP may yield novel insights on the timing and nature of Quaternary climate change in the Puna. Before meaningful millennial-scale palaeoenvironmental reconstructions can be attempted, however, modern calibration datasets are needed in order to fully deduce the meaning and fidelity of sedimentary indicators like bulk OM geochemistry.

REGIONAL OVERVIEW

The study site occupies the floor of the Cuenca de Pozuelos (*ca* 3650 m above sea-level), a NNE–SSW-oriented piggyback basin in the Puna morphotectonic province of the Andean cordillera (Allmendinger *et al.*, 1997). Tectonostratigraphic relationships indicate that basin formation occurred from 28 to 16 Ma (Rubiolo, 1997). The Cuenca de Pozuelos is *ca* 110 km long and *ca* 25 km wide. The flat-floored basin is bounded by westward-verging thrust sheets carrying Ordovician marine siliciclastic (St Victoria Group) and volcanic rocks (Fig. 1). Relief between the basin floor and the crests of marginal mountain ranges exceeds 700 m (Fig. 2). Small exposures of Cretaceous continental sediments crop out near the southern end of the basin, whereas Miocene ignimbrites are common along the eastern flank (Page, 1996). Mixed continental sediments of Miocene age, including volcaniclastics, sandstone, conglomerate, gypsiferous units and carbonates, are also present in the Sierras de Cochinoca (Fig. 1; Cladouhos *et al.*, 1994; Rubiolo, 1997). As a result, the eastern side of the basin represents a potential source of hard water to the playa lake. Ancient carbonate strata are absent in drainages along the western and southern margins of the basin; runoff to LP derived from these rocks is relatively dilute.

Laguna de los Pozuelos is a large, seasonally fluctuating playa lake. Satellite images and field observations indicate that the surface area of LP can exceed 135 km^2 during years with above-average precipitation (Mirande & Tracanna, 2009). Conversely, intervals of prolonged drought commonly lead to desiccation of the playa lake and exposure of the basin floor. Bathymetric variability is low due to the negligible basin-floor gradient. When completely filled, LP reaches a maximum depth near its centre (<2 m) and progressively shoals towards its margins. Ground water discharge probably provides the most important source of water to LP (Igarzábal, 1978). Springs were most commonly encountered as small, isolated pools on the basin floor south of the playa lake. In addition to ground water and rainfall, the playa lake is fed by three axial river systems: (i) the intermittent Río Santa Catalina, which enters from the north and drains the Sierras de Rinconada to the north-west; (ii) the Río Cincel, which enters from the south-east and drains the dominantly volcanic Sierras de Quichagua to the south; and (iii) the Río Chico, which enters from the south-west and drains the southern extent of the Sierras de Rinconada (Fig. 1). Numerous ephemeral streams emerge from adjacent highlands and build alluvial fans laterally along both sides of the playa lake (Fig. 2).

Total precipitation in the Cuenca de Pozuelos is *ca* 320 mm $year^{-1}$ and annual air temperatures range from 3 to 13°C (Legates & Willmott, 1990a,b). Climate in the region is controlled by the South American Summer Monsoon system (Zhou & Lau, 1998; Garreaud *et al.*, 2009). Rainfall is strongly seasonal, with *ca* 70% of the yearly total falling during the austral summer. As with many regions on the Puna plateau, the El Niño-Southern Oscillation (ENSO) phenomenon and North Atlantic sea surface temperatures modulate patterns of precipitation over the Cuenca de Pozuelos (Garreaud *et al.*, 2003); this is especially true during cold-phase La Niña intervals, which bring enhanced total rainfall and higher lake levels to LP. South-easterly summer winds are

© 2011 The Authors. Journal compilation © 2011 International Association of Sedimentologists,

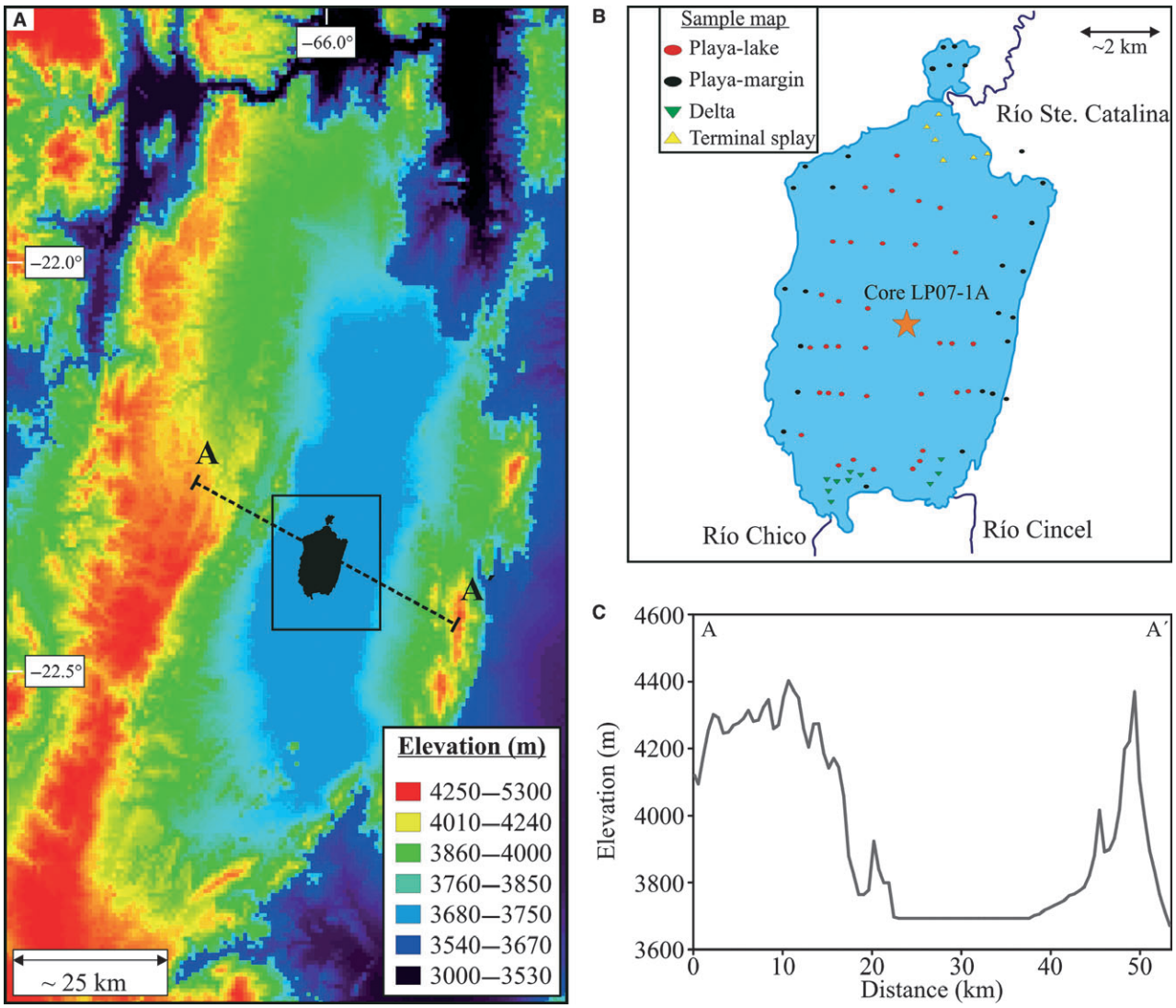

Fig. 2. (A) SRTM 90 digital elevation model of Cuenca de Pozuelos (modified from USGS, 2004). Inset map (B) shows locations of surface sediment samples and the core LP07-1A. Surface sediments (n = 79) were collected by hand from the playa-lake centre, margin, delta and terminal splay complex sub-environments. Inset profile along cross-section A–A′ (C) shows the relief created by hanging wall topographic barriers with the basin floor.

generally weak, whereas westerly winter winds are substantially stronger. Due to its occasional persistence through the dry season, LP provides an important habitat for numerous waterbirds, including all three species of New World flamingos: *Phoenicopterus chilensis*, *Phoenicoparrus andinus* and *Phoenicoparrus jamesi* (Caziani *et al.*, 2001; Mascitti, 2001; Moschione & Sureda, 2008).

A vegetation survey conducted in the basin indicates that plant assemblages generally follow topographic and soil-moisture gradients (Bonaventura *et al.*, 1995). C_3-pathway shrubs including *Fabiana densa* and *Baccharis boliviensis* are abundant on alluvial slopes, with minor CAM pathway succulents of varying species (including *Maihueniopsis glomerata* and *Opuntia soehrensii*) interspersed (Fig. 3). Grasses, including *Stipa ichu* (C_3), *Distichlis spicata* (C_4) and *Festuca* sp. (C_3), carpet the basin floor. Within LP, meadows of the halophyte *Ruppia* sp. are ubiquitous in shallow water around the southern river deltas (Fig. 3).

METHODS AND MATERIALS

Water chemistry was determined *in situ* using a YSI model 85 multi-meter (YSI Incorporated, Yellow Springs, OH, USA) for dissolved oxygen and conductivity, whereas a Hach Sension 1 meter (Hach Company, Loveland, OH, USA) was

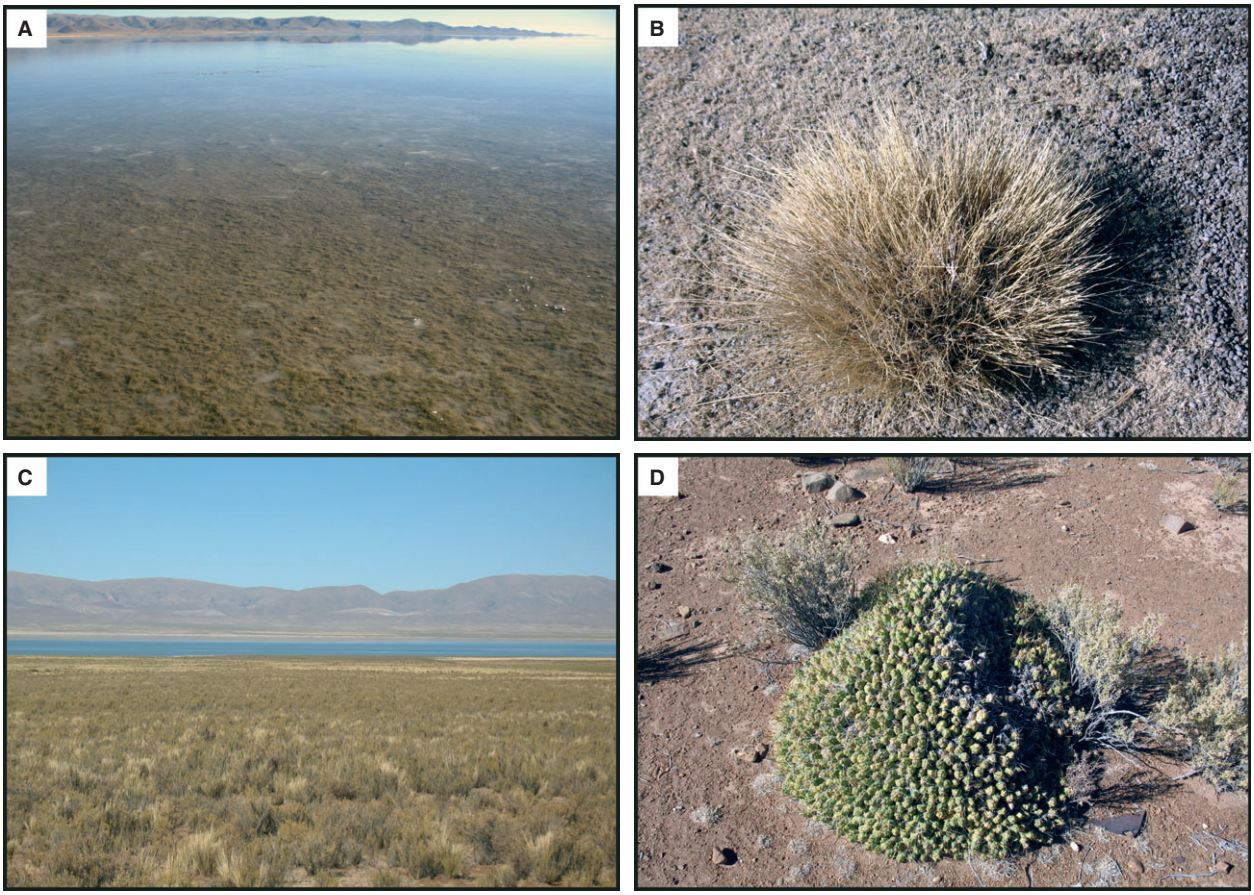

Fig. 3. Vegetation in the Cuenca de Pozuelos. Bonaventura *et al.* (1995) noted that the vegetation density exceeds other basins in the Puna, because mean annual rainfall approaches 300 mm. (A) Aquatic macrophytes dominated by *Ruppia* species. *Ruppia* sp. meadows in the foreground cover an area of *ca* 100 m^2, with individual branched stems up to *ca* 50 cm long. (B) Basin-floor C_3 vegetation, dominated by *Stipa* and *Festuca* spp. grasses; grass bunch in photograph is *ca* 10 cm tall. (C) Semi-arid steppe shrubs that cover alluvial slopes in the basin, dominated by *Fabiana densa* and *Baccharis boliviensis*. Individual shrubs in photograph foreground are up to 150 cm tall. (D) Succulent vegetation on alluvial slopes; cactus in photograph is *ca* 100 cm tall.

used to measure pH. Water samples retrieved from the playa-lake centre were analysed for major ions using a PerkinElmer Optima 5300 ICP-OES (PerkinElmer Inc., Waltham, MA, USA) at the University of Arizona.

Surface sediments (n = 79; Table 1) were collected from the floor of the Cuenca de Pozuelos and LP using a standard scoop sampler. The strategy for sediment retrieval focused on sampling each of the basin's different depositional sub-environments, including the playa-lake centre (submerged up to 70 cm during sampling in 2006), playa margins (wet and dry mud flats, in some areas influenced by alluvial fans) and axial deltas (Ríos Cincel and Chico) or terminal splay complex (Río Santa Catalina; Fig. 4). Sediment smear slides were inspected under a petrographic microscope to estimate major mineralogical and biogenic components. A sediment core (LP07-1A) was collected from the playa-lake centre during the dry season of 2007, when the water level was reduced to <2 to 3 cm (Fig. 2). Sediment geochronologies, in terms of both mass accumulation (g cm^{-2} $year^{-1}$) and linear sedimentation rates (cm $year^{-1}$), were derived from this core using multiple radioactive tracers, including excess ^{210}Pb ($t_{1/2}$ = 22·3 years) and ^{137}Cs ($t_{1/2}$ = 30·1 years). Crushed, dried sediment was sampled over 1 cm intervals and counted in a calibrated high-purity Ge well-type gamma detector using energies of 46·52 keV (^{210}Pb) and 661·6 keV (^{137}Cs) at the United States Geological Survey (USGS) Pacific Coastal and Marine Science Center. Precision in the activities of ^{210}Pb and ^{137}Cs were better than 10%. Excess ^{210}Pb-derived geochronologies were calculated following the methodology presented in Swarzenski *et al.* (2006).

Table 1. Surface sample geochemistry and sedimentology for Laguna de los Pozuelos (M = Playa margin; D = Delta; L = Playa-lake centre; S = R. Ste. Catalina Splay).

Sample name	Latitude (°S)	Longitude (°W)	Mean *D* (μm)	TIC (wt%)	TOC (wt%)	TN (wt%)	BiSi (wt%)	$\delta^{13}C$ (‰)	C/N (atm)	Lithology
LP06-01 (M)	22·2701	65·9858	13·52	0·29	0·93	0·03	2·42	−19·22	36	SiC (o, c)
LP06-02 (M)	22·2697	65·9817	9·70	0·33	0·95	0·05	2·36	−19·49	22	SiC (o, c)
LP06-03 (M)	22·2767	65·9898	59·02	0·23	0·63	0·01	2·14	−17·70	74	CSi
LP06-04 (M)	22·2755	65·9836	30·84	0·32	0·88	0·05	2·22	−19·86	21	SiC (o, c)
LP06-05 (M)	22·2757	65·9788	13·98	0·35	1·04	0·07	2·29	−19·57	17	SiC (c)
LP06-06 (S)	22·2910	65·9875	59·06	0·40	0·79	0·02	2·07	−21·73	46	CSa (d, om)
LP06-07 (S)	22·2982	65·9893	30·99	0·04	0·83	0·02	1·36	−22·38	48	CSi
LP06-08 (M)	22·3062	66·0332	54·16	1·55	1·38	0·06	1·77	−17·12	27	CA (o)
LP06-09 (M)	22·3058	66·0212	15·05	0·40	1·06	0·05	1·71	−19·82	25	SiC (o)
LP06-10 (M)	22·3044	66·0188	11·42	0·22	1·42	0·11	2·19	−20·29	16	SiC (om)
LP06-11 (M)	22·3036	66·0020	12·81	0·14	1·19	0·06	3·08	−21·38	23	SiC (d)
LP06-12 (S)	22·3036	65·9941	12·49	0·01	1·60	0·07	3·58	−23·46	25	Od (om)
LP06-13 (M)	22·3049	65·9493	14·77	0·10	1·07	0·03	2·05	−22·82	48	SiC
LP06-14 (S)	22·3048	65·9849	19·85	0·01	3·30	0·14	3·04	−24·59	27	SiC (d, om)
LP06-15 (S)	22·3074	65·9753	22·79	0·48	1·19	0·05	1·26	−20·45	28	SiC (o)
LP06-16 (S)	22·3068	65·9707	15·52	0·46	1·38	0·06	1·31	−19·74	29	SiC (o)
LP06-17 (M)	22·3129	66·0376	26·69	0·94	1·10	0·05	1·96	−17·72	26	SiC (o, c)
LP06-18 (L)	22·3132	66·0241	14·31	0·73	1·70	0·13	2·08	−18·60	15	Od (om)
LP06-19 (L)	22·3136	66·0133	12·88	0·41	1·30	0·05	1·64	−19·43	32	SiC
LP06-20 (L)	22·3149	66·0041	12·68	0·27	1·07	0·05	2·07	−20·26	21	SiC (d)
LP06-21 (L)	22·3179	65·9954	6·42	0·20	1·36	0·08	2·22	−20·14	20	Od (om)
LP06-22 (L)	22·3199	65·9858	11·06	0·16	1·24	0·09	1·85	−21·07	17	Od (om)
LP06-23 (M)	22·3237	65·9691	14·36	0·57	2·00	0·69	1·35	−19·49	3	CA (o, c, om)
LP06-24 (M)	22·3255	65·9568	11·74	0·13	1·24	0·09	0·49	−19·10	16	SiC
LP06-25 (M)	22·3411	65·9606	10·15	0·26	1·32	0·11	1·78	−19·90	14	SiC (o)
LP06-26 (L)	22·3345	65·9831	9·79	0·30	1·37	0·10	2·35	−20·34	16	Od
LP06-27 (M)	22·3554	65·9641	14·75	0·49	1·18	0·09	1·06	−19·40	15	SiC (o)
LP06-28 (M)	22·3539	65·9677	8·84	0·29	1·65	0·13	1·37	−19·90	15	SiC (o, c, om)
LP06-29 (L)	22·3318	65·9966	8·19	0·35	1·44	0·12	1·61	−20·43	14	SiC (d, om)
LP06-30 (L)	22·3313	66·0078	12·27	0·25	2·02	0·12	2·16	−21·24	21	Od (om)
LP06-31 (M)	22·3308	66·0181	11·59	0·73	1·49	0·10	1·25	−19·83	17	SiC (o, om)
LP06-32 (M)	22·3302	66·0249	11·06	0·81	1·38	0·09	1·15	−18·96	17	SiC
LP06-33 (M)	22·3452	66·0412	36·86	0·97	1·26	0·07	1·45	−17·61	21	CA (c, o)
LP06-34 (M)	22·3459	66·0341	10·10	1·25	1·97	0·10	1·09	−17·25	23	CA (c, om)
LP06-35 (L)	22·3472	66·0286	7·49	0·97	1·83	0·11	2·25	−18·92	20	SiC (o, d)
LP06-36 (L)	22·3494	66·0229	11·25	0·40	1·30	0·09	1·45	−20·40	17	SiC (o, d)
LP06-37 (L)	22·3515	66·0133	8·06	0·43	1·81	0·10	1·21	−18·64	21	SiC (om, d)
LP06-39 (M)	22·3636	66·0328	7·75	0·45	1·41	0·10	1·56	−20·13	17	SiC (o, d)
LP06-40 (L)	22·3635	66·0279	7·77	0·42	1·40	0·10	2·87	−20·34	16	Od (om, c)
LP06-41 (L)	22·3635	66·0231	9·71	0·34	1·42	0·09	2·56	−20·31	18	Od (om)
LP06-42 (L)	22·3642	66·0144	8·07	0·35	1·48	0·08	1·86	−19·09	21	SiC (d, om)
LP06-43 (L)	22·3633	65·9886	18·58	0·30	1·34	0·08	2·26	−20·00	19	Od (om)
LP06-44 (L)	22·3634	65·9848	9·05	0·38	1·82	0·09	1·62	−19·16	23	SiC (om, d)
LP06-45 (L)	22·3635	65·9773	10·23	0·54	1·58	0·10	1·27	−19·41	19	SiC (o, c, om)
LP06-46 (M)	22·3632	65·9659	16·44	0·52	1·29	0·08	1·71	−19·76	20	SiC (o, c)
LP06-47 (M)	22·3812	65·9668	90·92	0·13	0·76	0·04	0·83	−23·76	22	CSa
LP06-48 (M)	22·3795	65·9713	19·71	0·73	1·55	0·08	1·84	−19·60	23	CA (om)
LP06-49 (M)	22·3787	65·9748	18·82	0·85	2·30	0·08	2·68	−16·38	35	CA (om, d)
LP06-50 (L)	22·3787	65·9795	10·45	0·65	1·52	0·11	2·46	−20·29	16	SiC (d, o)
LP06-51 (L)	22·3789	65·9835	14·03	0·49	1·44	0·10	2·63	−20·34	16	SiC (o, d)
LP06-52 (L)	22·3792	65·9899	11·70	0·39	2·26	0·12	2·26	−17·34	22	Od (om)
LP06-53 (L)	22·3794	66·0192	5·17	0·34	1·36	0·11	1·56	−20·61	15	SiC (d, om)
LP06-54 (L)	22·3786	66·0225	7·88	0·35	2·35	0·13	2·69	−18·40	21	Od (om)
LP06-55 (L)	22·3782	66·0272	11·37	0·38	1·93	0·12	3·37	−18·83	19	Od (om, o)
LP06-56 (L)	22·3779	66·0299	12·71	0·54	1·48	0·12	2·62	−20·27	14	SiC (d, o, c)
LP06-57 (M)	22·3778	66·0317	10·03	0·68	2·04	0·12	1·97	−18·48	21	SiC (o, c, om)

Table 1. (*Continued*).

Sample name	Latitude (°S)	Longitude (°W)	Mean *D* (μm)	TIC (wt%)	TOC (wt%)	TN (wt%)	BiSi (wt%)	$\delta^{13}C$ (‰)	C/N (atm)	Lithology
LP06-58 (M)	22·3901	66·0426	156·3	0·93	0·93	0·01	1·41	−18·42	79	CSa (c, o)
LP06-59 (M)	22·3913	66·0365	13·38	0·50	1·44	0·12	0·97	−19·46	14	SiC (o, c)
LP06-60 (L)	22·3978	65·9965	9·57	0·21	1·64	0·11	2·45	−22·33	17	SiC (d, om)
LP06-61 (M)	22·3995	65·9915	15·61	0·32	1·43	0·09	1·75	−21·62	19	SiC (o, om)
LP06-62 (D)	22·4017	65·9875	120·0	0·14	0·88	0·02	1·00	−22·85	51	CSa
LP06-63 (D)	22·4042	65·9912	181·0	0·04	1·07	0·03	0·70	−24·60	42	CSa (om)
LP06-64 (L)	22·4010	65·9980	12·05	0·15	1·83	0·10	3·71	−22·30	21	Od (om)
LP06-65 (M)	22·3913	66·0365	18·22	0·93	1·49	0·09	3·07	−18·74	19	CA (d, om)
LP06-66 (D)	22·3901	66·0426	101·8	0·40	0·50	0·02	0·71	−19·21	29	CSa
LP06-67 (D)	22·4068	65·9937	154·7	0·04	0·14	0·02	1·03	−23·80	8	CSa
LP06-68 (D)	22·4039	65·9992	13·64	0·31	1·44	0·09	2·88	−21·92	18	SiC (d, om)
LP06-69 (L)	22·3996	66·0200	11·25	0·25	1·29	0·11	3·53	−20·95	14	Od (om)
LP06-70 (L)	22·3987	66·0239	7·56	0·32	1·37	0·11	2·70	−20·42	15	SiC (d, om)
LP06-71 (L)	22·4004	66·0241	6·61	0·34	1·59	0·11	1·46	−19·93	17	SiC (om, o)
LP06-72 (L)	22·4021	66·0193	11·69	0·23	1·30	0·10	2·99	−20·71	15	SiC (d)
LP06-73 (L)	22·4036	66·0158	7·45	0·29	1·40	0·10	1·84	−21·15	16	SiC (d, om)
LP06-74 (L)	22·4040	66·0141	6·93	0·25	1·45	0·09	3·25	−18·46	20	Od (om)
LP06-75 (M)	22·4076	66·0152	7·77	0·31	1·53	0·11	2·52	−21·25	16	SiC (d, om)
LP06-76 (D)	22·4065	66·0216	9·90	0·25	1·45	0·10	3·85	−21·21	17	Od (om)
LP06-77 (D)	22·4060	66·0276	10·15	0·80	2·06	0·12	2·68	−20·16	20	SiC (o, c, om)
LP06-78 (D)	22·4104	66·0276	128·7	0·02	0·23	0·13	1·13	−23·27	2	CSa
LP06-79 (D)	22·4119	66·0276	36·23	0·06	0·83	0·25	2·54	−21·40	4	CSi (d)
LP06-80 (D)	22·4066	66·0254	21·24	0·32	1·40	0·58	3·25	−21·01	3	CSi (d, om)

Primary sedimentary components are listed with capital letters (C = clay; Si = silt; Sa = sand; CA = calcareous mud; Od = diatom ooze) with major modifiers in lower-case letters in brackets (c = *Chara* fragments; d = diatoms; om = organic matter; o = ostracods).

Elemental and stable isotopic analyses of sedimentary OM were conducted at the University of Arizona to provide insights on biomass production, preservation and provenance at LP. Total organic carbon (TOC), total nitrogen and $\delta^{13}C_{om}$ values were measured on a continuous-flow gas-ratio mass spectrometer (Finnigan Delta PlusXL; Thermo Fisher Scientific Inc., Waltham, MA, USA) coupled to a Costech elemental analyser (Costech Analytical Technologies Inc., Valencia, CA, USA). Prior to measurement, carbonate was removed using an aqueous HCl digestion procedure (Talbot, 2001). Samples were combusted in the elemental analyser. Standardization is based on acetanilide for elemental concentration, NBS-22 (National Bureau of Standards-22) and USGS-24 for $\delta^{13}C_{om}$. Precision is better than ±0·09 for $\delta^{13}C_{om}$ based on repeated analysis of internal standards. Atomic C : N ratios presented in Table 1 were corrected for contributions of inorganic nitrogen following the methodology outlined by Talbot (2001). Select decalcified samples from across LP were analysed by Rock-Eval pyrolysis at the University of Houston in order to further discriminate the provenance of OM (Table 2; Espitalie *et al.*, 1977; Katz, 1983).

The composition of LP sediments were further evaluated through analyses of total inorganic carbon (TIC) and biogenic silica (BiSi). Weight per cent of TIC per sample was determined using a UIC Inc., total carbon coulometer (UIC Inc., Joliet, IL, USA) at the Limnological Research Center (LRC) of the University of Minnesota. Analytical precision associated with this technique was typically better than 0·2%. Biogenic silica analyses were also completed at the LRC, utilizing multiple extractions of hot alkaline digestions following a modified stepped time series protocol designed by DeMaster (1979). Sediments were exposed to boiling NaOH for a total of 200 min and reported values have an analytical precision of *ca* 1·0%.

Detrital particle size was measured to assess depositional energy and sedimentary processes at the University of Arizona. Particle-size analysis utilized a Malvern laser-diffraction particle size analyser coupled to a Hydro 2000S sample dispersion bench (Malvern Instruments Inc., Westborough, MA, USA). Sample pre-treatment followed the recommendations of Johnson & McCave (2008) for the isolation of the terrigenous fraction of lake sediments. Samples for particle-

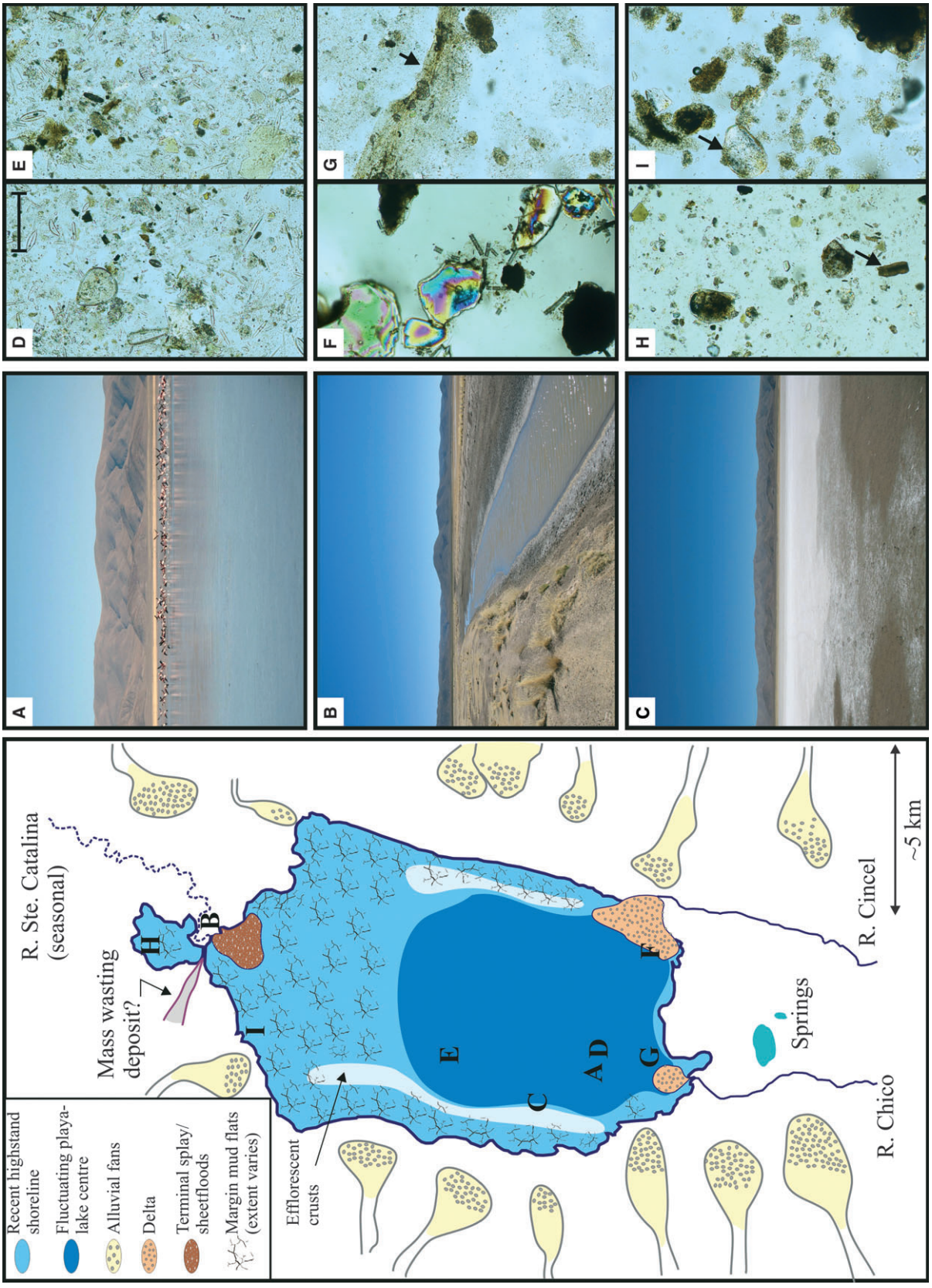
A
B
C
D
E
F
G
H
I
Recent highstand shoreline
Fluctuating playa-lake centre
Alluvial fans
Delta
Terminal splay/ sheetfloods
Margin mud flats (extent varies)
Efflorescent crusts
Mass wasting deposit?
R. Ste. Catalina (seasonal)
R. Cincel
R. Chico
Springs
~5 km

Table 2. Surface sediment Rock-Eval pyrolysis data, Laguna de los Pozuelos.

Sample name	S1 (mg HC gm^{-1} rk)	S2 (mg HC gm^{-1} rk)	HI (mg HC gm^{-1} TOC)	OI (mg CO_2 gm^{-1} TOC)	T_{max} (°C)
LP06-02	0·14	0·85	125	69	349
LP06-04	0·10	0·62	83	51	377
LP06-06	0·25	0·67	88	45	398
LP06-12	0·50	1·67	115	64	408
LP06-17	0·19	0·93	92	49	396
LP06-18	0·27	1·43	111	62	424
LP06-19	0·25	1·15	104	57	420
LP06-20	0·34	1·03	99	50	374
LP06-21	0·22	0·84	73	30	401
LP06-22	0·30	1·09	107	53	402
LP06-23	0·11	1·03	57	32	425
LP06-24	0·16	0·85	96	52	407
LP06-29	0·30	1·21	88	50	413
LP06-37	0·26	1·83	145	160	427
LP06-39	0·17	1·33	119	65	422
LP06-40	0·26	1·93	151	98	427
LP06-41	0·21	1·67	144	82	430
LP06-42	0·22	1·72	156	105	427
LP06-43	0·19	1·32	120	72	427
LP06-44	0·20	1·77	126	73	429
LP06-45	0·34	2·34	190	155	427
LP06-46	0·09	1·02	99	48	427
LP06-53	0·21	1·45	123	68	416
LP06-70	0·13	1·13	98	55	420
LP06-79	0·21	0·67	74	35	391
LP06-80	0·14	1·27	94	55	421

Coordinates for samples are presented in Table 1.

size analysis were also treated with 1 M HCl for 24 h to remove carbonate. Following completion of the digestions, samples were placed on a mechanical shaker in a dilute solution of sodium hexametaphosphate for several hours to disaggregate clays. Prior to analyses, sediments were examined optically to ensure that all the OM, BiSi and inorganic carbon had been removed.

RESULTS AND INTERPRETATIONS

The concentration of solutes is relatively high in LP, with Na^+ and Ca^{2+} (553 mg l^{-1} and 129 mg l^{-1}, respectively) dominating the cation composition, whereas Cl^- and HCO_3^- are the most significant anions (761 mg l^{-1} and 198 mg l^{-1}). Mg^{2+} is present at a concentration of 30 mg l^{-1}, indicating a relatively low Mg/Ca_{water}. Playa waters are oxygen saturated, brackish (4 to 29 ppt), basic (mean pH of 8·7) and appear to be spatially homogenous, at least during the austral winter when the readings were taken. These patterns probably result from wind mixing of the shallow water column and a low ground water table.

Modern sediments are compositionally diverse but typically dominated by siliciclastic material

Fig. 4. Basin-floor geomorphology and geology of the Cuenca de Pozuelos (letters on the map correspond to field photographs and smear slide photomicrographs at the right). Sierras de Rinconada in the background of photographs in panels (A) to (C) are *ca* 400 to 700 m above the lake surface. (A) Playa-lake environment, looking to the west. (B) Río Santa Catalina distributary channel (*ca* 25 m wide), looking to the west. Distal channels are narrow and commonly empty in the dry season. (C) Playa-margin mud flats with efflorescent crusts, looking to the west. Crusts encountered in the field were <0·5 cm thick. Mud cracking and bioturbation is common during the dry season. (D) Playa-lake centre diatom ooze with minor detrital grains and calcite. (E) Playa-lake centre diatom ooze with organic matter. Diatoms are heavily fragmented, due to wind mixing and bioturbation. (F) Deltaic sands (quartz and rock fragments) with minor diatoms. (G) Aquatic macrophyte fragment (marked by an arrow) and associated biogenic carbonate from intra-delta region, east of the distal Río Chico delta. (H) and (I) Playa-margin silty clay with abundant ostracods and charophyte stem casts (marked by arrows). The scale bar in panel (D) is 100 μm; this scale is common to all photomicrographs in panels (E) to (I).

© 2011 The Authors. Journal compilation © 2011 International Association of Sedimentologists, *Sedimentology*, **59**, 1237–1256

(Table 1). The playa-lake centre contains massive medium brown sediments, which in thin section are silty clays or diatom oozes with variable proportions of translucent OM (Fig. 4). Fine quartz and mica grains are common in playa-lake centre samples. Playa margin sediments are typically massive red–brown silty clays with minor amounts of carbonate. Carbonates encountered in playa margin environments are both inorganic and fragmented biogenic (ostracods and charophytes) remains (Fig. 4). Smear slides show that low-Mg calcite is the dominant form of carbonate accumulating along these low-gradient, low-energy margins, which is consistent with the relatively low Mg/Ca_{water} of LP. The majority of the calcite appears to be derived from broken ostracod carapaces, which are easily distinguished from inorganic precipitates in thin section based on relief, irregular grain shapes and grain diameters (Fig. 4). Coarse (>63 μm), tubular casts of *Chara* stems likewise are common, with calcified gyrogonites encountered in minor abundances (Fig. 4). Low-Mg calcite is also the most abundant carbonate mineral in the playa-lake centre. Closed basins marked by long-lived saline lakes often develop strong downslope mineral gradients, with evaporites crystallizing from highly evolved brines in the basin centre (Schuble & Lowenstein, 1987). Rapid evaporation of lake water, coupled with relatively dilute inflows, appears to constrain widespread crystallization of Mg-rich and Na-rich minerals in LP. Very fine needles of aragonite (*ca* 5 to 15 μm) were detected on smear slides (≤5 to 10%) and through qualitative analysis of powder X-ray diffraction data. Because the abundance of aragonite is highest on wet mud flats marked by thin white efflorescent crusts, it is likely that precipitation occurs due to evaporative pumping of shallow ground water (Fig. 4). Major two-theta peaks for other carbonates with the potential to form from LP brines (for example, dolomite and natrite) are absent on X-ray scans. If these phases exist in modern LP sediments, they do not account for more than a trace percentage of the total mineral assemblage. Sub-aerial exposure and desiccation of the playa margins occurs seasonally, as evidenced by vast networks of polygonal cracks; reworking by wind and foraging waterbirds and mammals in this sub-environment is common. The Río Cincel delta is dominated by sub-angular to sub-round, coarse terrigenous grains (quartz, sedimentary and volcanic rock fragments), usually with diatoms as a secondary component (Fig. 4). Sediments recovered from the distal fringes of the southern deltas and within intra-delta environments are clayey silts and clayey sands that are rich in macrophyte remains. Along the northern axis of LP, the Río Santa Catalina has the external morphology of a fluvially dominated delta, but intermittent discharge and evaporation has led to the development of a broad terminal splay complex (Fig. 4). Microfacies in this environment are commonly silty clays and clayey silts with minor to abundant diatoms and OM.

Sediment particle sizes are in the silt and clay fractions for most of the playa-lake centre (mean = *ca* 26 μm) and probably reflect a combination of suspension rainout and aeolian deposition (Fig. 5A). Coarse silt and sand-sized particles (>40 μm) deposited by traction flow are largely restricted to deltaic channels and lobes along the southern axial margin of the basin. At present, the Río Cincel builds a sandy delta (*ca* 3 km^2) near the south-eastern basin margin, whereas sandy deltaic deposits are smaller along the distal Río Chico. The Río Santa Catalina terminal splay complex is characterized by numerous narrow (<5 to 10 m), coalescing, empty, distributary channels that grade into the flat playa floor. In contrast to the southern deltas, mean particle sizes in this environment were <40 μm. Along the western margin of LP, restricted pockets of coarse silt and fine sand correlate with distal alluvial fan surfaces (Fig. 5A).

Values of BiSi range from 0·5 to 3·9 wt%, with a mean of 2·0 wt%. The BiSi concentrations are highest along the axial margins of LP, with samples exceeding 2·5 wt% near the Río Santa Catalina terminal splay and the Río Chico delta (Fig. 5B). Thin (<2 to 3 cm), intermittent mats of benthic diatoms were encountered offshore of the Río Chico delta. Moderate BiSi concentrations characterize the playa-lake centre, whereas the wet and dry mud flat margins of LP generally exhibit low (<1·0 wt%) values (Fig. 5B). Phytoplankton, particularly the diatoms *Cocconeis placentula*, *Nitzschia hungarica* and *Navicula* sp., represent the dominant source of BiSi within LP (Maidana *et al.*, 1998).

Concentrations of TIC follow a very different pattern than BiSi, with maximum values (>1·0 wt%) in mud-flat environments along the north-western margin of LP (Fig. 5C). Across the study area, values of TIC range from 0·01 to 1·6 wt%, with a mean of 0·4 wt%. At present, elevated TIC concentrations are associated exclusively with the margins of LP, where standing water evaporates rapidly and white efflorescent carbonate crusts develop on mud-cracked plains

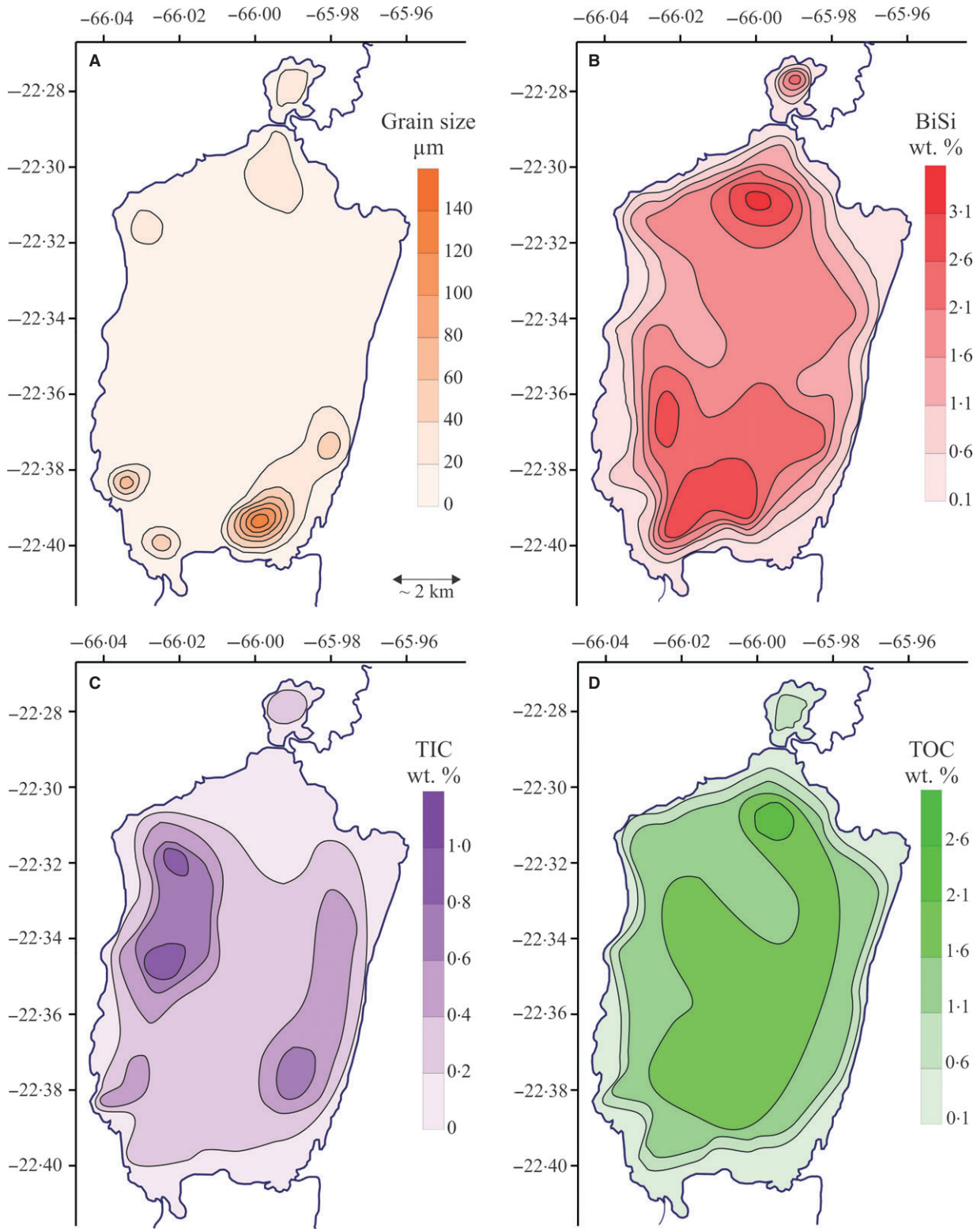

Fig. 5. Maps of surface sample physical sedimentology and geochemistry show: (A) mean terrigenous particle size (µm); (B) BiSi (wt%), representing dominantly diatoms; (C) TIC (wt%); and (D) TOC (wt%).

in the austral winter (Fig. 4). In contrast, in the basin centre and near the deltas, values of TIC are generally below 0·4 wt% (Fig. 5C).

Values of TOC range from 0·1 to 3·3 wt%, with a mean of 1·4 wt% (Fig. 5D). Samples exhibiting TOC values exceeding 1·5 wt% were collected

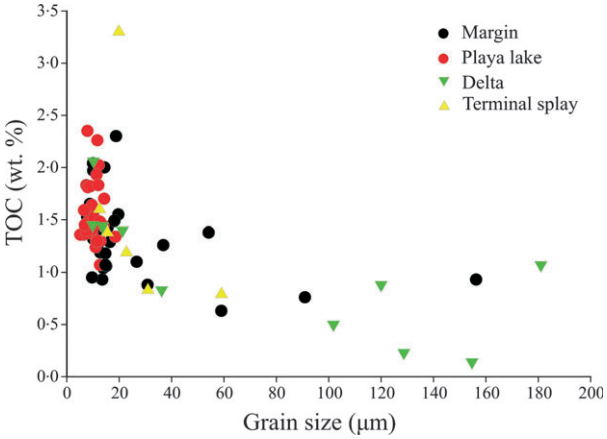

Fig. 6. Plot illustrating the inverse relation between mean grain size and TOC. Samples <20 μm are richest in organic carbon and are usually located in the basin axis, especially the playa-lake centre sub-environment. Samples in the coarse silt and sand size range have lower TOC values, indicating terrigenous dilution.

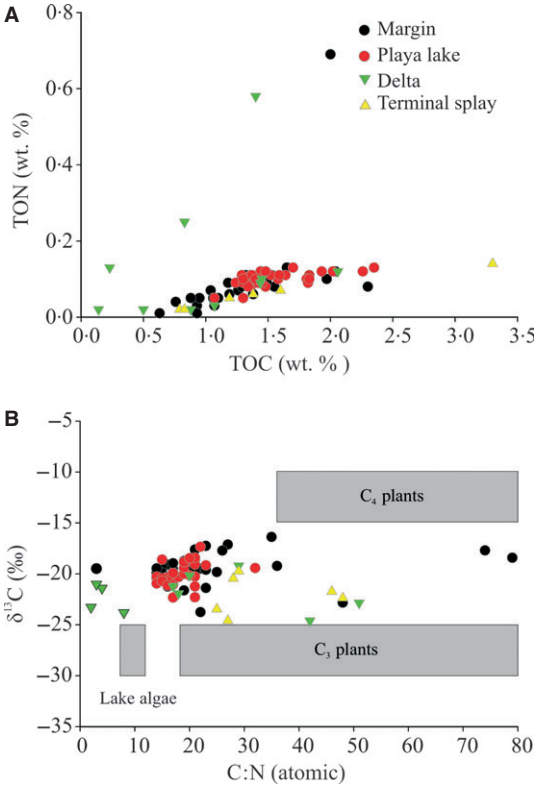

Fig. 7. (A) Total organic carbon (wt%) versus total organic nitrogen (wt%). (B) C : N versus $\delta^{13}C_{om}$. Grey boxes spanning general fields of known values for lacustrine algae, C_3 plants and C_4 plants from Meyers & Teranes (2001).

from all environments, but they are always fine-grained (<20 μm; Fig. 6). The TOC concentrations are richest within the distal reaches of the Río Santa Catalina splay (Fig. 5). Contours also illustrate elevated values of TOC in the playa-lake centre, whereas samples from the southern deltas and playa margins routinely exhibit TOC values ≤1·5 wt% (Fig. 5D). Samples from LP typically contain low total nitrogen (Table 1 and Fig. 7A). The C : N values range from 2 to 79 in the study area, with a mean of *ca* 22 (Fig. 7B). Samples collected from mud flats north-west of the main Río Santa Catalina channel and within the mouth of the Río Cincel delta exhibit low total nitrogen, leading to C : N values >30. Most of the playa-lake sediments have C : N values <20, which is typical for lakes with mixtures of algal and higher plant matter (Meyers & Teranes, 2001). An exception to this pattern is observed near the Río Chico delta, where values of total nitrogen substantially increase and C : N values fall to <5. Flamingo activity is high in this locale, probably due to the availability of food resources and favourable water depths. Seasonal foraging probably impacts both the carbon and nitrogen cycles across similar microhabitats in LP. Peterson & Fry (1987) noted that avian waste products, especially urea, are rich in organic nitrogen and ammonia. Local eutrophication from these waste products may result in phytoplankton blooms, as evidenced by elevated concentrations of BiSi in the distal Río Chico environment (Fig. 5B).

The $\delta^{13}C_{om}$ values range from −16·4 to −24·6‰, with a mean of −20·2‰ VPDB (Vienna Pee-Dee Belemnite; Table 1). Sedimentary OM derived exclusively from lacustrine phytoplankton typically exhibits lighter isotopic values (−25·0 to −30·0‰; Meyers & Teranes, 2001). The $\delta^{13}C_{om}$ values reported in this study indicate a substantial contribution of ^{13}C-enriched OM to the basin. In the playa-lake centre, smear slides reveal a mixture of algae and macrophyte remains (Fig. 4). Hydrogen index (HI) values reach their maximum (up to 190 mg HC gm^{-1} TOC) in this sub-environment (Table 2). Taken together, $\delta^{13}C_{om}$, HI and smear slide data indicate that sedimentary OM is derived from mixed autochthonous sources, including: (i) algal primary producers; and (ii) perennial aquatic macrophytes, especially *Ruppia* sp. transported from shallow water meadows. The HI values are lower in playa margin and deltaic sub-environments, with values <100 mg HC gm^{-1} TOC probably reflecting contributions of oxidized autochthonous and terrestrial vegetation (Fig. 8; Talbot & Livingstone, 1989). The Cuenca de Pozuelos is unique in the Puna for the density of its watershed vegetation (Bonaventura *et al.*, 1995). Published $\delta^{13}C$ data on Andean steppe taxa

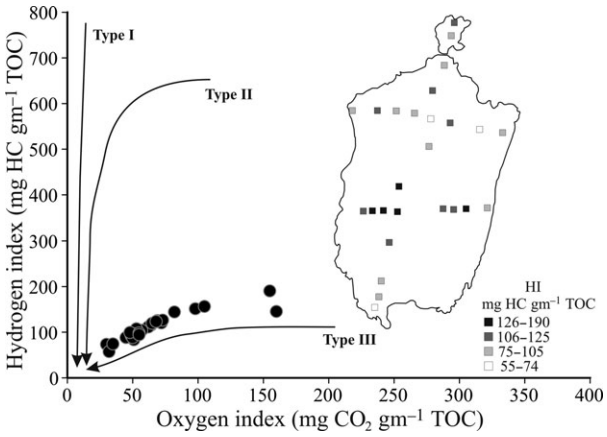

Fig. 8. Modified van Krevelen diagram for a select transect of surface samples that span Laguna de los Pozuelos both axially and laterally. Inset map shows spatial distribution of the samples. Note increasing HI values with increasing distance from playa margins and deltas.

are rare, but Quade *et al.* (2007) measured values exceeding −21·0‰ on *Fabiana* and *Baccharis* shrubs at elevations similar to those in the study area, indicating a local source of isotopically enriched allochthonous OM that could influence the geochemistry of margin sediments.

Figure 9 illustrates sedimentation and mass accumulation rates inferred from core LP07-1A, collected from the centre of the playa lake. Encompassing the upper *ca* 14 cm of red–brown (5YR 3/4), silty clay in core LP07-1A, decay of excess ^{210}Pb implies sedimentation with negligible deflation at a mean rate of 0·14 cm year^{-1}, similar to many lake records over shorter periods (Sadler, 1981). The ^{137}Cs data are consistent with the ^{210}Pb results and show a pronounced peak related to atmospheric weapons testing in 1963 (Fig. 9). The concentration of TOC increases towards the top of the core, indicating better organic preservation at the core site in recent years. Bulk sediment and organic carbon mass accumulation rates at the core site average 0·22 g cm^{-2} year^{-1} and 2·89 mg cm^{-2} year^{-1}, respectively. Mass accumulation rates of organic carbon in LP over the historical past exceed those of smaller, high-altitude basins in the Andes (Abbott *et al.*, 1997). These rates of organic carbon accumulation are broadly comparable to larger endorheic basins, such as Lake Titicaca and lowland Andean foreland basin lakes during regressive intervals (Binford *et al.*, 1992; Piovano *et al.*, 2002).

DISCUSSION

Playas are typical depositional environments in topographically closed basins with low effective precipitation, and their sediments are important but complex archives of palaeohydrology (Teller & Last, 1990). In piggyback basins, thrust faulting creates hanging wall topographic barriers that focus fluvial and ground water flow paths towards footwall flats, where playa lakes can develop if climatic conditions favour basin underfilling (Carroll & Bohacs, 1999; Garcia-Castellanos *et al.*, 2003). Ground water

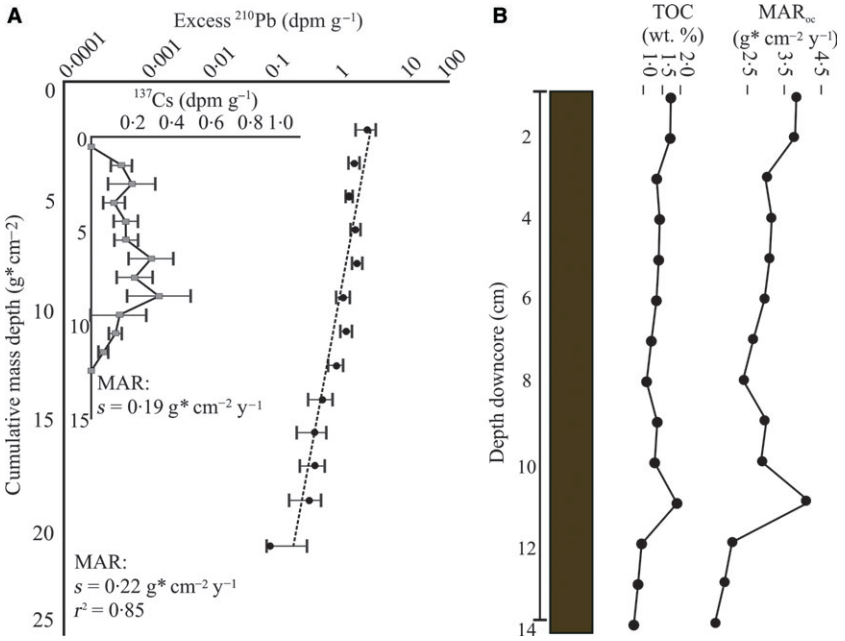

Fig. 9. ^{210}Pb and ^{137}Cs data from sediment core LP07-1A, with TOC and organic mass accumulation rate (MAR) profiles. Systematic decay of excess ^{210}Pb indicates negligible deflation and sediment reworking at the core site. Organic carbon concentration (mean = 1·31 wt%) and MAR$_{oc}$ (mean = 2·89 mg cm^{-2} year^{-1}) increase towards the top of the dated interval. Carbonate concentration (not depicted) varies from *ca* 0·3 to 2·0 wt% over the dated interval.

© 2011 The Authors. Journal compilation © 2011 International Association of Sedimentologists, *Sedimentology*, **59**, 1237–1256

discharge, evaporation and downslope seepage are critical processes that lead many playa lakes to accumulate thick suites of chemical sediments that are zoned according to the basin-floor gradient (Eugster & Hardie, 1978; Smoot & Lowenstein, 1991; Rosen, 1994). In contrast, playas can be siliciclastic deposystems, especially where permeable basin-floor strata promotes infiltration of brines into deeper aquifers, constraining chemical sedimentation at the surface (Teller & Last, 1990). Igarzábal (1978) suggests that infiltration may occur seasonally at LP, principally following heavy rainfall events in the austral summer. Siliciclastic deposition in other modern and ancient playas also has clear linkages to catchment geology and the chemical composition of inflows (Turnbridge, 1984; Chivas *et al.*, 1986). Major rivers entering LP drain the western and southern extents of the watershed, where siliciclastic and volcanic rocks favour relatively dilute runoff (Fig. 2). Together, these processes help to explain the dominance of siliciclastic material in LP sediments.

Abundant carbonate, fine detrital quartz and salt crusts are highlighted in early qualitative environmental descriptions of the Cuenca de Pozuelos (Igarzábal, 1978). Quantitative insights from coulometry indicate that carbonate deposition is presently minor and focused along both playa margins, with efflorescent crusts especially prominent on the western margin (Fig. 5). Importantly, hydrochemistry data presented herein and in other more recent studies (Mirande & Tracanna, 2009) do not replicate the elevated salinity levels reported in Igarzábal (1978). Although direct comparisons are difficult, variability in the amount of chemical sedimentation over several decades may be attributed to transient differences in seasonal rainfall, aquifer levels and brine evolution. Moisture carried to LP by the easterlies is intercepted by the Sierras de Cochinoca, which suggests that recharge of deep aquifers along the eastern side of the basin should accompany increased rainfall. This process is manifest in strongly asymmetrical accumulations of carbonate and diatomaceous earth on the eastern margins of many Andean basins (Quade *et al.*, 2008). Roughly symmetrical TIC contours on lateral margins and elevated BiSi concentrations along axial margins suggest that comparatively dilute, shallow ground water and riverine inflows are influential to present-day patterns of deposition (Fig. 4). In contrast, ground water discharge from deeper, more saline eastern aquifers may have promoted greater chemical sedimentation during the field explorations of Igarzábal (1978). Vertical variability in TIC concentrations (*ca* 0·3 to 2·0 wt%) within core LP07-1A are consistent with this interpretation, although lithofacies and sedimentation rate data over the ^{210}Pb-dated interval indicate that dramatic shifts in basin hydrology were unlikely.

Patterns of OM accumulation in LP are clearly linked to depositional environment and seasonal hydrology (Huc *et al.*, 1990; Fig. 10). Particle size is inversely correlated with TOC concentration in LP, suggesting that terrigenous dilution is an important process, especially near the Río Cincel and Río Chico deltas. The TOC concentrations are higher near the terminus of the Río Santa Catalina, which is interpreted to result from different depositional processes and less coarse detrital input. Fluvial–lacustrine transitional environments in arid basins can be highly dynamic and their facies are varied (Dill, 1992; Lang *et al.*, 2004; Saéz *et al.*, 2007; Alonso-Zarza *et al.*, 2009). A dominance of silt and clay-sized particles in the distal Río Santa Catalina splay complex suggests fall out of suspended load in decelerating flows, probably indicative of sheetflood deposition in this environment. Similar mean grain-size trends are reported from sheetflood-dominated distal splays in other large playa complexes (Paik & Kim, 2006; Fisher *et al.*, 2008). Regardless, contributions of basin-floor grasses and steppe vegetation probably influence both axial depositional sub-environments, as C : N values commonly exceed 25 and highly variable $\delta^{13}C_{om}$ values point to allochthonous OM (Fig. 7). In distal deltaic plains and the central playa lake, TOC, HI and BiSi values are higher, whereas C : N values typically decline, suggesting greater contributions from algae to the OM pool (Fig. 10). Smear slides validate these geochemical inferences, as fine-grained biogenic oozes with variable abundances of macrophyte remains are common in these environments (Fig. 4). Because particle sizes are small, interstitial oxygen is limited, promoting better preservation of autochthonous OM (Fig. 5A; Gray, 1981). Playa margin facies, marked by lower TOC concentrations and higher TIC, are strongly influenced by evaporation, bioturbation and deflation. Under modern climate conditions, this environment is not conducive to the accumulation of substantial OM, instead favouring the development of ostracod-rich silty clay with thin aragonite crusts.

Key factors affecting the development of autochthonous OM in LP include the availability of nutrients, rates of primary productivity and basin

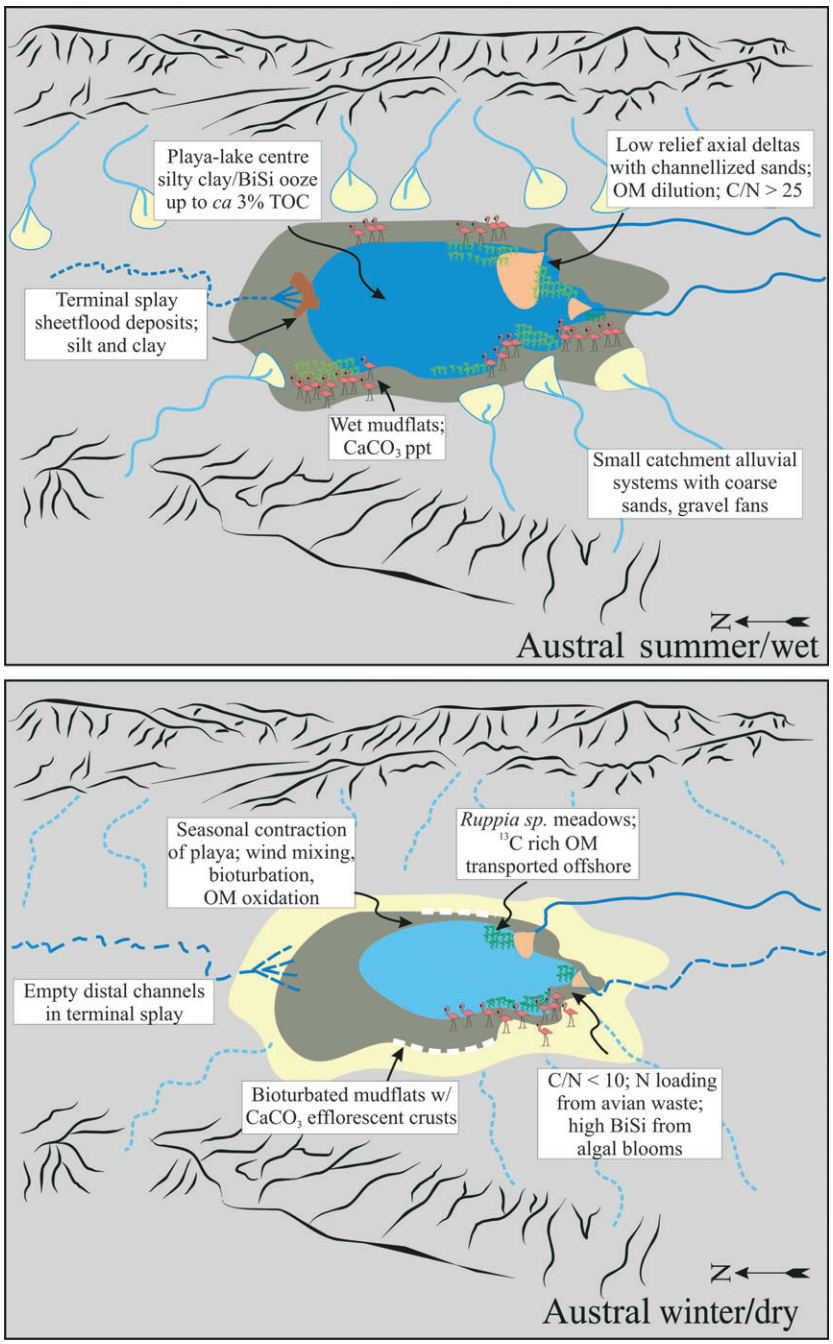

Fig. 10. Synthesis of modern–recent (*ca* 100 years) sedimentation at Laguna de los Pozuelos. See text for details.

hydrology. Nutrient loading has not been well-studied at LP, but important contributions probably come from: (i) ground water and river-borne solutes; (ii) imported nitrogen from migratory waterbird waste; and (iii) mineral aerosols. Ecological studies of LP demonstrate that its algal biomass, dominated by chlorophytes (for example, *Chlamydomonas tremulans*) and diatoms, exceeds that of other high-altitude wetlands in the region, due in part to moderate salinity and annual water availability (Mirande & Tracanna, 2009). These same factors have helped macrophyte meadows to flourish in the intradeltaic areas along the southern axis of LP. The preservation of autochthonous biomass, however, is limited by the mixing regime and shallow bathymetry of LP. Prevailing winds mix LP throughout the year, as ice cover is commonly restricted to shoreline ribbons in the austral winter. Low molecular weight organic components are especially labile in polymictic

lakes, as wind mixing rapidly resuspends OM following sedimentation, subjecting it to further degradation by aerobic respiration. Similar processes in marine environments are known to account for substantial diagenetic losses of OM (Henrichs, 1992). Seasonal desiccation produces a similar effect and serves to reduce TOC concentration along the lateral margins of LP (Fig. 5D). Wind mixing is also likely to be responsible for the transport of ^{13}C-enriched macrophyte OM from shallow margins into deeper environments (Fig. 10). Valero-Garces *et al.* (1999) noted the importance of physical processes in high-altitude lakes (for example, evaporation, old carbon reservoirs and degassing of volcanic CO_2) for elevating $\delta^{13}C_{om}$ values in the absence of ^{13}C-rich parent material. At LP, however, live *Ruppia* exhibit relatively high $\delta^{13}C_{om}$ values (−14·5‰; n = 1) and do not show substantial reservoir effects (post-bomb conventional age, laboratory number AA80800, n = 1), thus supporting the interpretation of transported macrophyte OM to the playa-lake centre. Because LP is alkaline, assimilation of HCO_3^- during photosynthesis may also enrich phytoplankton-derived $\delta^{13}C_{om}$. Alternatively, high $\delta^{13}C_{om}$ values could reflect OM diagenesis (Talbot & Livingstone, 1989). Selective loss of ^{12}C during oxidative fractionation typically leads to a 1 to 2‰ increase in $\delta^{13}C_{om}$ values, which alone cannot explain the mean values observed in LP (Fig. 7). As a result, a mixed autochthonous provenance for OM in the playa-lake centre appears to be most likely.

As nitrogen is a key limiting nutrient in many subtropical and arid lake systems, the impact of waterbirds on biogeochemical cycles at LP is important (Cowell & Dawes, 1991; Lebo *et al.*, 1992). Similar to many high-altitude Andean lakes, flamingoes are abundant at LP in the austral summer. However, LP is unique in that large flocks of waterbirds persist on site throughout the austral winter as well (Caziani *et al.*, 2001; Mascitti, 2001). The concentration of mineral nitrogen in LP waters is below the detection limit of standard ion chromatography analysis, thus indicating that allochthonous organic nitrogen delivery may be critical for phytoplankton productivity. As a result, organic facies development may be linked to year-round nitrogen delivery and algal fertilization from avian waste (Fig. 10).

A particularly intriguing aspect of the carbon cycle at LP is the role of waterbirds in bioturbation. Hurlbert & Chang (1983) were among the first to note the impact of flamingoes on lacustrine microbenthos in the Andes. Flamingoes feed by filtering algae and zooplankton through their bills – a process that requires inverting their heads and stirring up lake-bottom sediment. Data on foraging microhabitats for New World flamingoes suggest a preference for playa margin and shallow playa-lake environments (Mascitti, 2001). At LP, flamingo bioturbation in these environments reduces the preservation potential of OM due to prolonged persistence in near-surface, well-oxygenated sediments. A number of authors suggest a link between bioturbation and low values of TOC and HI (Pratt, 1984; Ariztegui *et al.*, 1996). Data from LP support this link, as Rock Eval data indicate that only samples in the playa-lake centre have hydrocarbon-source potential (S1 + S2 > 2·0; after Tissot & Welte, 1978). Water depths in the playa-lake centre routinely exceed *ca* 40 cm, thus limiting bioturbation by wading birds (Mascitti, 2001). Eocene Fossil Basin, a piggyback basin in the Western Cordillera of North America, shares similarities with the Cuenca de Pozuelos, including basin shape and tectonic origin. The geological record of Fossil Basin, noted for its kerogen-rich lacustrine deposits, exhibits facies patterns that resemble LP, such as basin-centred concentrations of TOC and massive, TIC-rich, TOC-poor sediments along the margins (Buchheim & Eugster, 1998). Green River strata in general, and Fossil Lake in particular, are well-known for bird fossils (Feduccia & McGrew, 1974; Weidig, 2010). Leggitt *et al.* (1998) noted the intimate association of waterbirds and lake environments in Fossil Basin. Although under-reported in the literature (see Genise *et al.*, 2009 for an exception), the results of the present study indicate that the foraging behaviour of gregarious waterbirds probably influences patterns of OM preservation and facies characteristics in piggyback lake systems.

Over short time scales (10^1 to 10^4 years), climate exerts a primary control on hydrology and therefore sedimentation and OM accumulation in LP. The persistence of a high-altitude playa lake in the Andes necessitates enough precipitation to maintain local ground water discharge and stream base flow through the austral winter. Drought-related depression of the ground water table exposes playa-lake systems to aeolian re-working and erosion (Rosen, 1994). Consequently, OM preservation in LP hinges on the maintenance of the water table elevation at or near the ground surface, which has implications for developing palaeoenvironmental records from the basin. Excess ^{210}Pb data demonstrate that, over the last *ca* 100 years, deflation has not

impacted LP at the coring site in a significant manner. Eugster & Hardie (1975) surmised that seasonal oxygen minima in strongly evaporative playa lakes may occur following seasons with heavy precipitation, as fresh water lenses overlie remnant brines, enhancing OM preservation through the development of pycnoclines (i.e. temporal meromixis). Pycnocline formation is probably a highly transient process in modern LP, as soluble evaporite minerals are absent and the sediment colour and TOC concentrations within the ^{210}Pb interval indicate the maintenance of an oxidizing environment. Reducing waters associated with pycnoclines probably expand sub-environments that preserve OM at LP during highstand intervals when effective precipitation is higher. Shifts in major facies (for example, from subaerial terminal splays into subaqueous channellized deltas) and increased delivery of nutrients and terrestrial OM from fluvial sources are likewise predicted with greater effective precipitation and a transition to wet-phase under-filled or balance-filled lake conditions (Bohacs *et al.*, 2000). Major hydrological transitions spurred by higher rainfall are likely to prompt prolonged ground water discharge from deep sources on the eastern side of the basin. This effect may have implications for radiocarbon reservoir effects in some late Quaternary organic materials produced in LP, due to the geology of the Sierras de Cochinoca (Fig. 1).

CONCLUSIONS

The results of this integrated geological assessment of Laguna de los Pozuelos (LP) provide insights on sedimentation and the processes that affect the accumulation of organic matter (OM) in high-altitude, arid piggyback basins. Sedimentological and bulk OM geochemistry indicates that organic facies development is dominantly controlled by basin hydrology, climate and biological feedbacks (both nutrient cycling and bioturbation) from waterbirds.

1 Modern sediments in LP are compositionally diverse but dominated by siliciclastic material, and shallow ground water and dilute inflows appear to play important roles in depositional processes. In the playa-lake centre, silty clays and diatom oozes with variable amounts of OM are common. Along the low-gradient playa margins, minor carbonate deposition becomes important, especially low-Mg calcite from biogenic sources and aragonite associated with efflorescent crusts. Sedimentary processes in the southern axial deltas result in the deposition of coarse sands with minor diatom content, whereas sheetfloods are more common in the northern Río Santa Catalina terminal splay complex, resulting in the deposition of silty clays.

2 Concentrations of total organic carbon (TOC) reach maximum values (up to 3·3 wt%) along the axis of the playa-lake centre of LP. Playa margins, which are prone to seasonal evaporation and heavy bioturbation, are not conducive to the preservation of organic carbon. At most sample sites, the mean particle size exhibits an inverse relationship with TOC, suggesting that detrital dilution and depositional environment strongly influence patterns of OM accumulation. Sediments rich in BiSi (>3·0 wt%) are accumulating principally along the axial margins of the basin, near sites where gregarious wading birds are active and diatom productivity is high.

3 Basin hydrology exerts a fundamental control on OM preservation and, as a result, bulk OM geochemistry provides useful insights for palaeoenvironmental analysis at LP. Sediments in the playa-lake centre can occasionally remain subaqueous, even during the austral winter. The ^{210}Pb data imply rapid sediment mass accumulation and minimal deflation in this sub-environment during the historical past. Although oxidation through wind mixing detracts from the preservation of OM, the centre of the playa lake escapes additional re-suspension from flamingo bioturbation because of its depth.

4 Both $\delta^{13}C_{om}$ and C : N data indicate a mixed provenance for the OM preserved in LP sediments. The $\delta^{13}C_{om}$ values range from −16·4‰ to −24·6‰, probably in response to contributions from aquatic macrophytes that have mixed with algae in the playa-lake centre or allochthonous OM (also reflected in high C : N values) delivered to basin margin sub-environments from watershed grasses and steppe vegetation. The hydrogen index values and smear slide observations are consistent with a mixed organic provenance model in the playa-lake centre and degradation of OM by oxidation on deltas and playa margins.

5 Waterbird activity strongly impacts the biogeochemical cycles at LP. Bioturbation of playa margin and shallow playa-lake sediments from waterbird foraging reduces the amount of OM preserved in sediments because of the oxidation that accompanies re-suspension. Waste products

from birds are a valuable source of allochthonous nitrogen to the lake that fertilizes various autotrophic communities. Data from ancient analogues imply that such processes are an under-appreciated component of carbon and nitrogen cycles in high-altitude lakes.

ACKNOWLEDGEMENTS

Major grants from NSF (EAR-0542993), ACS/PRF (45910-AC8) and ExxonMobil Upstream Research provided the financial support for this research. Smaller grants in aid of research to MM from AAPG, GSA, Sigma Xi and the University of Arizona-Chevron Corporation Summer Research fund helped to support field activities in Argentina. The authors gratefully acknowledge the logistical assistance of J. Omarini, E. Piovano and A. Kirschbaum during their involvement in the project. The staff at Monumento Naturale Laguna de los Pozuelos provided vital access during the field campaigns. The authors deeply appreciate the assistance of C. Gans, F. Cordoba, M. Barrionuevo and E. Gleeson in the field, and M. Fan, X. Zhang, J. Ash and M. Trees in the laboratory. PWS graciously acknowledges continued support from the USGS Coastal and Marine Geology Program. Conversations with S. Ivory, A. Kowler, C. Johnson, R. Renaut and comments from two anonymous reviewers improved aspects of this work. The staff at the Limnological Research Center at the University of Minnesota, R. Schow, H. Steblay and M. Murphy graciously hosted MM while laboratory work for this project was completed.

REFERENCES

Abbott, M.B., Seltzer, G.O., Kelts, K.R. and **Southon, J.** (1997) Holocene Paleohydrology of the tropical Andes from lake records. *Quatern. Res.*, **47,** 70–80.

Allmendinger, R.W., Jordan, T.E., Kay, S.M. and **Isacks, B.L.** (1997) The evolution of the Altiplano-Puna Plateau of the central Andes. *Annu. Rev. Earth Planet Sci.*, **25,** 139–174.

Alonso-Zarza, A.M., Zhao, Z., Song, C.H., Li, J.J., Zhang, J., Martín-Pérez, A., Martín-García, R., Wang, X.X., Zhang, Y. and **Zhang, M.H.** (2009) Mudflat/distal fan and shallow lake sedimentation (upper Vallesian–Turolian) in the Tianshui Basin, Central China: evidence against the late Miocene eolian loess. *Sed. Geol.*, **219,** 42–51.

Ariztegui, D., Farrimond, P. and **McKenzie, J.A.** (1996) Compositional variations in sedimentary lacustrine organic matter and their implications for high Alpine Holocene environmental changes: Lake St. Moritz, Switzerland. *Org. Geochem.*, **24,** 453–461.

Assine, M.L. and **Silva, A.** (2009) Contrasting fluvial styles of the Paraguay river in the northwestern border of the Pantanal wetland, Brazil. *Geomorphology*, **113,** 189–199.

Baker, P.A., Rigsby, C.A., Seltzer, G.O., Fritz, S.C., Lowenstein, T.K., Bacher, N. and **Veliz, C.** (2001) Tropical climate change at millennial and orbital timescales on the Bolivian Altiplano. *Nature*, **409,** 698–701.

Beer, J.A., Allmendinger, R.W., Figueroa, D.A. and **Jordan, T.E.** (1990) Seismic stratigraphy of a neogene piggy-back basin, Argentina. *AAPG Bull.*, **74,** 1183–1202.

Binford, M.W., Brenner, M. and **Engstrom, D.E.** (1992) Temporal sedimentation patterns in the nearshore littoral of Lago Huinaimarca. In: *Lake Titicaca: A Synthesis of Limnological Knowledge Volume 68: Monographiae Biologicae* (Eds C. Dejoux and A. Iltis), pp. 29–39. Kluwer Academic Publishers, Dordrecht.

Bohacs, K.M., Carroll, A.R., Neal, J. and **Mankiewicz, P.** (2000) Lake Basin type, source potential, and hydrocarbon character: an integrated sequence-stratigraphic-geochemical framework. In: *Lake Basins Through Space and Time* (Eds E. Gierlowski-Kordesch and K. Kelts), *AAPG Stud. Geol.*, **46,** 3–34.

Bonaventura, S.M., Tecchi, R. and **Vignale, D.** (1995) The vegetation of the Puna Belt at laguna de Pozuelos Biosphere Reserve in northwest Argentina. *Plant Ecol.*, **119,** 23–31.

Buchheim, H.P. and **Eugster, H.P.** (1998) Eocene Fossil Lake: the Green River Formation of Fossil Basin, southwestern Wyoming. In: *Modern and Ancient Lake Systems: New Problems and Perspectives* (Eds J.K. Pitman and A.R. Carroll), *Utah Geol. Assoc. Publ.*, **26,** 191–208.

Carroll, A.R. and **Bohacs, K.M.** (1999) Stratigraphic classification of ancient lakes: balancing tectonic and climatic controls. *Geology*, **27,** 99–102.

Castiglia, P.J. and **Fawcett, P.J.** (2006) Large Holocene lakes and climate change in the Chihuahan Desert. *Geology*, **34,** 113–116.

Caziani, S.M., Derlindati, E.J., Talamo, A., Suredam, A.L., Trucco, C.E. and **Nicolossi, G.** (2001) Waterbird richness in Altiplano wetlands of Northwestern Argentina. *Waterbirds*, **24,** 103–117.

Chivas, A.R., De Deckker, P., Nind, M., Thiriet, D. and **Watson, G.** (1986) The Pleistocene palaeoenvironmental record of Lake Buchanan: an atypical Australian playa. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **54,** 131–152.

Cladouhos, T.T., Allmendinger, R.W., Coira, B. and **Farrar, E.** (1994) Late Cenozoic deformation in the central Andes: fault kinematics from the northern Puna, northwest Argentina, and southwest Bolivia. *J. South Am. Earth Sci.*, **7,** 209–228.

Cowell, B.C. and **Dawes, C.J.** (1991) Nutrient enrichment experiments in three central Florida lakes of different trophic status. *Hydrobiologia*, **220,** 217–231.

Cupper, M.L. (2006) Luminescence and radiocarbon chronologies of playa sedimentation in the Murray Basin, southeastern Australia. *Quatern. Sci. Rev.*, **25,** 2594–2607.

Dargam, R.M. and **Depetris, J.** (1996) Geochemistry of waters and brines from the Salinas Grandes basin, Córdoba, Argentina. II. Gypsum dissolution-calcite precipitation, and brine evolution. *Int. J. Salt Lake Res.*, **5,** 81–101.

Dean, W.E. and **Gorham, E.** (1998) Magnitude and significance of carbon burial in lakes, reservoirs, and peatlands. *Geology*, **26,** 535–538.

DeCelles, P.G. and **Giles, K.A.** (1996) Foreland basin systems. *Basin Res.*, **8,** 105–123.

DeCelles, P.G. and **Hertel, F.** (1989) Petrology of fluvial sands from the Amazonian foreland basin, Peru and Bolivia. *Geol. Soc. Am. Bull.*, **101,** 1552–1562.

DeMaster, D.J. (1979) *The marine budgets of silica and Si-32*. PhD Thesis, Yale University, New Haven, CT, 308 pp.

Dill, H.G. (1992) A numerical analysis of grain-size and colour variations of a fan-lake transition, Upper Carboniferous Bechtsrieth Formation, Southern Germany. *Sed. Geol.*, **75,** 193–208.

Duarte, C.M., Prairie, Y.T., Montes, C., Cole, J.J., Striegl, R., Melack, J. and **Downing, J.A.** (2008) CO_2 emissions from saline lakes: a global estimate of a surprisingly large flux. *J. Geophys. Res.*, **113,** 1–7.

Dyni, J.R. (2006) *Geology and Resources of Some World Oil-Shale Deposits*. U.S. Geological Survey Scientific Investigations Report 2005-5294, 42 pp. U.S. Geological Survey, Reston, Virginia.

Espitalie, J., Laporte, J.L., Madec, M., Marquis, F., Leplat, P., Paulet, J. and **Boutefeu, A.** (1977) Methode rapide de caracterisation des roches meres, de leur potential petrolier et de leur degre d'evolution. *Rev. Inst. Fr. Pétrol.*, **32,** 23–42.

Eugster, H. and **Hardie, L.A.** (1975) Sedimentation in an ancient playa-lake complex: the Wilkins Peak Member of the Green River Formation of Wyoming. *Geol. Soc. Am. Bull.*, **86,** 319–334.

Eugster, H. and **Hardie, L.A.** (1978) Saline lakes. In: *Lakes: Chemistry, Geology and Physics* (Ed. A. Lerman), pp. 237–293. Springer-Verlag, New York.

Feduccia, A. and **McGrew, P.** (1974) A flamingo-like wader from the Eocene of Wyoming. *Contrib. Geol.*, **13,** 49–61.

Fisher, J.A., Krapf, C.B.E., Lang, S.C., Nichols, G.J. and **Payenberg, T.H.D.** (2008) Sedimentology and architecture of the Douglas Creek terminal splay, Lake Eyre, central Australia. *Sedimentology*, **55,** 1915–1930.

Fritz, S.C., Baker, G., Seltzer, G.O., Ballantyne, A., Tapia, M., Cheng, H. and **Edwards, R.L.** (2007) Quaternary glaciation and hydrologic variation in the South American tropics as reconstructed from the Lake Titicaca drilling project. *Quatern. Res.*, **68,** 410–420.

Gangui, A.H. (1998) *A combined structural interpretation based on seismic data and 3D gravity modeling in the northern Puna/Eastern Cordillera, Argentina*. PhD Thesis, Freien Universität, Berlin, 176 pp.

Garcia-Castellanos, D., Vergès, J., Gaspar-Escribano, J. and **Cloetingh, S.** (2003) Interplay between tectonics, climate and fluvial transport during the Cenozoic evolution of the Ebro Basin (NE Iberia). *J. Geophys. Res.*, **208,** 23–47.

Garreaud, R., Vuille, M. and **Clement, A.C.** (2003) The climate of the Altiplano: observed current conditions and mechanisms of past changes. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **194,** 5–22.

Garreaud, R.D., Vuille, M., Compagnucci, R. and **Marengo, J.** (2009) Present-day South American climate. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **281,** 180–195.

Genise, J.F., Melchor, R.N., Archangelsky, M., Bala, L.O., Straneck, R. and **de Valais, S.** (2009) Application of neoichnological studies to behavioural and taphonomic interpretation of fossil bird-like tracks from lacustrine settings: the Late Triassic-Early Jurassic? Santo Domingo Formation, Argentina. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **272,** 143–161.

Gierlowski-Kordesch, E.H., Jacobson, A.D., Blum, J.D. and **Valero-Garcés, B.L.** (2008) Watershed reconstruction of a Paleocene–Eocene lake basin using Sr isotopes in carbonate rocks. *Geol. Soc. Am. Bull.*, **120,** 85–95.

González, M.A. and **Maidana, N.I.** (1998) Post-Wisconsinian paleoenvironments at Salinas del Bebedero basin, San Luis, Argentina. *J. Paleolim.*, **20,** 353–368.

Gray, J.S. (1981) *The Ecology of Marine Sediments: An Introduction to the Structure and Function of Benthic Communities*. Cambridge University Press, Cambridge, 185 pp.

Henrichs, S.M. (1992) Early diagenesis of organic matter in marine sediments: progress and perplexity. *Mar. Chem.*, **39,** 119–149.

Horton, B.K. and **DeCelles, P.G.** (1997) The modern foreland basin system adjacent to the central Andes. *Geology*, **25,** 895–898.

Horton, B.K. and **DeCelles, P.G.** (2001) Modern and ancient fluvial megafans in the foreland basin system of the central Andes, southern Bolivia: implications for drainage network evolution in fold–thrust belts. *Basin Res.*, **13,** 43–63.

Huc, A.Y., LeFournier, J., Vandenbroucke, M. and **Bessereau, G.** (1990) Northern Lake Tanganyika; an example of organic sedimentation in an anoxic rift lake. In: *Lacustrine Basin Exploration; Case Studies and Modern Analogs* (Ed. B.J. Katz), *AAPG Mem.*, **50,** 169–185. Tulsa, OK.

Hurlbert, S.H. and **Chang, C.C.Y.** (1983) Omitholimnology: effects of grazing by the Andean flamingo *(Phoenicoparrus andinus). Proc. Natl Acad. Sci. USA*, **801,** 4766–4769.

Igarzábal, A.P. (1978) La Laguna de Pozuelos y su Ambiente Salino. *Acta Geol. Lilloana (Argentina)*, **15,** 80–103.

Johnson, T.C. and **McCave, I.N.** (2008) Transport mechanism and paleoclimatic significance of terrigenous silt deposited in varved sediments of an African rift lake. *Limnol. Oceanogr.*, **53,** 1622–1632.

Jordan, T.E. (1995) Retroarc foreland and related basins. In: *Tectonics of Sedimentary Basins* (Eds C.J. Busby and R.V. Ingersoll), pp. 331–362. Blackwell Science, Cambridge, MA.

Katz, B.J. (1983) Limitations of ''Rock-Eval'' pyrolysis for typing organic matter. *Org. Geochem.*, **4,** 195–199.

Katz, B.J. (2001) Lacustrine basin hydrocarbon exploration – current thoughts. *J. Paleolim*, **26,** 161–179.

Lang, S.C., Payenberg, T.H.D., Reilly, M.R.W., Hicks, T., Benson, J. and **Kassan, J.** (2004) Modern analogues for dryland sandy fluvial-lacustrine deltas and terminal splay reservoirs. *Aust. Petrol. Prod. Explor. Assoc. J.*, **44,** 329–356.

Lebo, M.E., Reuter, J.E., Rhodes, C.L. and **Goldman, C.R.** (1992) Nutrient cycling and productivity in a desert saline lake: observations from a dry, low productivity year. *Hydrobiologia*, **246,** 213–229.

Legates, D.R. and **Willmott, C.J.** (1990a) Mean seasonal and spatial variability in gauge-corrected, global precipitation. *Int. J. Clim.*, **10,** 111–127.

Legates, D.R. and **Willmott, C.J.** (1990b) Mean seasonal and spatial variability in global surface air temperature. *Theor. Appl. Climatol.*, **41,** 11–21.

Leggitt, V.L., Buchheim, H. and **Biaggi, R.E.** (1998) The stratigraphic setting of three Presbyornis nesting sites: Eocene Fossil Lake, Lincoln County, Wyoming. In: *National Park Service Paleontological Research, Volume 3* (Eds V.L. Santucci and L. McClelland), pp. 61–68. United States Department of the Interior - National Park Service - Geologic Resource Division, Denver, CO.

Leier, A.L., DeCelles, P.G. and **Pelletier, J.D.** (2005) Mountains, monsoons, and megafans. *Geology*, **33,** 289–292.

Maidana, N., Vigna, M. and **Mascitti, V.** (1998) Ficoflora de la Laguna de Pozuelos (Jujuy, Argentina), I: Bacillariophyceae. *Bol. Soc. Arg. Bot.*, **33,** 171–179.

Markgraf, V., Bradbury, J., Forester, R.M., Singh, G. and **Sternberg, R.S.** (1984) San Agustin Plains, New Mexico: age and paleoenvironmental potential reassessed. *Quatern. Res.*, **22,** 336–343.

Mascitti, V. (2001) Habitat changes in Laguna de Pozuelos, Jujuy, Argentina: implications for South American Flamingo populations. *Waterbirds*, **24,** 16–21.

Meyers, P.A. and **Teranes, J.L.** (2001) Sediment organic matter. In: *Tracking Environmental Change Using Lake Sediments, Volume 2, Physical and Geochemical Methods* (Eds W.M. Last and J.P. Smol), pp. 239–269. Springer, New York.

Mirande, V. and **Tracanna, B.C.** (2009) Estructura y controles abióticos del fitoplancton en humedales de altura. *Ecol. Aust.*, **19,** 119–128.

Moschione, F.N. and **Sureda, A.L.** (2008) Monitoring high-Andes flamingos at Laguna de los Pozuelos National Monument, Argentina: preliminary results. *Flamingo*, **16,** 48–50.

Nicoll, K. (2004) Recent environmental change and prehistoric human activity in Egypt and Northern Sudan. *Quatern. Sci. Rev.*, **23,** 561–580.

Ori, G.G. and **Friend, F.** (1984) Sedimentary basins formed and carried piggyback on active thrust sheets. *Geology*, **12,** 475–478.

Page, R. (1996) *Mapa Geologico de la Provincia de Jujuy, Republica Argentina, Escala 1:500000*. Servicio Geológico Minero de Argentina, Buenos Aires.

Paik, I.S. and **Kim, H.J.** (2006) Playa lake and sheetflood deposits of the Upper Cretaceous Jindong Formation, Korea: occurrences and palaeoenvironments. *Sed. Geol.*, **187,** 83–103.

Peterson, B.J. and **Fry, B.** (1987) Stable isotope in ecosystem studies. *Annu. Rev. Ecol. Syst.*, **18,** 293–320.

Piovano, E.L., Ariztegui, D. and **Damatto Moreira, S.** (2002) Recent environmental changes in Laguna Mar Chiquita (central Argentina): a sedimentary model for a highly variable saline lake. *Sedimentology*, **49,** 1371–1384.

Placzek, C., Quade, J. and **Patchett, J.** (2006) Geochronology and stratigraphy of late Pleistocene lake cycles on the southern Bolivian Altiplano: implications for causes of tropical climate change. *Geol. Soc. Am. Bull.*, **118,** 515–532.

Pratt, L.M. (1984) Influence of paleoenvironmental factors on preservation of organic matter in Middle Cretaceous Greenhorn Formation, Pueblo, Colorado. *AAPG Bull.*, **68,** 1146–1159.

Quade, J., Rech, J.A., Latorre, C., Betancourt, J.L., Gleason, E. and **Kalin-Arroyo, M.** (2007) Soils at the hyperarid margin: the isotopic composition of soil carbonate from the Atacama Desert. *Geochim. Cosmochim. Acta*, **71,** 3772–3795.

Quade, J., Rech, J.A., Betancourt, J.L., Latorre, C., Quade, B., Rylander, K.A. and **Fisher, T.** (2008) Paleowetlands and regional climate change in the central Atacama Desert, northern Chile. *Quatern. Res.*, **69,** 343–360.

Rosen, M.R. (1994) The importance of groundwater in playas: a review of playa classifications and sedimentology and hydrology of playas. In: *Paleoclimate and Basin Evolution of Playa Systems* (Ed. M.R. Rosen), *Geol. Soc. Am. Spec. Pap.*, **289,** 1–18.

Rubiolo, D.G. (1997) Esquema de evolución tectonosedimentaria para las Cuencas Cenozoicas de la Cordillera Oriental (22° a 23° lat. S.), Argentina. *Acta Geol. Hisp.*, **32,** 77–92.

Sadler, M. (1981) Sediment accumulation rates and the completeness of stratigraphic sections. *J.Geol.*, **89,** 569–584.

Saéz, A., Anadón, P., Herrero, M.J. and **Moscariello, A.** (2007) Variable styles of transition between Palaeogene fluvial fan and lacustrine systems, southern Pyrenean foreland, NE Spain. *Sedimentology*, **54,** 367–390.

Schuble, K.A. and **Lowenstein, T.K.** (1987) Criteria for the recognition of shallow-perennial-saline lake halites based on recent sediments from the Qaidam Basin, Western China. *J. Sed. Res.*, **67,** 74–87.

Sinha, R. and **Friend, P.F.** (1994) River systems and their sediment flux, Indogangetic plains, northern Bihar, India. *Sedimentology*, **41,** 825–845.

Smoot, J.P. and **Lowenstein, T.K.** (1991) Depositional environments of nonmarine evaporites. In: *Evaporites, Petroleum, and Mineral Resources* (Ed. J.L. Melvin), *Dev. Sedimentol.*, **50,** 189–347.

Swarzenski, P.W., Baskaran, M., Orem, W.H. and **Rosenbauer, R.J.** (2006) Historical reconstruction of contaminant inputs in Mississippi River delta sediments. *Estuar. Coast. Mar. Sci.*, **29,** 1094–1107.

Talbot, M.R. (2001) Nitrogen isotopes in palaeolimnology. In: *Tracking Environmental Change Using Lake Sediments, Volume 2, Physical and Geochemical Methods* (Eds W.M. Last and J. Smol), pp. 401–439. Springer, New York.

Talbot, M.R. and **Livingstone, D.A.** (1989) Hydrogen index and carbon isotopes of lacustrine organic-matter as lake level indicators. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **70,** 121–137.

Talling, J., Lawton, T.F., Burbank, D.W. and **Hobbs, R.S.** (1995) Evolution of latest Cretaceous–Eocene nonmarine deposystems in the Axhandle piggyback basin of central Utah. *Geol. Soc. Am. Bull.*, **107,** 297–315.

Teller, J.T. and **Last, W.M.** (1990) Paleohydrological indicators in playas and salt lakes, with examples from Canada, Australia, and Africa. *Palaeogeogr. Palaeoclim. Palaeoecol.*, **76,** 215–240.

Tissot, B. and **Welte, D.H.** (1978) *Petroleum Formation and Occurrence, Second Revised and Enlarged Edition*. Springer-Verlag, New York, 699 pp.

Turnbridge, I.P. (1984) Facies for a sandy ephemeral stream and clay playa complex; the Middle Devonian Trentishoe Formation of North Devon, UK. *Sedimentology*, **31,** 697–715.

Uba, C.E., Kley, J., Strecker, M.R. and **Schmitt, A.** (2009) Unsteady evolution of the Bolivian Subandean thrust belt: the role of enhanced erosion and clastic wedge progradation. *Earth Planet. Sci. Lett.*, **281,** 134–146.

USGS (2004) *Shuttle Radar Topography Mission, 1 Arc Second scene SRTM_u03_n008e004, Unfilled Unfinished 2.0*, Global Land Cover Facility, University of Maryland, College Park, MA, February 2000.

Valero-Garces, B.L., Delgado-Huertas, A., Ratto, N. and **Navas, A.** (1999) Large ^{13}C enrichment in primary carbonates from Andean Altiplano lakes, northwest Argentina. *Earth Planet. Sci. Lett.*, **171,** 253–266.

Waters, M.R. (1989) Late Quaternary lacustrine history and paleoclimatic significance of pluvial Lake Cochise, southeastern Arizona. *Quatern. Res.*, **32,** 1–12.

Weidig, I. (2010) New birds from the Lower Eocence Green River Formation, North America. *Rec. Aust. Mus.*, **62,** 29–44.

Zhou, J. and **Lau, K.-M.** (1998) Does a monsoon climate exist over South America? *J. Climate*, **11,** 1020–1040.

Manuscript received 24 June 2010; revision accepted 13 October 2011