

Reconstruction of paleoenvironments of the Great Salt Lake Basin during the late Cenozoic

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Abstract

This study summarizes the results of micropaleontological, sedimentological, and isotope geochemical analyses of cuttings from five deep wells drilled in the Great Salt Lake (Utah, USA). Spanning the last 5.0 million yrs, our environmental history of the Great Salt Lake distinguishes four intervals based on paleobiological and sedimentological characteristics, using a previously developed tephrochronology for age control. For most of its history, the Great Salt Lake Basin has been occupied by a mixture of marsh, shallow lacustrine and sand flat conditions. In contrast, open lake conditions, typical of the Bonneville cycles and the modern Great Salt Lake apparently have only dominated the basin for the past 0.6–0.8 Ma. The two main structural basins in the study area (the North and South Basins) experienced different lacustrine histories. Large but frequently saline lakes occupied the North Basin after about 0.6 Ma. In the South Basin, ephemeral, saline lacustrine conditions started at 2.1 Ma and developed to full lacustrine conditions at 0.3 Ma. Our paleoenvironmental interpretations are broadly consistent with the aquatic palynological records from the same wells, as well as with the prior core- and outcrop-based lines of evidence. However, the differences in lake history between the North and South Basin have not been previously recognized.

Introduction

The reconstruction of Cenozoic climatic and environmental history of southwestern North America has been the focus of much research over the last 100 yrs (e.g. Gilbert, 1890; Eardley, 1938; Morrison, 1991; Oviatt & Currey, 1987). The Bonneville Basin has played a particularly important role in understanding this history. During the late Cenozoic, this basin was frequently occupied by one or more lakes, among them the well known late Quaternary Lake Bonneville. This lake reached its maximum size 17 000 to 15 000 ¹⁴C yrs B.P., when it covered an area of 51 700 km² (Morrison, 1991). The modern Great Salt Lake is a much smaller remnant of that huge lake.

Here we report new micropaleontological, sedimentological, and stable isotope data from several deep wells drilled by AMOCO in the Great Salt Lake in the

late 1970s that cover a much earlier phase of that lake basin's history. Based on these data, we propose new paleoenvironmental reconstructions for the central part of the Bonneville Basin for the last 5 million yrs. Earlier paleoenvironmental reconstructions of the Bonneville Basin were based on detailed analyses of comparatively short cores or outcrops and near surface information from different localities around the lake, and have mostly concentrated on the late Quaternary history of the basin (Eardley & Gvosdetsky, 1960; Eardley et al., 1973; Spencer et al., 1984; Oviatt et al., 1990, 1994a; Morrison, 1991). In contrast, our study is based on lower resolution data from well cuttings which cover a much longer time interval. Thus, our data compliment and extend in time the earlier reconstructions.

Study area

The Great Salt Lake is a large (4400 km², shallow (average depth ~ 4 m) lake located in northern Utah (Figure 1). The lake lies in the northeastern part of the Bonneville Basin, the north-easternmost corner of the Basin and Range physiographic Province. The Bonneville Basin is filled by Cenozoic deposits overlying Paleozoic and Precambrian basement rocks. Surrounding mountain ranges are comprised of sedimentary and metamorphic rocks of Precambrian to Tertiary age (Cohenour & Thompson, 1966).

The Neogene tectonic history of the area was dominated by extension and characterized by development of low-angle detachment faults (Morrison, 1991), with high-angle listric faults developed above the zone of detachment. Most of the listric faults have been active throughout the Quaternary. In the Great Salt Lake Basin area, the most important Quaternary faulting occurs along the Basin's eastern margin in a 100–150 km wide zone characterized by pull-apart, dip-slip and northerly

trending faults (Morrison, 1991).

The modern Great Salt Lake occupies three N-S oriented, fault-bounded depressions. Two normal faults cross the Great Salt Lake Basin, the Carrington fault and the East Great Salt Lake fault (Mohapatra, 1996). The Carrington fault, one of the listric normal faults of the Cordilleran foreland, cuts the lake from north to south along an S-shaped trend (Figure 1) (Constenius, 1996). The fault divides the lake into the two major structural basins discussed in this paper, the North Basin and the South Basin. The South Basin is further subdivided by the East Great Salt Lake fault. During the Neogene, the two basins have differed in their sedimentation rates (Moutoux, 1995; Moutoux & Davis, 1995). The North Basin, especially near the fault, has experienced sedimentation rates about 1.5 times faster than the South Basin (Figure 2). In both basins a marked increase in sediment accumulation rate across the Miocene-Pliocene boundary is probably a reflection of increased activity along the major basin bounding faults. Also, the South Basin may have experienced more frequent

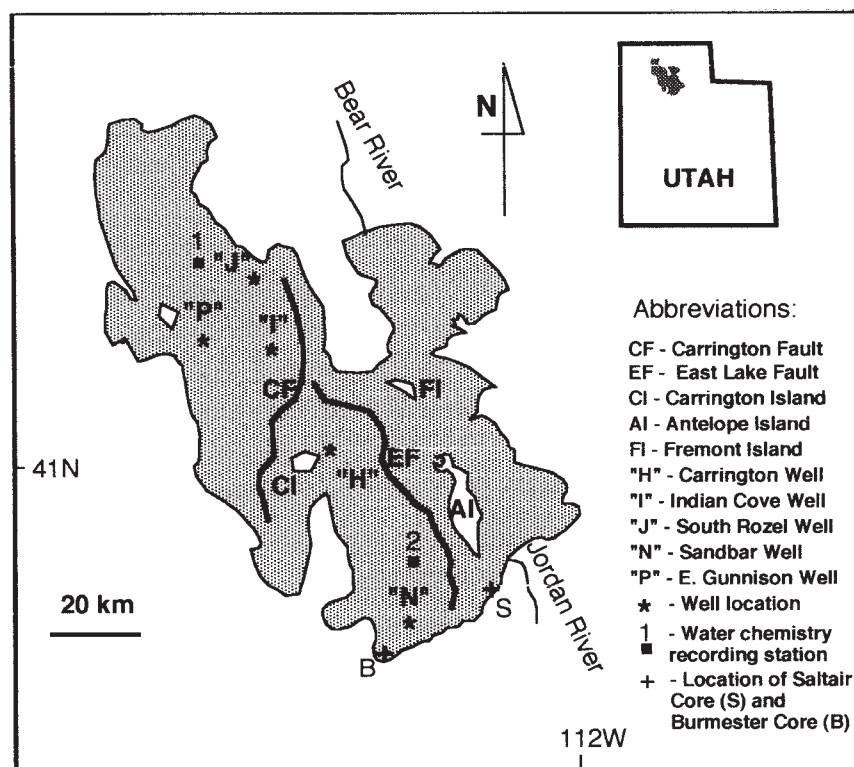


Figure 1. The Great Salt Lake at its average historical level (modified from Gwynn, 1980). The location of five analyzed wells is indicated. The two normal listric faults cut across the Lake: the Carrington Fault which divides the lake into the North and the South Basins (Constenius, 1996) and the East Great Salt Lake fault (Mohapatra, 1996). Location of the Great Salt Lake in Utah is shown on the inset map.

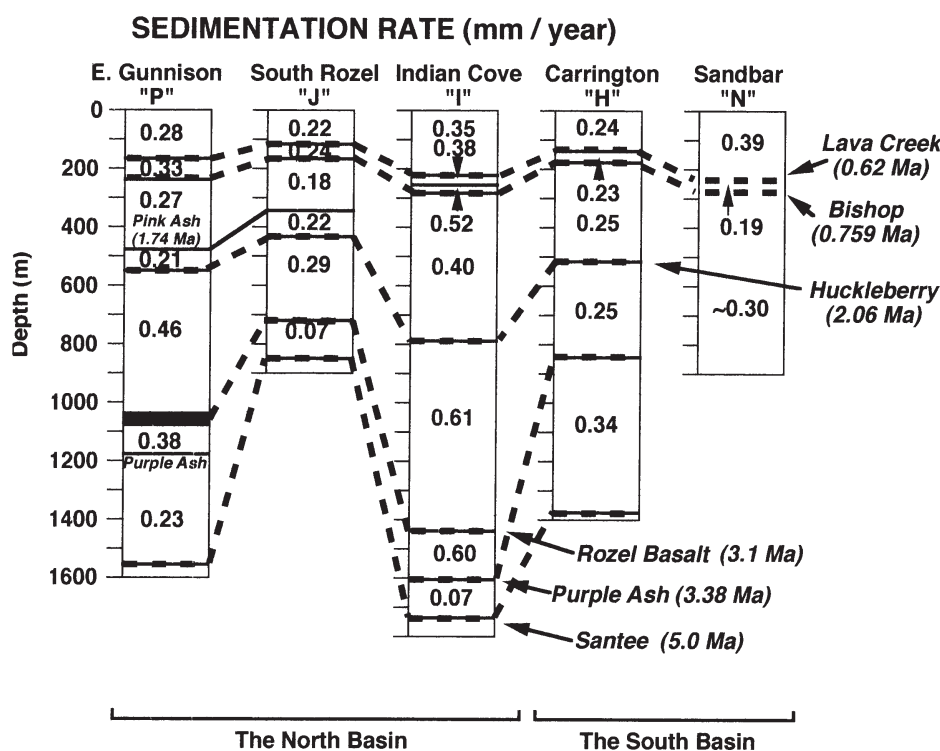


Figure 2. Sedimentation rates for all five discussed wells (also see text).

episodes of sediment and water starvation. Sedimentation in the basin has also been influenced by the discharge pattern of several rivers that either currently or intermittently enter the basin. The Bear River began to drain into the Great Salt Lake about 310 000 years ago (Davis & Moutoux, 1997). The Jordan River connects the Great Salt Lake with Utah Lake. The river was probably formed after the contraction of Lake Bonneville and has served since then as an outlet for Utah Lake which is topographically higher than the Great Salt Lake (Dave Madsen, Utah Department of Natural Resources, pers. comm., 1996). The Ogden River enters the lake in the northeast, and probably postdates the uplift of the Wasatch Range, which it drains. The Weber River, which enters the lake near the Ogden River, arises in the Uinta Mountains, and crosscuts (and is probably antecedent to) the Wasatch Range. The Sevier and Beaver Rivers, south of present-day Great Salt Lake, would also enter the lake during high stand conditions. The only other large river contributing to the Bonneville Basin in the past was the Snake River but the connection was interrupted about 2 m.y. ago and has never been reestablished (Taylor & Bright, 1987). Today deposition

in the lake is dominated by siliciclastic muds, oolitic and stromatolitic (biohermal) carbonates, and evaporites (halite) (Cohenour & Thompson, 1966).

The climate of the Great Salt Lake area today is semi-arid, with annual precipitation ranging from 125 to 375 mm and mean-monthly temperatures ranging from -2.2°C to 25.3°C (Table 1). Mean annual air temperature in the northern part of the lake is 1°C cooler than the southern part. Precipitation is very seasonal, with the heaviest rainfall during spring and fall and a dry season during June and July (Cohenour & Thompson, 1966).

The lake is polymictic and hypersaline with high concentrations of Na^+ and Cl^- ions (Table 1). The southern and northern parts of the lake differ from one another in the concentration of major ions (Table 1). Seasonal changes in lake chemistry are attributable to seasonal differences in the precipitation/evaporation ratio.

Table 1. Climatic and limnologic data on the Great Salt Lake. Precipitation data are from Peck and Richardon (1966) all other data were obtained from Dr J. W. Gwynn from the Utah Geological Survey

Year	Precipitation [mm]		Air temperature [°C]		North Basin (station 1)			South Basin (station 2)		
	max.	min.	max.	min.	Na ⁺	Cl ⁻ [g l ⁻¹]	TDS	Na ⁺	Cl ⁻ [g l ⁻¹]	TDS
1966	375	125	24.8	—	103.5	180.2	336.7	80.9	117.4	229.5
1970	—	—	25.3	5.5	109.0	185.3	346.9	63.4	141.2	243.0
1975	—	—	25.3	-2.2	105.3	183.9	329.8	37.7	66.0	119.8
1980	—	—	24.2	1.6	106.5	184.0	337.8	76.4	131.4	238.9
1985	—	—	19.2	1.1	95.0	160.5	289.9	60.9	104.4	191.3
1990	—	—	24.8	4.4*	71.7	121.8	218.0	37.1	63.8	115.3
1995	—	—	—	—	98.6	164.8	301.1	45.7	75.7	138.3

*data for December 1989.

Methods

Cores and cuttings

All of our samples were obtained from cuttings derived from a series of exploration wells drilled by AMOCO to depths of between 640 to 3700 m. Using geological logs, seismic logs, and the general geology of the area, we selected five of those wells for detailed study: Carrington 'H', Indian Cove 'I', South Rozel 'J', Sandbar 'N', and East Gunnison 'P' (Figure 1), hereafter referred to simply as 'H', 'I', 'J', 'N', and 'P'. These wells allow for comparison between the North and South Basins (Figure 1) and provide a relatively continuous sedimentary record of the lake. We collected 336 samples, including 214 samples from the North Basin and 122 samples from the South Basin (Table 2). Most samples come from three cores: (1) 'P' (39.8%); (2) 'N' (20.6%); and 'H' (15.8%). The tephrochronology and palynology of four out of the five cores ('H', 'I', 'J', 'P') were analyzed by Moutoux (1995) and Moutoux & Davis

Table 2. Sampling summary for the five AMOCO cores selected for this study

Core	Samples		Samples with more than 10 ostracodes/g	
	number	%	number	%
East Gunnison 'P'	134	39.8	34	25.4
South Rozel 'J'	30	8.9	4	13
Indian cove 'I'	50	14.9	0	0
Carrington 'H'	53	15.8	14	26.4
Sandbar 'N'	69	20.6	3	4.3

(1995). We estimated the timing of major paleolimnologic events by using linear interpolation between dated horizons (Figure 2). Because Moutoux found highly constant rates of accumulation within the studied time interval, these interpolations are probably fairly accurate. The fifth core ('N'), which was not analyzed for pollen and tephra, was correlated on the basis of lithology and the occurrence of undated tephra. Lithostratigraphy was based on sedimentary logs provided by AMOCO. The vertical resolution of the measured stratigraphy on the logs was approximately 3 m. Sample material was well cuttings collected at either 9 or 30 m intervals. Data are compiled at a 10 m vertical resolution, which corresponds to the average spacing of cuttings. Given the inherent uncertainty about sample ages and stratigraphic mixing that likely affect data derived from cuttings, our results must be interpreted cautiously. Consequently, we are conservative in our interpretations about event history.

Sample processing and analysis

From each cutting bag, we collected one sub-sample of dry sediment. Cutting samples made available to us ranged in weight from 2 to 20 g of dry sediment. Because samples were of variable size, it was necessary to use smaller than optimal samples for many intervals: sample size varied from 1 to 10 g (± 0.1 g). We used a modified version of the ostracode extraction procedure developed by the U.S. Geological Survey (Forester, 1986). We disaggregated sediment samples by subjecting them to four freeze-thaw cycles in distilled water. Each sample was gently washed and sieved using a 149 μ (#100 U.S. mesh size) screen. The coarser fraction was drained,

oven-dried at 40 °C, and reweighed to determine the percentage of the fine fraction (< 149 µ).

The dried > 149 µ samples were analyzed for micro-invertebrates using an Olympus SZH stereo microscope. Taxonomic identification was based on the literature (Swain, 1946, 1947, 1964, 1974, 1985, 1986a, b; Dickinson & Swain, 1967; Delorme, 1970a, b, c, d, 1971a, b; Lister, 1975, 1976) as well as through comparison with the University of Arizona ostracode collection. Because ostracodes were uncommon in most samples, all specimens found in each sample were counted. We also noted the proportion of juveniles to adults and described the taphonomic condition of ostracode valves such as oxidation/reduction, staining, and breakage.

We also collected data from the coarse fraction sediments on mollusks and fecal pellets of the brine shrimp *Artemia*. The preservation of mollusks was very poor and did not permit any reliable taxonomic identification. We ranked all samples qualitatively according to the abundance of mollusks, brine shrimp fecal pellets, and pyrite (including both framboidal and pyritized fossil fragments). We defined the three following abundance classes: '2' (abundant) – defined as exceeding 50 counts per sample; '1' (present) – observed in a sample; and '0' (absent) – not observed in a sample.

Stable isotope data $\delta^{18}O$ and $\delta^{13}C$

We analyzed oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotopes from ostracode valves. Ostracode valves are thought to form in near isotopic equilibrium for $\delta^{18}O$ with their ambient water mass, whereas the shell $\delta^{13}C$ integrates ambient water, sediment/water interface water, metabolic and methanogenic signals (Talbot, 1990; Palacios-Fest et al., 1994; Curry et al., 1997). All valves selected for isotopic analysis were collected from cores 'H' and 'P', the two cores that contained a large number of ostracode-rich samples. To minimize the potential problems of vital effects in isotopic fractionation (Xia et al., 1997), we confined our isotope analyses to the two most abundant species of ostracodes, *Candona rawsoni* and *Cyprideis beaconensis*. Adult forms of both species are relatively large and heavy, so when possible we used single ostracode valves for analysis. Where both species were present and well preserved in a single sample, we analyzed each of the two species separately.

We prepared a total of 170 samples consisting of 1 to 6 ostracode valves. Because of their smaller valve size, the *Candona rawsoni* samples included more than one

valve more often than the *Cyprideis beaconensis* samples. We chose only pristine, complete, unstained, and uncoated valves. Well-preserved specimens are less likely to have been transported from other areas or to have been subjected to diagenetic overprinting (especially for $\delta^{13}C$ and are, therefore, most likely to yield reliable isotopic data representative of the water mass at the time of deposition. Ostracode valves were soaked for 5 min in a 3% solution of hydrogen peroxide and then cleaned with a fine brush to remove any remaining sediment. The clean valves were then rinsed three times in distilled water. Isotope analyses for $\delta^{18}O$ and $\delta^{13}C$ were performed by the Stable Isotope Laboratory, Department of Geology at the University of Michigan using a Finnigan MAT Model 251 mass spectrometer coupled to a Kiel carbonate preparation device. Valves were heated under vacuum at 380 °C for 1 h prior to analysis. Standard analytical accuracy for carbonate is ± 0.08 ‰ for $\delta^{18}O$ and ± 0.05 ‰ for $\delta^{13}C$. The results are presented relative to the PDB standard.

Because our cutting samples are highly time-averaged, potentially spanning long intervals of time (on average 30 000 years), we also performed multiple analyses from selected horizons using samples from the Carrington 'H' well. From the five uppermost samples, eight valves of *Cyprideis beaconensis* were collected and isotopic analyses were done for each one of them separately to determine variability within individual core cuttings samples. The results were compared to results from the other analyses for that well.

Results and interpretation

We describe below the stratigraphy and paleontology for each of the five wells used in this study. The description begins with the northernmost well and ends with the southernmost well (Figure 1). For four of five wells, excluding well 'N', the sedimentological description covers the core interval from the surface to the depth at which the Santee Ash occurs. For well 'N', the description covers the core interval from 850 m to the surface. For well 'N', we do not have dated ash layers and there are no reports of ash layers below 300 m, therefore, we include the core interval from the depth of our lowest observations. For two wells ('P' and 'J'), correlation was based on chemistry and optical properties of key ash beds (Moutoux, 1995). For two wells ('I' and 'H'), we have identified the Santee Ash by stratigraphic comparison with wells 'P' and 'J' and by stratigraphic relationship with other ashes. The pale-

ontological analysis covered the entire interval above the lowermost occurrence of ostracodes in the well.

The late Cenozoic deposits of the Great Salt Lake Basin are predominantly clastic with the prominent exception of the Indian Cove 'I' well, which includes up to 140 m of limestone between the Santee Ash and the Bishop Ash. Interbedded thin layers of limestones and evaporites occur in wells 'P' and 'J' and evaporites occur in well 'N'. Well 'H' is exclusively clastic. Deposits tend to be finer toward the top of the wells. Granulometric and well log sediment data on texture did not always agree, probably because the cutting samples (from which the granulometry is derived) represent only occasional, random samples of heterogeneous deposits, whereas the logs provide semicontinuous, if less precise data.

We counted 8044 ostracodes from 36 species belonging to 12 genera. Two species, *Cyprideis beaconnensis* and *Candona rawsoni*, make up 55% and 24% of all collected ostracodes and normally vary inversely in their frequency. According to the North America ostracode database, that lists environmental distribution of modern ostracodes (B. Curry, written communication, 1997), *Cyprideis beaconnensis* occurs today in ground-water-fed marshes and littoral zones of lakes. *Candona rawsoni* is a lacustrine species. The two species may co-exist, but the dominance of *Cyprideis beaconnensis* is probably indicative of marshes. This interpretation is supported by its common association with abundant *Typha* pollen discussed below. The changes in the relative proportion between the two species, especially when combined with the stable isotope information, may offer clues to the precipitation/evaporation regimes. Other species that make up more than 1% of the total fauna include *Candona adunca* (4.6%), *Limnocythere ceriotuberosa* (3.7%), *Cypridopsis vidua* (2.0%), *Limnocythere friabilis* (2.0%), and *Candona caudata* (1.9%). Rare taxa that are important for environmental reconstructions include exotic ostracodes that were previously known from Pliocene Lake Idaho, a long-lived, deep lake north of the Bonneville Basin. These species were originally described by Swain (1947, 1986a, b), and their paleoecological significance was later discussed by Forester (1991). The wells differ in their overall diversity, both, at the generic and species levels. Nineteen species are present in well 'H', 6 in well 'I', 12 in well 'J', 13 in well 'N', and 32 in well 'P'. The distribution of major taxa varies vertically in the cores and this variation, as shown below, is often associated with facies changes.

The East Gunnison well ('P')

The East Gunnison well ('P') is one of the three wells situated in the northern part of the lake. The total depth of the well is 1568 m (logged between 1568 and 30 m below the surface). Paleontological and granulometric data are available from 1373 to 30 m. (Figure 3a). Cutting samples throughout the well are pyrite-bearing, with one particularly pyrite-rich zone at 176 m, just below the Lava Creek 'B' Ash. Near the base of the well, at 1568 m, a layer of volcanic ash occurs, that is dated at 5.0 Ma and correlated with the Santee Tephra (Table 3).

Sediments from 1568 to 1070 m (~ 5.0–3.1 Ma) are predominantly sandstone and include the Purple Ash (Table 3). This sandstone interval is capped by the Rozel Basalt. Between the Rozel Basalt (~ 3.1 Ma) and the Huckleberry Ash (2.057 Ma) sediments are finer-grained and composed predominantly of silty sandstones. From the Huckleberry Ash up to 410 m (~ 1.5 Ma), deposits are again dominated by slightly coarser sandstones. From 410 m up to 140 m (~ 0.4 Ma), deposits are dominated by clay-rich sandstones, with minor limestone intercalations at 405–400 m (~ 1.45 Ma) and at 350–345 m (~ 1.25 Ma). Above a depth of 140 m, siliciclastic sediments give way to at least 110 m of evaporites, dominated by anhydrite. No log records were available for the upper 30 m (~ last 0.1 Ma) of the well.

Ostracodes occur continuously in low abundance in the cutting samples between 1159 and 30.5 m (~ 3.3–0.1 Ma). We identified a total of 3829 individual ostracodes, including 12 genera and 32 species. The abundance of ostracodes varies from 0–1338 valves per g of sediment (Figures 3a and 4a). *Cyprideis beaconnensis* (68%) and *Candona rawsoni* (18%) are the dominant ostracodes throughout the entire well. The

Table 3. Summary data on tephra layers sampled from the five wells in the Great Salt Lake. The names, ages and depths showed by plain numbers are from Moutoux (1995). The depths shown by underlined numbers are extrapolated from the stratigraphic position of tephra in the wells (see also text). The wells are arranged in order from North to South

Tephra/basalt Name	Age [Ma]	Depth [m]				
		'P'	'J'	'I'	'H'	'N'
Lava Creek 'B'	0.62	172	137	220	149	<u>250</u>
Blue Ash	0.7	—	—	250	—	—
Bishop	0.759	218	171	281	181	<u>277</u>
Pink Ash	1.74	479	345	—	—	—
Huckleberry	2.057	546	415	798	506	—
Rozel Basalt	3.1	1070–1022	720	<u>1433</u>	—	—
Purple Ash	3.38	1182	—	<u>1601</u>	<u>833</u>	—
Santee	5.0	1568	845	<u>1723</u>	<u>1383</u>	—

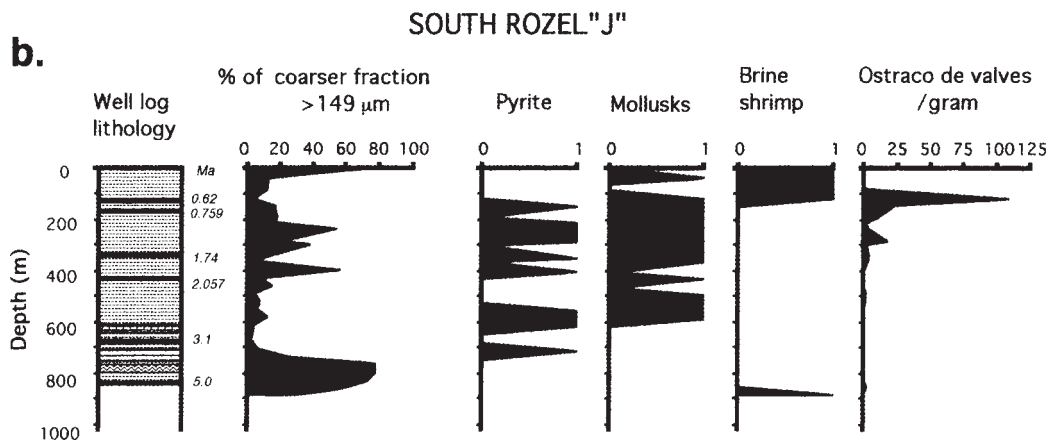
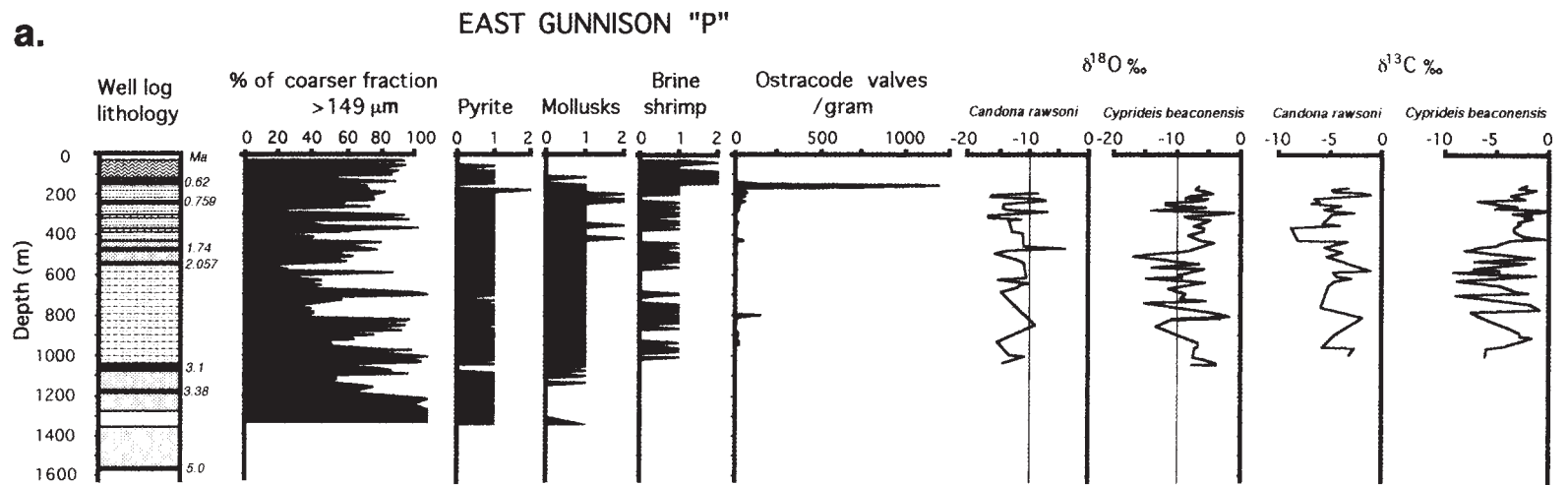
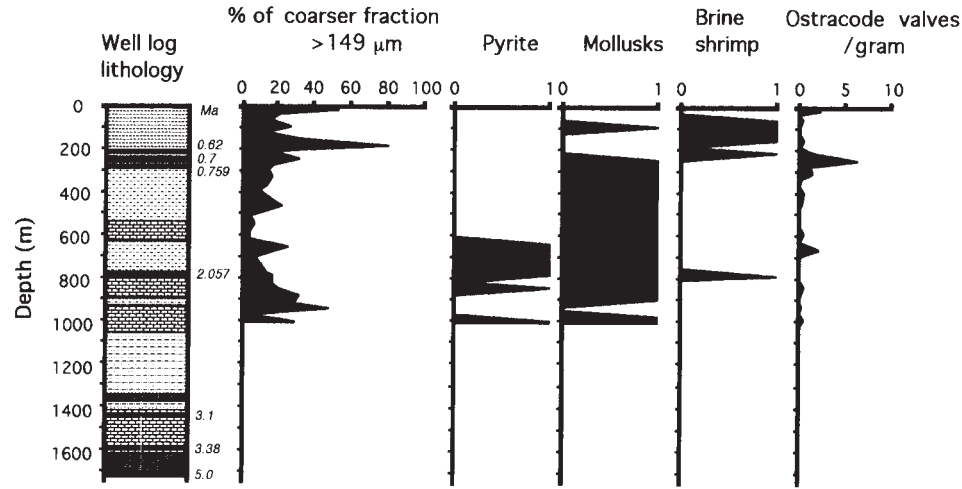


Figure 3. Sedimentological, paleontological, and isotope data combined for (a) East Gunnison 'P', (b) South Rozel 'J', (c) Indian Cove 'I', (d) Carrington 'H', and (e) Sandbar 'N' wells. Wells are arranged in order from North to South

c.

INDIAN COVE "I"



d.

CARRINGTON "H"

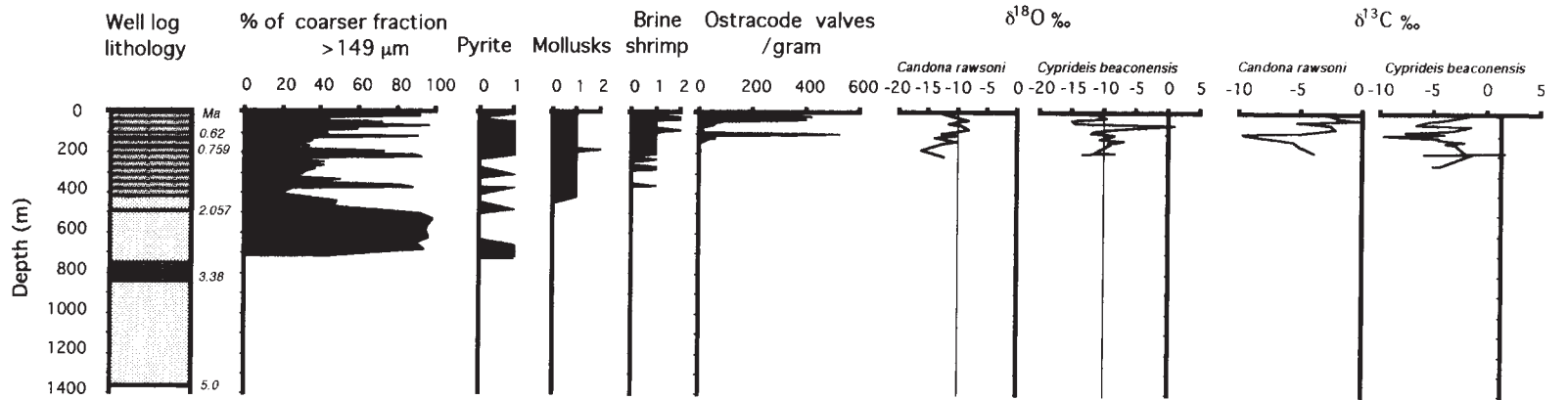


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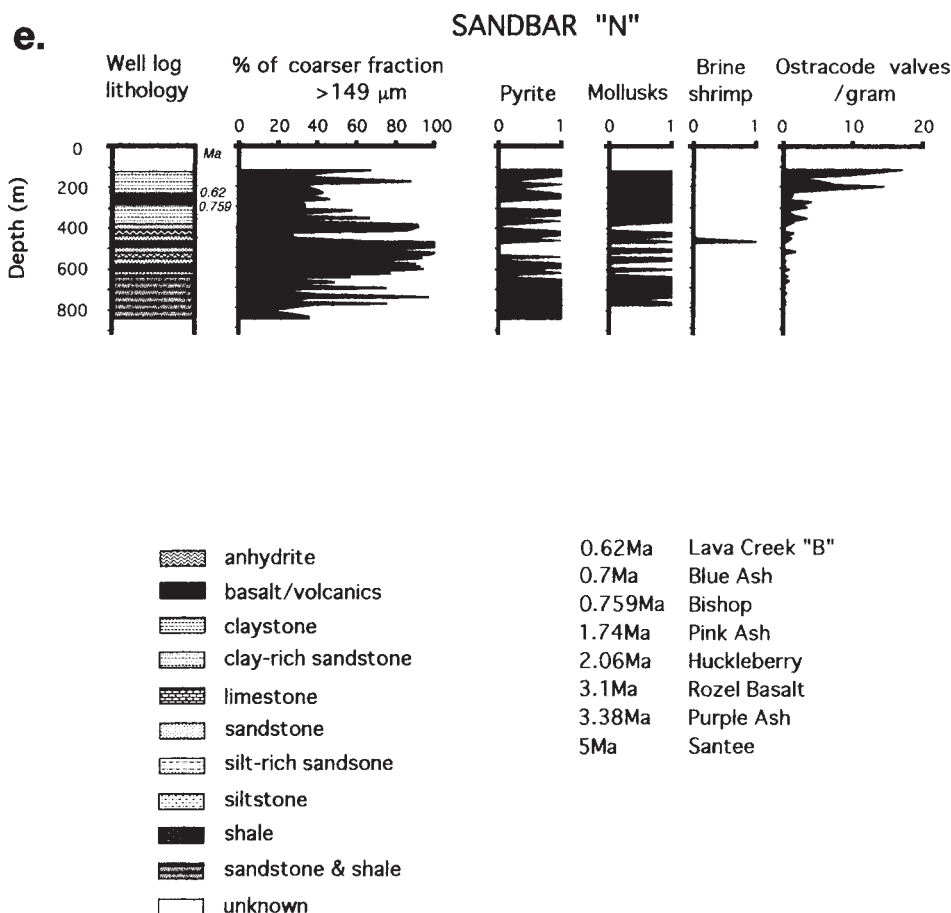


Figure 3. Continued.

well can be divided into five intervals on the basis of fossil occurrence and abundance.

Between 1373 and 1034 m (~ 4.2 – 3.1 Ma), ostracode diversity and abundance are extremely low (< 1 ostracode gm^{-1}) and the two main species do not occur. Fossils are poorly preserved and mostly broken, suggesting they may have been transported. Four taxa occur here: *Candona* sp., exotic candonids, *Limnocythere* sp., and *Tuberocypris* sp. Shells of mollusks are also occasionally present.

Between 1034 and 707 m (~ 3.1 – 2.4 Ma) ostracodes are more common (but still generally < 30 gm^{-1}), more diverse and much better preserved than below. Twenty species occur in this interval, eleven of which occur more frequently than 1% of all ostracodes (in order of abundance these include: *Cyprideis beaconensis*, *Candona rawsoni*, an unidentified exotic limnocytherid, *Tuberocypris quadralis*, *Tuberocypris acuminatus*, an unidentified limnocytherid,

Elkocythereis sp., an unidentified exotic candonid, *Candona* sp., *Limnocythere* cf. *friabilis*, and *Elkocythereis minutidontis*). Mollusks occur throughout the interval, mostly as broken fragments. There are a few occurrences of brine shrimp fecal pellets.

Between 707 and 424 m (~ 2.4 – 1.5 Ma), diversity, abundance and preservation are similar to that of the previous interval. Eighteen species occur here, nine commonly (*Cyprideis beaconensis*, *Candona rawsoni*, *Candona caudata*, *Limnocythere ceriotuberosa*, *Limnocythere friabilis*, *Limnocythere* sp., *Elkocythereis minutidontis*, *Candona adunca*, *Candona* sp.). The most important difference between this and the previous interval is a higher frequency of *Candona rawsoni* (almost equal with *Cyprideis beaconensis*) and the disappearance of most exotic species. Mollusks occur throughout the interval, mostly as broken fragments. Brine shrimp fecal pellets occur in two intervals, from 707

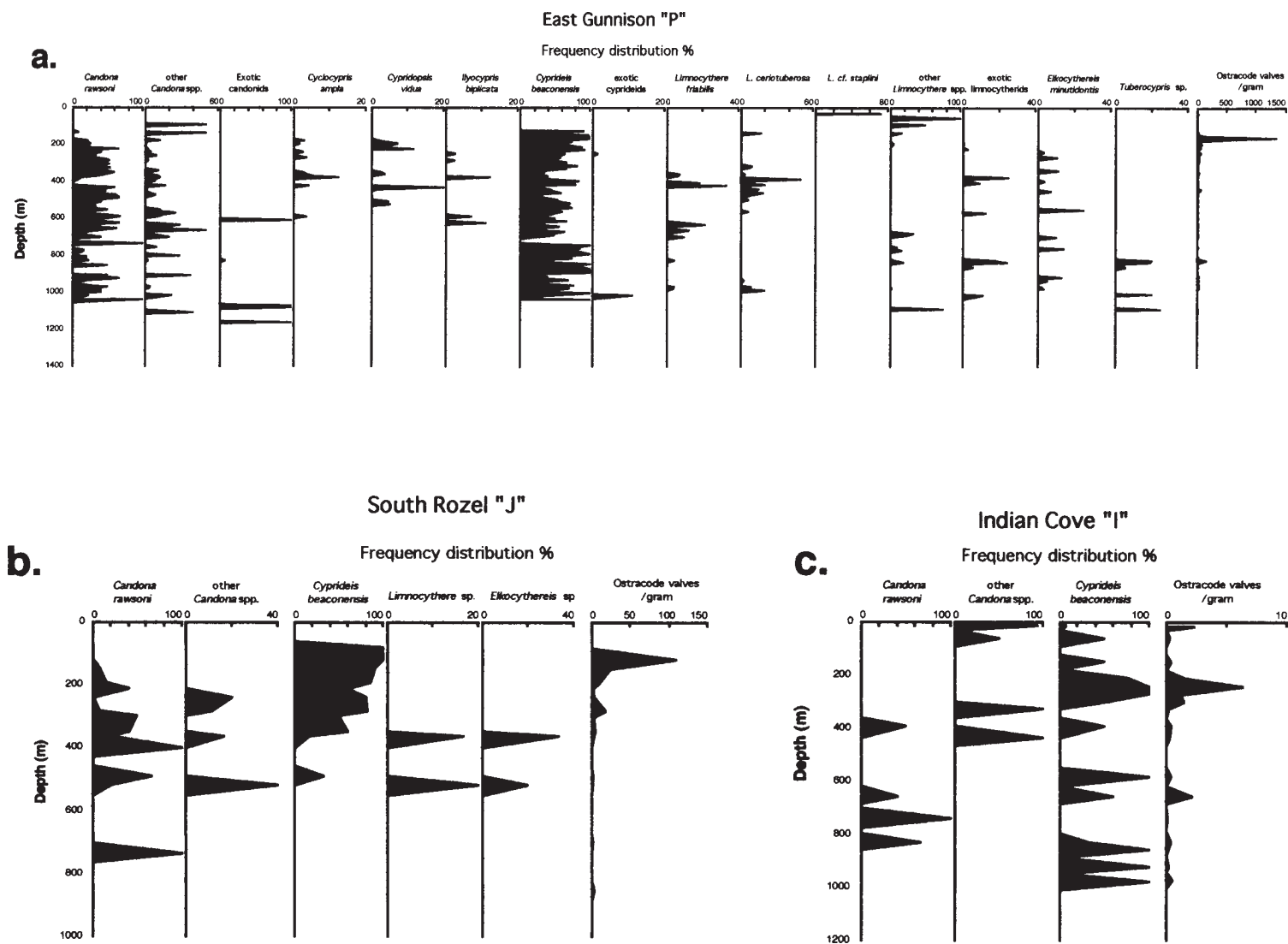


Figure 4. Ostracode stratigraphy for the wells studied in this report. (a) East Gunnison 'P', (b) South Rozel 'J', (c) Indian Cove 'I', (d) Carrington 'H', and (e) Sandbar 'N'. Wells are arranged in order from North to South.

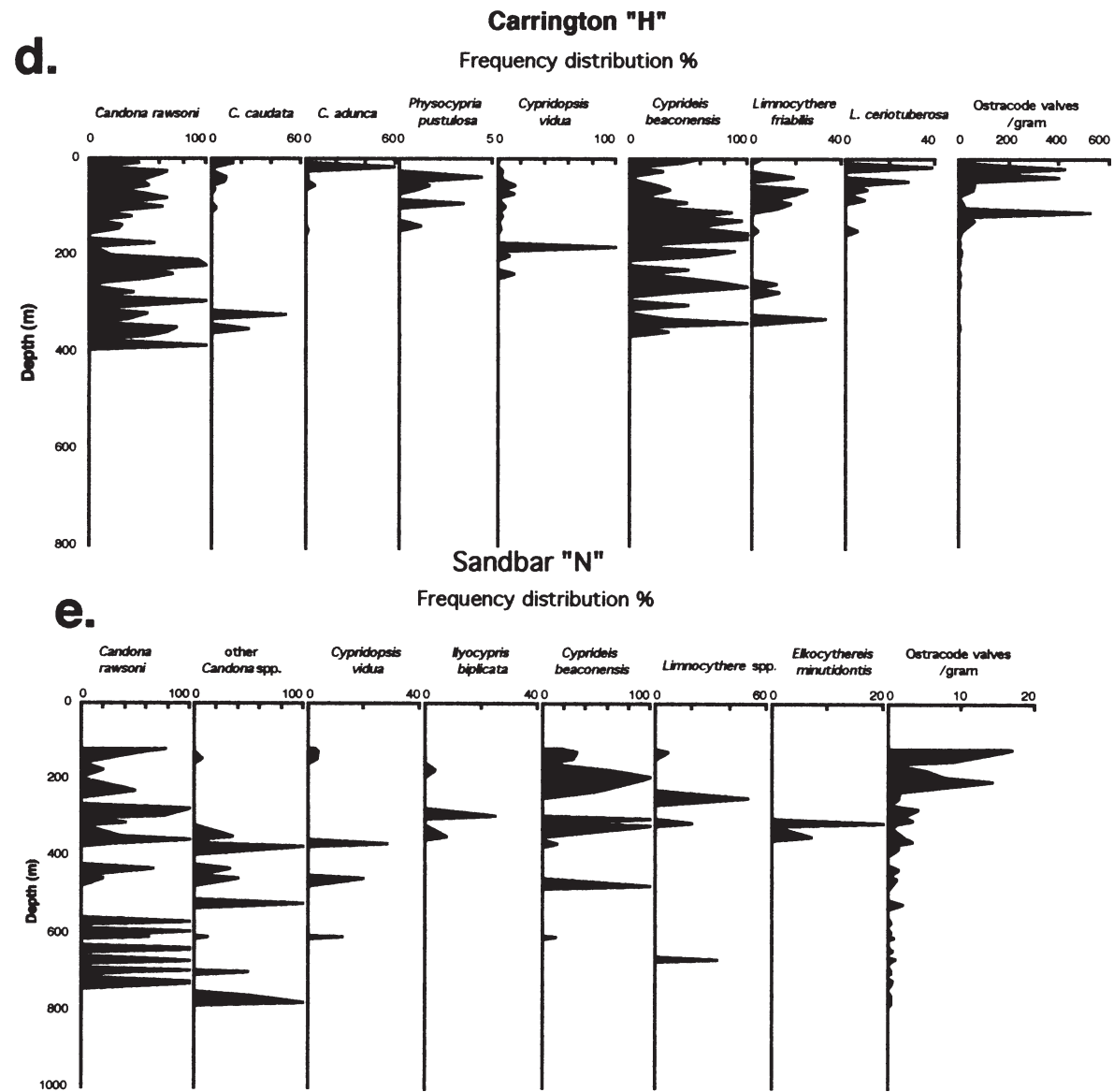


Figure 4. Continued.

to 689 m (~2.4 Ma) and from 570 to 442 m (~2.1–1.6 Ma).

Between 424 and 168 m (~1.5–0.6 Ma), diversity is similar to the two previous intervals and fossils are well preserved but abundance is much higher (up to 1338 gm⁻¹). Nineteen species occur here, three commonly (*Cyprideis beaconensis*, *Candona rawsoni* and *Candona caudata*). Mollusk fragments are very common and shrimp fecal pellets are present in the interval.

Between 168 and 131 m (~0.6–0.4 Ma), diversity is lower than in the two previous intervals but fossils are still well preserved and abundance is much higher (up to 1338 gm⁻¹). Six species occur here and four are common: *Cyprideis beaconensis* (the overwhelming dominant) *Candona rawsoni*, *Limnocythere cerio-tuberosa*, and *Limnocythere* sp. Mollusk fragments are present in the lower part of the interval and shrimp fecal pellets are present and very common in the upper part of the interval.

Between 131 and 30.5 m (~0.4–0.1 Ma), ostracodes are extremely rare (< 9 gm⁻¹) and nondiverse, although the preservation is good. Five species occur here, but only one, *Limnocythere* cf. *staplini*, is represented by more than a single valve. *Cyprideis beaconensis* and *Candona rawsoni* are absent. Mollusks are absent in this interval but brine shrimp fecal pellets are very common. In addition to lithological and paleontological data, we also analyzed 92 ostracode samples for stable isotopes, $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$: (including 58 samples of *Cyprideis beaconensis* and 34 of *Candona rawsoni*). Changes in isotopic concentrations can only be traced for the well interval between 1015 and 131 m (~3.1–0.4 Ma) (Figure 3a). Between 1373 and 1015 m (~4.2–3.1 Ma) and between 131 and 30 m (~0.4–0.1 Ma), ostracodes either did not occur or were too poorly preserved to be suitable for analysis. Very dramatic changes occur between neighboring samples. Also, within samples, both isotopes vary widely. For example, for $\delta^{13}\text{C}$ values for directly adjacent samples of *Candona rawsoni* ranged from -6.5‰ at 222 m to -1.1‰ at 204 m, and for *Cyprideis beaconensis* -7.0‰ at 780 m and -1.0‰ at 771 m. For $\delta^{18}\text{O}$, for *Candona rawsoni* we observed a range of -13.0‰ at 451 m to -3.9‰ at 442 m, and for *Cyprideis beaconensis* -1.1‰ at 259 m and -4.1‰ at 250 m. Changes in isotopic ratios between the two species are higher than those within the same species among the samples. For *Candona rawsoni* $\delta^{18}\text{O}$ ranges from -3.9‰ to -16.5‰ and averages -12.0‰. For *Cyprideis beaconensis*, $\delta^{18}\text{O}$ ranges from -1.1‰ to -16.9‰ and averages -7.3‰. The value of $\delta^{13}\text{C}$ also shows a wide range: for *Candona rawsoni* it ranges from -1.1 to 8.9‰ and averages -4.3‰, and for

Cyprideis beaconensis it ranges from -0.1 to -8.9‰ and averages -3.6‰.

The extreme variation and very light values of $\delta^{13}\text{C}$, may result from the presence of abundant rotting plant debris in the local depositional environment. This is also consistent with the abundance of the marsh species *Cyprideis beaconensis* and *Typha* in these sediments. Marsh environments are characterized by high benthic productivity. As aquatic plants grow, they uptake $\delta^{12}\text{C}$ preferentially, and consequently, plant tissue is isotopically very light in $\delta^{13}\text{C}$ (-20 to -30‰). During the subsequent decay of the plant material, the light carbon is re-released into the water at the sediment-water interface, providing large quantities of light bicarbonate that can be then taken up by ostracodes in the formation of their shells.

Comparison between species show isotope values consistently more depleted in $\delta^{18}\text{O}$ for *Candona rawsoni* than for *Cyprideis beaconensis*. There are two possible explanations for this observed difference. First, given the broad analytical time averaging inherent in an analysis of cuttings, this observation may be an indication that *Cyprideis beaconensis* and *Candona rawsoni* populations actually dominated the lake's ostracode fauna under widely varying conditions, with *Cyprideis beaconensis* dominant during the periods of substantially lower precipitation/evaporation ratios. This interpretation is supported by the much larger excursions in $\delta^{18}\text{O}$ values observed in *Cyprideis beaconensis* relative to that observed in *Candona rawsoni*. This may be indicative of substantial hydrochemical and freshwater inflow variation during the intervals when *Cyprideis beaconensis* populations were established. Although the two species can both tolerate high salinities, Engstrom and Nelson (1991) have shown that optimum salinities for *Candona rawsoni* are only in the 1–10‰ range. Second, the differences in the isotopic ratios between *Cyprideis beaconensis* and *Candona rawsoni* may have resulted from vital effects in the uptake of ^{18}O . Different genera of ostracodes may vary widely in their isotopic fractionation (Chivas et al., 1986). This is especially likely in this case, because *Cyprideis beaconensis* has a much thicker shell than *Candona rawsoni* and this thick shell probably calcifies at a much higher rate.

The relation between $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ can be expressed using cross plots to detect patterns of covariance (Talbot, 1990). For both species there is a significant correlation between these two variables, with *Cyprideis beaconensis* showing a much higher correlation ($r = 0.86$, $p < 0.0001$, where $r =$ Pearson's correlation coefficient)

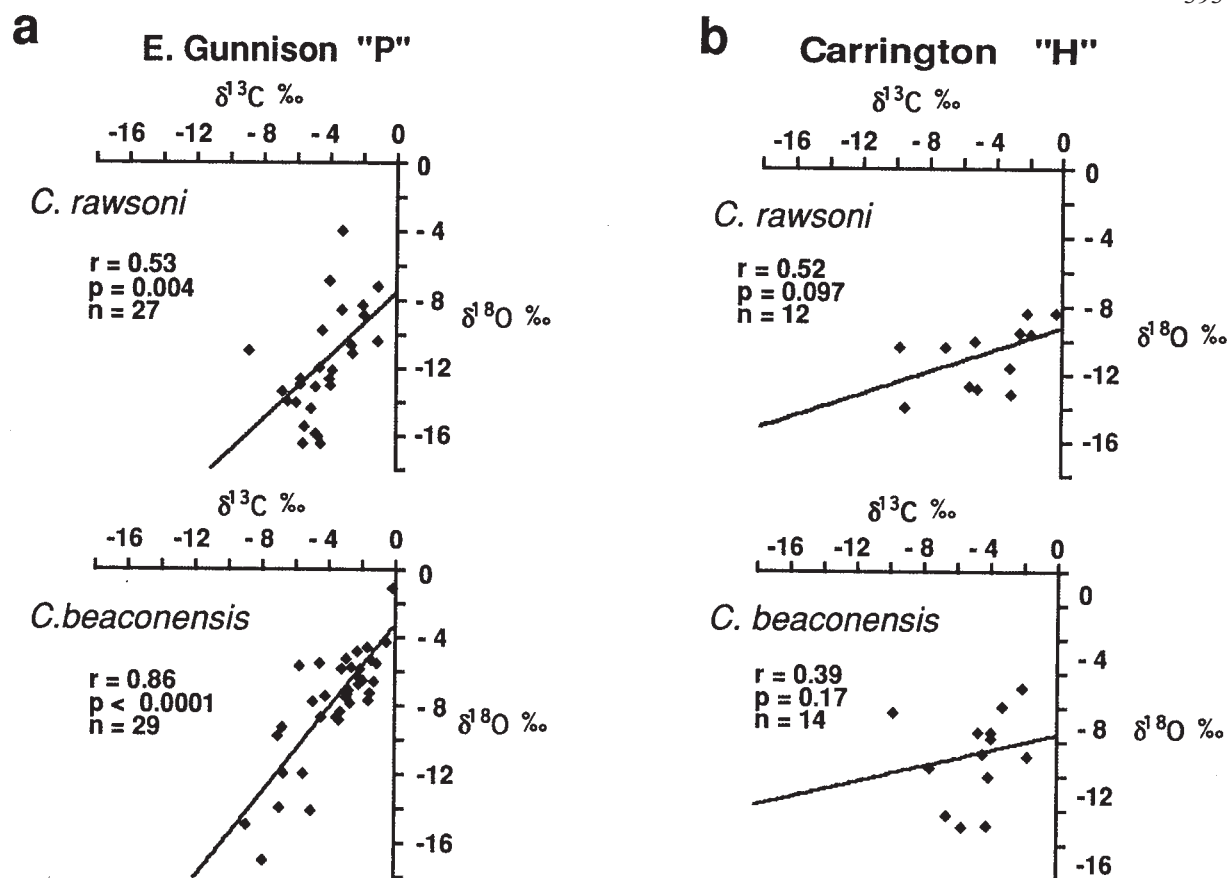


Figure 5. Plots of covariance between $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ for Carrington well 'H' (a) and East Gunnison well 'P' (b). Also see text.

than *Candona rawsoni* ($r = 0.53, p = 0.004$), (Figure 5a). Talbot (1990) has argued that a high correlation between $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ is typical of closed lake systems. The stronger correlation observed for *Cyprideis beaonensis* may also reflect the fact that this species may have acquired a more stable isotopic signature as a result of living in waters with a relatively large contribution of groundwater (see above).

Well 'P' facies indicate a gradual change from coarse clastic, non-lacustrine (probably sand flat) deposits prior to ~ 3.1 Ma, through the deposition of fine-grained clastic marsh deposits, to somewhat coarser clastics and limestones of marsh and lacustrine origin, and finally, to the deposition of lacustrine evaporites. Abundant pyrite throughout the lacustrine interval suggests the existence of reducing conditions close to the sediment-water interface. The distribution of ostracodes and other faunal and floral indicators is consistent with the lithology. In the lower part of the

well, there are very few aquatic fossils and those present are broken and transported. From 3.1 to 1.5 Ma, *Cyprideis beaonensis* is dominant, indicating marsh environments (this is also consistent with the carbon isotope data, see above). The presence of exotic ostracodes with affinities to the Snake River Plain (Lake Idaho) fauna during this time suggests that there was at least an intermittent hydrologic interconnection between the two lake systems during the late Pliocene. It is noteworthy that the oxygen isotopic values from the Great Salt Lake Basin carbonates of this age are consistently more enriched in ^{18}O than are those of Lake Idaho, suggesting that if there was a surface connection between the two lakes, it ran from north (Lake Idaho) to the south (northern GSL Basin). After about 2 Ma, exotic candonids disappear, possibly reflecting a termination of hydrologic connections to the Snake River Plain. Starting about 1.5 Ma and continuing until 0.4 Ma, the absolute abundance of ostracodes as well

as their species diversity increases. *Candona rawsoni* and other taxa become more frequent, but *Cyprideis beaconnensis* is still the most abundant species. During this time interval marsh environments were still dominant but they were probably punctuated by fully lacustrine intervals. From 0.6 to 0.4 Ma, the abundant and diverse ostracode fauna, suggests the presence of fully lacustrine conditions. In the uppermost (evaporite) interval (~ 0.4–0.1 Ma), ostracodes are limited to hypersaline limnocytherid species, brine shrimp are abundant, and mollusks almost totally disappear. All of these signals indicate the presence of extremely saline waters.

The South Rozel well ('J')

The South Rozel well ('J'), is located in the northern part of the lake (Figure 1). The total depth of the well is 845 m and paleontological and granulometric data are available from almost the entire well interval (Figure 3b). Pyrite-bearing sediments are much more restricted in this well than in the 'P' well, limited to two occurrences at 700 to 550 m (~ 3.0–2.5 Ma) and from 400 to 190 m (~ 2.0–0.9 Ma).

Between 845 and 760 m (~ 5.0–3.7 Ma), deposits are dominated by mixed claystone and anhydrite. Between 760 and 745 m (~ 3.7–3.5 Ma), no cuttings were collected. From 745 m to the surface, deposits are dominated by claystones. At 720 m, basalt layer about 3 m thick occurs which, is likely to be the Rozel Basalt (~ 3.1 Ma). Minor limestone units occur between 670 and 640 m (~ 2.9–2.8 Ma).

Ostracodes occur continuously but in very low abundance between 845 and 82 m (~ 5.0–0.4 Ma). We identified 6 genera and 12 species. The abundance of ostracodes varies from 0–108 valves per g of sediment. There is only one well interval with relatively common ostracodes (i.e., more than 50 ostracode per g): from 146–118 m (~ 0.7–0.5 Ma). The two most dominant species throughout the entire well are *Cyprideis beaconnensis* (92%) and *Candona rawsoni* (4.6%) (Figure 4b). The well can be divided into four intervals according to taxonomic composition and abundance of fossils. Between 845 and 735 m (~ 5.0–3.5 Ma), we did not recover any ostracodes or mollusks, and fecal pellets of brine shrimp occur in only one sample. Between 735 and 298 m (~ 3.5–1.5 Ma), both ostracode diversity and abundance are extremely low. Fossils are relatively well preserved, although mollusks are often broken. Nine species occur here, five of which are represented by more than a single ostracode valve (*Candona raw-*

soni, *Cyprideis beaconnensis*, *Candona adunca*, *Elkocythereis minutidontis*, and *Tuberoocypris centrotonus*). Brine shrimp fecal pellets are not present.

From 298 to 82 m (~ 1.5–0.4 Ma), ostracode diversity is still low but their abundance increases slightly. Six species occur here, but only two exceed 1% of all ostracodes (*Cyprideis beaconnensis* (96%) and *Candona rawsoni* (4%)). Shell fragments of mollusks are common. Brine shrimp fecal pellets are absent.

Between 82 m and the surface (~ 0.4–0.0 Ma), we did not recover any ostracodes. Mollusks are present from 64 to 36 m (~ 0.3–0.2 Ma). Only brine shrimp fecal pellets occur throughout the entire interval. The absence of a freshwater fauna in the uppermost samples suggests that the Late Pleistocene Lake Bonneville deposits may not be represented in the uppermost cutting samples.

The lithological pattern in the well 'J' indicates a gradual change from mixed fine grained clastic and evaporite deposition prior to 3.5 Ma to the deposition of exclusively fine grained clastic sediments. Pyrite is not very common in the well which may suggest a well oxidized environment (probably shallow, nearshore waters). The combination of fine grained, well oxidized clastics and a scarcity of ostracodes, suggests that many of those water bodies may have been short-lived and shallow-water. The ostracode distribution pattern is characterized by an increase in *Cyprideis beaconnensis* frequency and a decline in *Candona rawsoni*. The association of *Cyprideis beaconnensis* with shallow water sediments is consistent with the interpretation of this species as being dominant in littoral or marsh environments. At around 1.5 Ma, there is an increase in ostracode abundance. This shift, which also occurs in well 'P', suggests that lacustrine conditions became more widespread in the North Basin after about 1.5 Ma. The interval of highest ostracode abundance correlates both with the occurrence of fine-grained deposits (mostly claystones) and an increase in the abundance of brine shrimp fecal pellets (0.4 Ma). This pattern suggests an increase in the nutrient content and salinity. After 0.4 Ma brine shrimp fecal pellets are the only important fossils suggesting that hypersaline conditions began to occur (at least periodically) at about this time.

The Indian Cove well ('I')

The Indian Cove well ('I'), is located in the north-central part of the lake (Figure 1). The well was logged between 1723 to 15 m below the surface. Paleontological and granulometric data are available from 1006 m (2.4 Ma)

to the surface (Figure 3c). Pyrite was uncommon and restricted to two zones in the lower part of the well at 1006 m (~2.4 Ma) and from 854 to 656 m (~2.1–1.7 Ma). A basalt layer occurring at 1433 m is the Rozel Basalt (3.1 Ma), and we correlate the two underlying ash layers, at 1601 m and 1723 m, as the Purple Ash (3.38 Ma) and the Santee Ash (5.0 Ma) respectively (Table 3). Several additional ash layers have been identified from the upper part of this well.

Between 1723 and 1610 m (~5.0–3.5 Ma), deposits are primarily shale, overlain from 1610 to 1410 m (~3.5–3.1 Ma) by limestone. Between 1410 and 1060 m (~3.5–2.5 Ma), silt-rich sandstone occurs. From 1060 m up to 260 m (~3.5–0.7 Ma), deposits consist of several hundred meters of interbedded limestone and siltstone. Between 260 and 15 m (~0.7–0.04 Ma), deposits are predominantly claystone. No log records were available for the upper 15 m.

Ostracodes occur in cutting samples between 976 and 15 m (~2.3–0.04 Ma), although in extremely low abundance (0–6 gm⁻¹). We identified only 68 individual ostracodes, classified into 4 genera and 6 species. *Cyprideis beaonensis* (63%) and *Candona* sp. (18%) make up most of the fossils. The well can be divided into four intervals according to fossil content (Figure 4c). Between 976 and 854 m (~2.3–2.1 Ma), we recovered only 4 ostracode valves. Mollusks are common but brine shrimp fecal pellets are not present. Between 854 and 326 m (~2.1–0.9 Ma), we recovered very rare *Cyprideis beaonensis* and *Candona rawsoni*. Shells of mollusks are present. Brine shrimp fecal pellets are present from 793 to 774 m (2.0 Ma). Between 326 and 61 m (~0.9–0.2 Ma), we only recovered rare (but well preserved) *Cyprideis beaonensis*. Molluscs are present from 326 to 244 m (~0.9–0.7 Ma). Brine shrimp fecal pellets are present from 210 to 61 m (~0.6–0.2 Ma). Between 61 and 15 m (~0.2–0.04 Ma), we recovered 16 well preserved ostracode valves, most of which were *Candona* sp. Mollusks are not present. Brine shrimp fecal pellets are present from 61 to 30 m (~0.2–0.1 Ma).

The lithology of well 'I' includes a variety of shallow lacustrine deposits, including carbonates and both coarse and fine clastics. Pyrite is rare, suggesting relatively shallow, oxidized environments. Ostracodes are rare through the well, although (as in other wells) the abundance increases slightly just prior to the appearance of brine shrimp, signaling the onset of more saline conditions about 0.8 Ma. From 0.4 to 0.2 Ma, brine shrimp fecal pellets are the only fossils present, suggesting a very saline lake. After 0.2 Ma, fresh water conditions were prevalent at the well site. The abundance of fine grained limestones and the mollusk fauna re-

covered both suggest that the 'I' well area experienced the most persistent lacustrine conditions of the northern basin well sites from 5 Ma to the Recent. The absence of ostracodes through most of the interval however is puzzling. It may be the result of high salinity, low productivity, or, perhaps, a secondary effect of dissolution processes associated either with the oxidation of methane or pyrite, or with the presence of pore waters undersaturated with respect to CaCO₃.

The Carrington well ('H')

The Carrington well ('H') is located in the south-central part of the Great Salt Lake (Figure 1). The study interval of the well is from 1383–0 m below the surface (~5.0–0.03? Ma). Paleontological and granulometric data are available above 732 m (~3.0 Ma) (Figure 3d). Pyrite occurs sporadically throughout the well. Sandstone dominates most of the core, except for two intervals, 860–730 m (~3.4–3.0 Ma) and 460–0 m (~1.9–0.03? Ma), which are dominantly shale or interbedded sand and shale. The presence of the Purple, Huckleberry, Bishop, Blue and Lava Creek 'B' ashes provide firm radiometric control for this well. The time interval from the latest Pleistocene (Bonneville lake cycle) through the Holocene is probably not represented in this well, based on the significant difference between the $\delta^{18}\text{O}$ values in our highest samples and those found throughout the Bonneville lake cycle (Oviatt et al., 1994b).

Ostracodes occur continuously in the cutting samples between 384 and 0 m, though generally at very low abundances (Figure 4d). We identified a total of 3278 individual ostracodes, classified into 9 genera and 19 species. The two dominant species throughout the entire well are *Cyprideis beaonensis* (36.8%) and *Candona rawsoni* (31.6%).

This well can be divided into four intervals according to fossil occurrence and abundance. Between 732 and 393 m (~3.0–1.6 Ma), both ostracodes and brine shrimp are absent. Mollusk fragments, however, were found from 420 to 393 m (~1.7–1.6 Ma). Between 393 and 146 m (~1.6–0.6 Ma), ostracode diversity and abundance are extremely low but fossils are well preserved. Five species are represented by multiple valves: *Candona rawsoni*, *Cyprideis beaonensis*, *Cypridopsis vidua*, *Limnocythere friabilis*, and *Candona caudata*. Mollusk shells are common. Brine shrimp fecal pellets are present from 375 to 366 m (~1.9 Ma) and from 219 to 201 m (~0.9–0.8 Ma). Between 146 and 73 m (~0.6–0.3 Ma) ostracode diversity is higher, fossils are more common, and preservation is better than in the lower intervals.

Twelve species occur in this interval, four of which are common (*Cyprideis beaconensis*, *Candona rawsoni*, *Cypridopsis vidua*, and *Limnocythere ceriotuberosa*). Mollusks and brine shrimp fecal pellets are also common. Between 73 m and the surface (~0.3–0.01? Ma), ostracode diversity and abundance are high and fossils are well preserved. Sixteen species occur here and eight are common (*Candona rawsoni*, *Cyprideis beaconensis*, *Candona adunca*, *Limnocythere ceriotuberosa*, *Limnocythere friabilis*, *Cypridopsis vidua*, *Candona caudata*, and *Physocypria pustulosa*). Mollusks and brine shrimp fecal pellets are common.

We analyzed 32 ostracode samples isotopically from the Carrington Well cuttings, 18 samples of *Cyprideis beaconensis* and 14 samples of *Candona rawsoni*. Changes in isotopic ratios could be only traced continuously for the interval between 210 and 0 m. Between 732 and 210 m, ostracodes were either too rare or too poorly preserved to be suitable for analysis. For both species, isotopic ratios do not show any consistent vertical trends. Very large excursions in $\delta^{18}\text{O}$ values, up to 15‰ between adjacent samples suggest highly unstable hydrological regimes during the post Lava Creek 'B' period. $\delta^{18}\text{O}$ values range for *Candona rawsoni* from -8.26 to -16.26 ‰, averaging -12.13 ‰, and for *Cyprideis beaconensis* from -6.74 to -14.89 ‰, averaging -10.61 ‰. $\delta^{13}\text{C}$ values range for *Candona rawsoni* from -0.22 to -9.72 ‰, averaging -4.58 ‰, and for *Cyprideis beaconensis* from -1.46 to -9.73 ‰, averaging -3.97 ‰.

As in the case of the isotopic record for well 'P', comparison between species shows a more $\delta^{18}\text{O}$ -depleted isotopic signature for *Candona rawsoni* than for *Cyprideis beaconensis*. Differences in the isotope values between the two species are higher than those within the same species among different samples. Like well 'P', the difference may reflect real environmental changes or vital effects (see above).

The $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ cross-plots are not highly correlated in the Carrington well (Figure 5b). The correlation is slightly higher for *Candona rawsoni* ($r = 0.52$) than for *Cyprideis beaconensis* ($r = 0.39$) but neither one is statistically significant ($p = 0.097$ for *Candona rawsoni*, $p = 0.17$ for *Cyprideis beaconensis*). Talbot (1990) has argued that a lack of covariance between the two isotopic ratios may indicate open hydrologic systems with short residence times, suggesting periodic external drainage from the southern lake system (perhaps into the North Basin or another low sump).

To further investigate intrasample isotopic variability, we analyzed sets of eight *Cyprideis beaconensis* valves

from cuttings taken from five different depths in well 'H'. Stable isotope data obtained in the additional analysis were compared with the results from our other analyses (Figure 6). All five sets show extraordinary within-sample variation (up to 15‰) suggesting that precursor lakes of the Great Salt Lake were highly unstable hydrologically over time scales of 30 Ka (average cutting sample spacing) throughout, at least, the past 300 Ka. For the four upper samples (depths: 109, 64, 27, and 0 m), the isotopic results from the first analysis (i.e. Figure 3D) falls within the range of values obtained from the detailed analysis of eight ostracodes, although the first analysis datum differs significantly from the mean of the eight. For the sample from 137 m, the value from the first analysis is slightly outside of

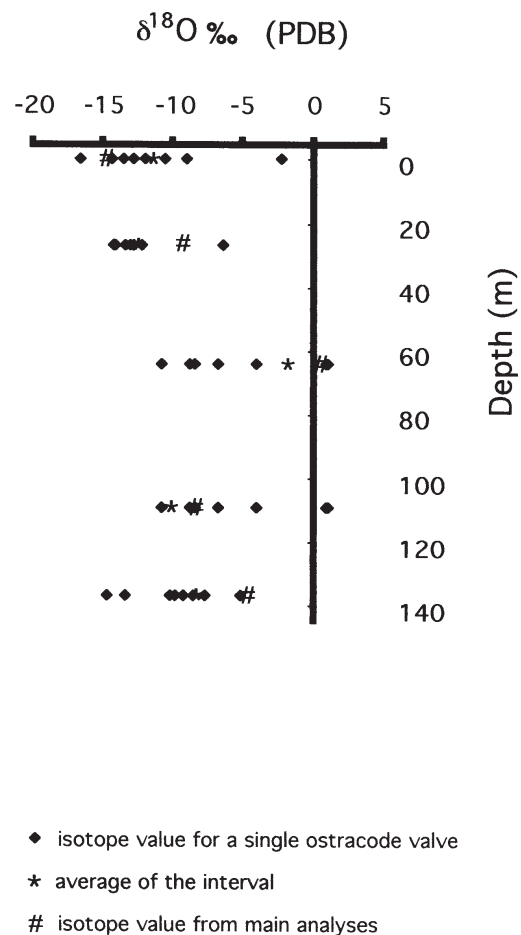


Figure 6. Results of single valve analyses from the upper part of the Carrington well 'H'; testing for degree of isotopic data averaging in our samples. The single values from main analysis is compared to average from the analysis for the particular depth and to the distribution of all eight values from that depth.

the range of subsequent values. This illustrates that isotopic trends from cuttings samples must be interpreted cautiously. It is possible that the southern basin waterbodies were small and underwent rapid $\delta^{18}\text{O}$ fluctuations as a result of seasonal runoff under conditions of high evaporation (a process which would have had much less of an effect on the enormous Lake Bonneville). However, it is noteworthy that much of our data suggest environments significantly more depleted in $\delta^{18}\text{O}$ than the late Pleistocene Lake Bonneville (Oviatt et al., 1994b). Oviatt et al. (1994b) reported $\delta^{18}\text{O}$ values oscillating over a wide range: from -10 to -4% , and an even wider (though slightly more positive) range of variation has been reported in $\delta^{18}\text{O}$ for the latest Pleistocene and early Holocene by Spencer et al. (1984). According to Oviatt et al. (1994b), such dramatic variation cannot be explained by temperature variation alone, but must have resulted from variation introduced by the input of different freshwater inflow to the lake, for example from different rivers. Our results support this argument by demonstrating an even broader range of variability in the mid-Pleistocene.

The predominantly coarse, clastic lithology of well 'H', and the relatively low abundance of pyrite throughout the well both suggest relatively shallow water. Ostracode and other fossil abundances correlate with a noticeable fining of the sediment (above ~ 500 m below the surface). In the lower part of the fossiliferous zone (1.6–0.6 Ma), ostracodes are not very abundant with *Candona rawsoni* and *Cyprideis beaconnensis*, alternating in dominance. *Cyprideis beaconnensis* briefly achieved dominance in the fauna between about 0.75–0.6 Ma, coincident with the first noticeable increase in ostracode abundance. After about 0.6 Ma, a decline in *Cyprideis beaconnensis* and an increase in first ostracode and then brine shrimp fecal pellet abundance probably signals the end of nearby marsh conditions and the onset of widespread large lake conditions, coincident with the early Bonneville cycles. A replacement of marshes by open lake conditions at this time is also indicated by a simultaneous and rapid decline in the abundance of *Typha* and *Sparaganium* pollen (Moutoux, 1995). This series of coordinated changes also suggests an increase in salinity and productivity (0.6–0.3 Ma). After the fossiliferous interval, there is a short decline and then a very rapid increase in the abundance of fossils. In this interval, the most common ostracodes are a mix of fresh and saline lake species of *Candona* and *Limnocythere* (0.3–0.1 Ma).

Sandbar well ('N')

The Sandbar well ('N') is located in the extreme southern part of the lake (Figure 1). Age control for this well is relatively poor, except for the uppermost section (Table 3). We analyzed samples in this well between 850 and 118 m below the surface (Late Pliocene? -0.2 Ma), (Figure 3e). Cuttings samples throughout the well are pyrite-bearing, especially below 650 m. Between a depth of 850 and 630 m deposits are dominated by interbedded shales and sandstones. From 630–390 m deposits are somewhat coarser, with sandstones and thin interlayers of shale and anhydrite spread throughout the interval. The upper part of the well (390–118 m) is composed predominantly of a clay-rich sandstone, somewhat finer than the unit below. No log records were available for the upper 118 m.

Ostracodes occur continuously in the cutting samples between 786 and 118 m, though generally in extremely low abundance (0–17 valves per g, Figure 3e). Five genera and 12 species are present in the well, the two most dominant of which are *Cyprideis beaconnensis* (45.6%) and *Candona rawsoni* (33.2%).

The well can be divided into four intervals by fossil occurrence and abundance. Between 850 and 786 m (~ 2.3 – 2.1 Ma), we did not recover any ostracodes. Mollusks are present from 789 to 786 m. Brine shrimp fecal pellets are absent from the entire interval. Between 786 and 375 m (~ 2.1 – 0.9 Ma), ostracodes are extremely rare and poorly preserved. Only eight species are present, six of which are represented by more than one valve: *Candona rawsoni*, *Candona caudata*, *Candona* sp., *Cyclocypris ampla*, *Cypridopsis vidua*, and *Cyprideis beaconnensis*. Mollusk shells are common. Brine shrimp fecal pellets are present from 481 to 472 m.

Between 375 and 146 m (~ 0.9 – 0.3 Ma), ostracodes are still very rare, though slightly more abundant (up to 14/gm) and diverse (9 species) than the previous interval. Ostracodes in this interval are also poorly preserved. Five species make up more than 1% of the aggregate fauna each (*Cyprideis beaconnensis*, *Candona rawsoni*, *Candona caudata*, *Cypridopsis vidua*, and *Ilyocypris biplicata*). Mollusks are common. Brine shrimp fecal pellets are not present.

From 146 and 118 m (~ 0.3 – 0.2 Ma) ostracode diversity is again extremely low (only *Candona rawsoni*, *Cyprideis beaconnensis*, *Cypridopsis vidua*, and *Limnocythere ceriotuberosa*). Abundance is also very low (< 17 /gm) and fossils are poorly preserved. Mollusks are common but brine shrimp fecal pellets are absent.

The facies pattern in well 'N' indicates a variety of

marsh, shallow lacustrine and fluvial environments. Deposits are predominantly coarse to fine clastics with a few horizons of lacustrine evaporites. The common presence of pyrite may be secondary or related to anoxic ponds/lakes existing in the area (Late Pliocene – 0.9? Ma). Ostracodes are rare throughout the well. The slight increase in their abundance correlates with an increase in proportion of the littoral ostracode *Cyprideis beaconnensis* (0.9?–0.3 Ma). However, there is no record of brine shrimp following that time. In contrast to the indication of very saline lakes after 0.4 Ma in the North Basin, the youngest facies analyzed at ‘N’ suggest fresher water conditions. This difference may be related to the diversion of the Bear River to the Bonneville Basin at about this time (Davis & Moutoux, 1997). Because the Promontory Mountains were rising starting about 2 Ma (McClellan, 1977) and the East Gunnison fault was still active (Figure 2), it is possible that only the South Basin was exposed to fresh water influx. Fossils from well ‘N’ are highly abraded. This suggests they were deposited in relatively high energy environments, such as rivers, or streams, or the shallow littoral zones of lakes, where they would undergo constant agitation.

Discussion

We have reconstructed the paleolimnological history of the Great Salt Lake Basin for the Pliocene and Early Pleistocene, based on lithologic logs and our ostracode and stable isotope data supplemented by the results of palynologic studies of the Great Salt Lake cores (Moutoux, 1995; Moutoux & Davis, 1995). Moutoux and Davis (1995) documented the occurrence of aquatic and wetground pollen and palynomorphs from plants such as *Myriophyllum*, *Azolla*, *Sparganium*, *Typha* and the alga *Pediastrum*. Fossils of the former, emergent plants indicate marsh or littoral conditions. The presence of *Pediastrum* (> 5%) in a sample indicates lacustrine conditions. In contrast, the common occurrence of fungal spores indicates nonlacustrine conditions (Batten, 1996; O. Davis, pers. commun., 1996). Although the fossil record suggests that environmental preferences of *Pediastrum* may have changed through time, this alga has apparently never been tolerant to high salinity (Reynolds & Allen, 1968; Zippie et al., 1992; Batten, 1996).

The North and the South Basin display different histories for most of the Late Neogene. Therefore, we will present separate reconstructions for each of the two

basins, then compare and contrast the two basins, and finally, discuss our interpretation in the context of prior research in the area.

The North Basin

We have identified four distinct intervals in the environmental history of the North Basin in the last 5 Ma. The proxy environmental evidence varies among the wells (especially with regards to well ‘I’). This is due to the spatial environmental variation within the area covered by the wells. Also, the quality and resolution of the data vary from core to core.

Between 5 and 3 Ma, very different environmental conditions existed among the three sites. At locality ‘P’, located to the west (Figure 1), a combination of fluvial and sand flat environments occurred. At locality ‘J’, located to the northeast, intermittent saline lakes and playas existed. At locality ‘I’, located to the southeast, more continuous lacustrine conditions existed. However, aquatic palynomorphs are rare and fungal spores are common (Moutoux, 1995; Moutoux & Davis, 1995) suggesting that the lakes in this region were relatively small and probably saline (although less saline than the playas to the north). Our paleoenvironmental reconstructions for this interval (Figures 6 and 7a-1) suggest that the deepest part of the North Basin was located towards the east side of the present day lake near well ‘I’. This area was also characterized by the highest sediment accumulation rates of the North Basin (Figure 2), associated with high subsidence rates controlled by the directly adjacent Carrington fault (Figure 1). The lake intermittently extended toward the north, and underwent episodic desiccation. During more humid times, fresh water inflow may have entered the basin from the west or northwest, as indicated by the exotic candonids in well ‘P’, which start to appear just before 3 Ma. The similarity of these taxa to species known from the late Pliocene of the Snake River Plain suggests a possible connection between the Bonneville Basin and Lake Idaho (Swain, 1947, 1986a, b; Forester, 1991). Inflow from the west may have resulted in the repeated termination of evaporite deposition and subsequent development of clastic lacustrine deposits in the northeast. Based on upland palynological evidence from the same wells that we have examined, Davis (1997) has proposed that precipitation increased slightly during the early Pliocene, stabilizing in the late Pliocene, and that temperatures rose between 5–4 Ma and then declined through the remainder of the Pliocene. There is no simple relationship between this pattern of

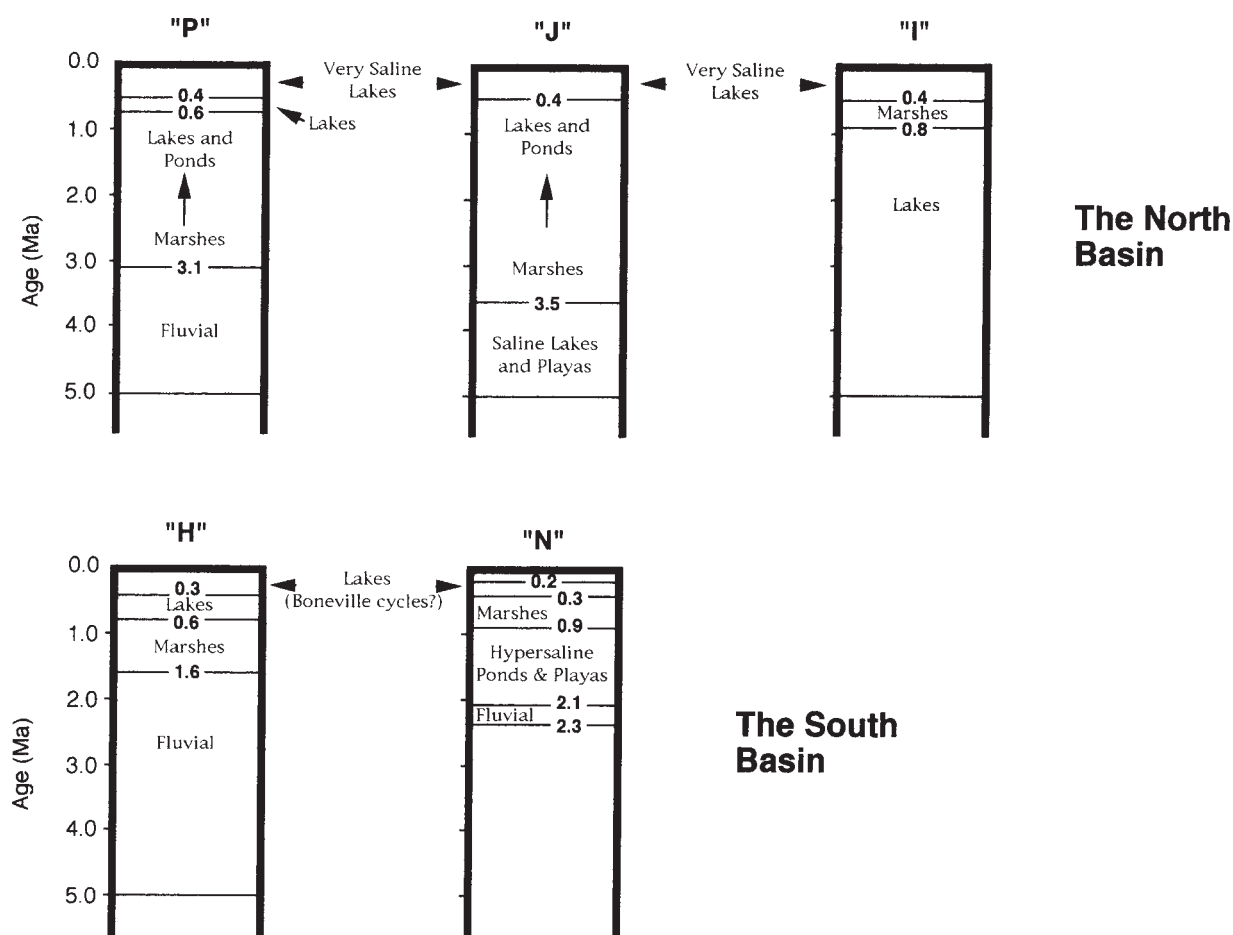


Figure 7. Paleoenvironmental interpretation of our data.

climatic change and the history of marsh expansion and lake levels within the basin. This suggests that the late Pliocene expansion of aquatic environments in the north basin may have been controlled to a great degree by some combination of drainage capture and tectonics (increased accommodation space for standing water migrating west from the Carrington Fault).

Between 3 and 0.6 Ma, the environmental record is more uniform among the wells. During that time, marsh and shallow lacustrine conditions were more widespread in the North Basin (Figures 7 and 8a-2). The sedimentary and fossil record of well 'P' both suggest the presence of marshes and temporary ponds in the west. Dramatic fluctuations in $\delta^{18}\text{O}$ also suggest lakes with variable residence times, and periodic input of fresh water. In the northeast (well 'J'), fresh water marshes and lakes became less ephemeral. During dry intervals the lake repeatedly retreated to the east, leaving

marshes and ponds to the west. Simultaneously, another very large, shallow and apparently saline lake existed in northeastern Utah, near Junction Hill (McClellan, 1977). However, a direct hydrologic connection between this basin and the area west of the Carrington fault seems unlikely.

Expansion of aquatic environments may be correlated with the simultaneous expansion of Lake Idaho to the north during the time when the Glens Ferry Formation was deposited (Swirydczuk et al., 1979; Bradbury & Krebs, 1982; Kimmel, 1982; Wood, 1994). The simultaneous Pliocene expansion of Lake Idaho and aquatic environments within the Great Salt Lake basin might be evidence for some regional increase in precipitation, though again there is no evidence for this from palynological data from the Great Salt Lake Basin (Davis, 1997). In contrast, Thompson (1996) has argued that the Snake River Plain and Lake Idaho area was

The North Basin

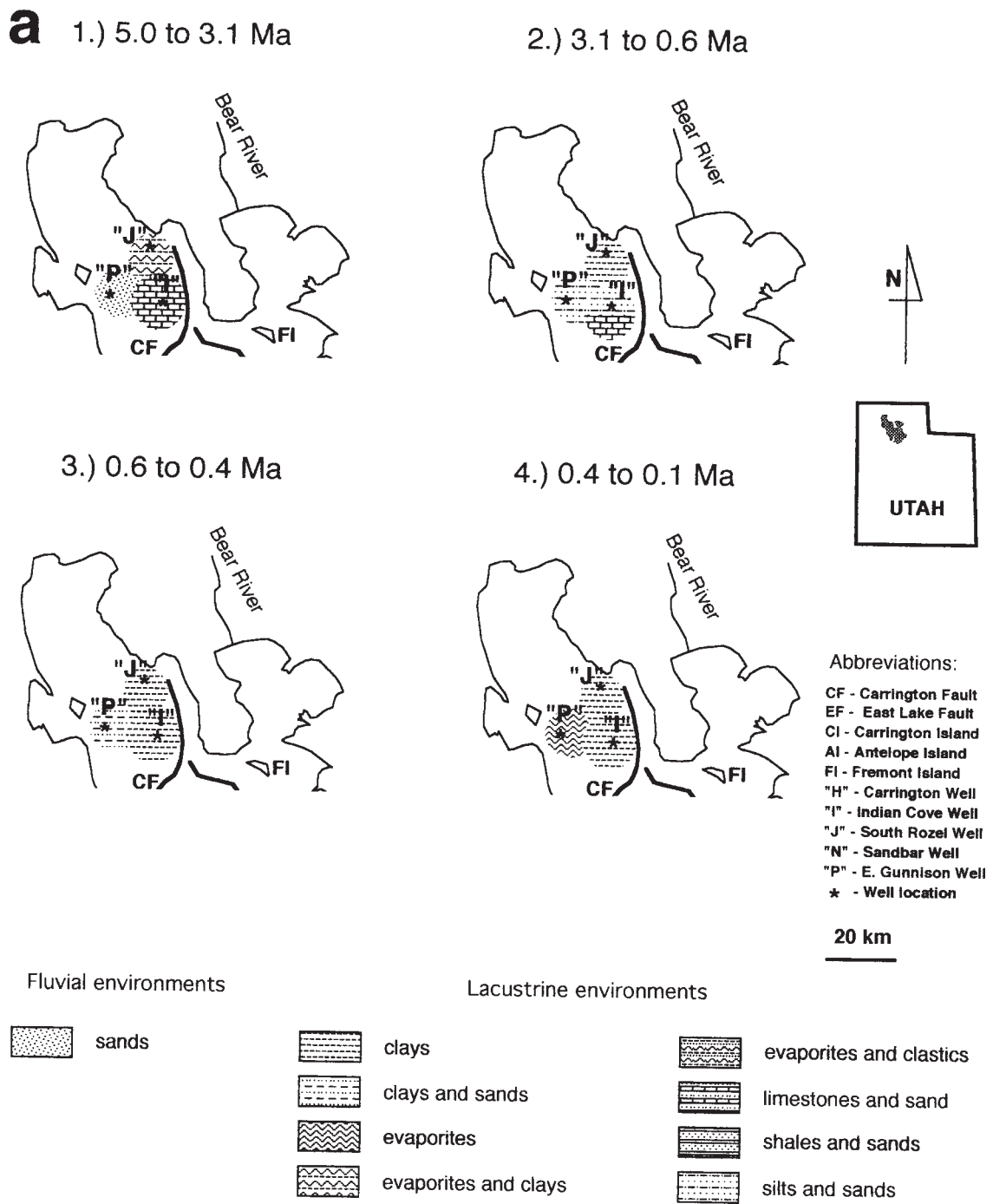


Figure 8. Interpretative lithofacies and paleoenvironments for (a) the North Basin and (b) the South Basin. *For reconstruction 4 in the North Basin, hypersaline conditions may have commenced slightly earlier at 'P' than 0.4 Ma.

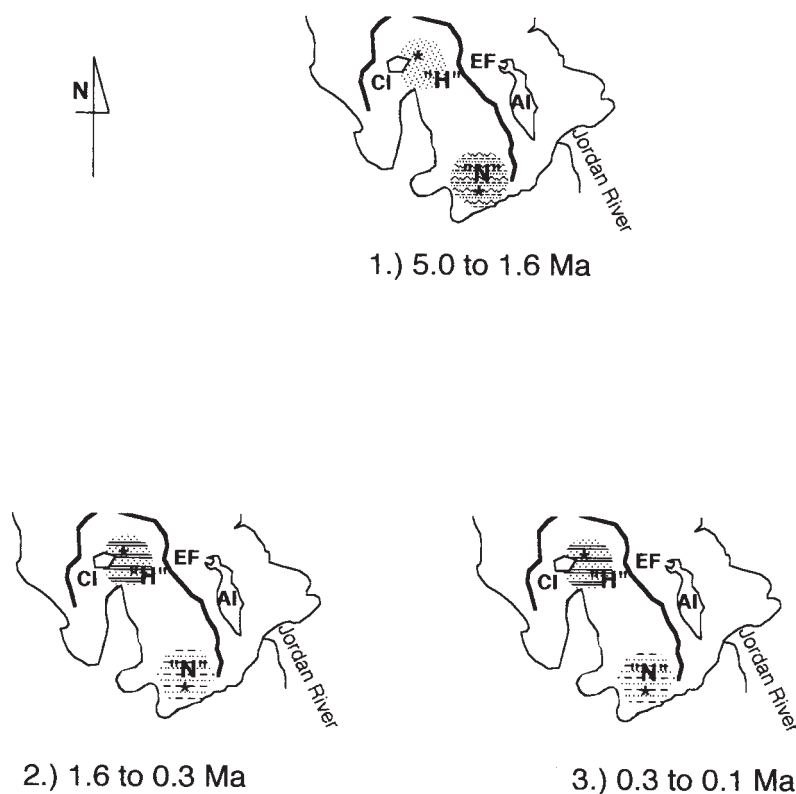
b**The South Basin**

Figure 8. Continued.

moister than present during the Pliocene. One possible explanation for this discrepancy is that the Snake River Plain region may have been sitting at a significantly higher elevation relative to the Great Salt Lake Basin than at present. Significantly, the oxygen isotopic contrast between carbonates from Lake Idaho and contemporary carbonates from the northern Great Salt Lake basin suggests that if there was a hydrologic connection between the two lakes it was from Lake Idaho south into the Great Salt Lake, whereas the Great Salt Lake today (and particularly, its drainage outlet) lies at a slightly higher elevation than the shoreline elevations of Lake Idaho.

In both wells there is a noticeable increase in diversity and productivity indicators after 1.5 Ma. Snake River Plain type exotic ostracodes disappear from the Great Salt Lake after about 1.7 Ma, shortly after the drainage

of Lake Idaho and their extinction on the Snake River Plain. Davis (1996) has shown that marsh and lacustrine environments existed at the well 'I' during the early Pleistocene. These environments persisted until 0.8 Ma, but the sedimentation regime changed from predominantly carbonate to predominantly clastic, and the lake probably became more saline towards the latter part of the interval. A reduction in abundance of *Pediastrum* coupled with an increase in fungi up to about 10% in well 'I' suggest that the lake was shallow in the area (Moutoux, 1995; Moutoux & Davis, 1995). A reduced rate of accumulation in well 'I' at this time also suggests a reduction in vertical motions along the Carrington fault (Figure 2). Between 0.8 and 0.6 Ma, the basin depocenter appears to have shifted from the southeast to the northwest. *Myriophyllum*, *Azolla*, and *Potamogeton* are not very common but are present in this

interval. *Typha* is common at the beginning of this interval but declines very rapidly after about 0.75 Ma, along with *Cyprideis beaconnensis*, signaling the end of extensive marsh conditions in the North Basin and the beginning of the Bonneville open lake cycles. *Pediastrum* is common in limestone-dominated intervals suggesting at least a periodic presence of freshwater conditions. Fungal spores are still present, but not as abundant as before, suggesting deeper and more persistent water (Moutoux, 1995; Moutoux & Davis, 1995). During this time interval, the area covered by the lake(s) was much greater than in the early Pleistocene, and during more humid intervals, the North Basin was probably covered by one large lake.

Between 0.6 and 0.4 Ma, lacustrine environments were well established in the north part of the Basin (well 'P'). Both northern wells record predominantly lacustrine conditions (Figures 7, and 8a-3). Lacustrine conditions are also evident up to 30 km further north in the basin, based on well log data for AMOCO's Cub and Spring wells. Wells 'P' and 'J' display very similar facies patterns, suggesting the continuous presence of a large lake. At the site of well 'I', marsh conditions which started at 0.8 Ma are still persistent. The assemblage and abundance of ostracodes, fluctuations in the abundance of *Azolla* and *Pediastrum* and almost total disappearance of *Typha* suggest that the water bodies were probably eutrophic with slightly elevated salinity (Batten, 1996), and that littoral depths rarely occurred at the well sites (indicative of large lake level fluctuations). Fungal spores noticeably decline suggesting deepening of the lake (Moutoux, 1995; Moutoux & Davis, 1995). The isotopic record, as in the previous interval, shows a wide variation among samples but coupled with other data seems to suggest lakes with periodic inputs of the fresh water. The covariance between $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ for the entire well suggests a closed hydrologic system. The fact that the isotopic composition of the two different species of ostracodes differ consistently suggests that the lake underwent regular and profound changes in salinity and water balance.

From 0.4 Ma until the late Pleistocene, lacustrine conditions dominated. However, the records for all three wells suggest profound changes in the limnology and ecology of the lake (Figures 7 and 8a-4). In particular, we observe an increase in the abundance of brine shrimp fecal pellets and a dramatic decrease in the diversity and abundance of ostracodes. Ostracodes indicative of lacustrine environments (*Limnocythere* cf. *staplina* in well 'P' and *Candona* sp. in well 'I') appear in the wells at about the same time (~ 0.1 Ma). Also, in

well 'P' we observe very thick accumulations of lacustrine evaporites. All aquatic palynomorphs gradually disappear towards the top of the well and fungal spores become abundant (Moutoux, 1995; Moutoux & Davis, 1995). We infer that for much of this time interval the North Basin was occupied by lakes that were shallower and considerably more saline than those documented for the earlier time-interval.

The South Basin

The paleoenvironmental histories of the Carrington 'H' and Sandbar 'N' wells are very different until 0.9 Ma. Thus, for much of the last 5 Ma, the South Basin may have been subdivided into smaller basins, each with distinct environmental histories. Well 'N' is located in an area that was within a small, fault-controlled subbasin with an independent and unique structural setting, and consequently, with an independent paleoenvironmental history (R. Johnson, pers. commun., 1995). Thus, we provide separate reconstructions for wells 'H' and 'N', emphasizing 'H' because it is more likely to be representative of the South Basin environments and because it has much more complete record (from 5 Ma to Recent) than well 'N' (from about 2.3 to 0.2 Ma). Also plant fossils from well 'N' were not analyzed by Moutoux and Davis (Moutoux, 1995; Moutoux & Davis, 1995).

Between 5 to 1.6 Ma, fluvial deposition and sand flat environments occurred at well 'H', as inferred from well logs (Figures 7 and 8b-1). *Azolla* is present, though not common, at 2.7 Ma, indicating the existence of marshes and small ponds. At the same time, fungal spores are very abundant (Moutoux, 1995; Moutoux & Davis, 1995).

Between 1.6 and 0.6 Ma, the well 'H' site was occupied by marsh. This interpretation is supported by co-occurrence of *Candona rawsoni* and *Cyprideis beaconnensis* (Figures 7 and 8b-2), light $\delta^{13}\text{C}$ (possibly indicating high productivity for marsh-dwelling taxa), as well as plant fossil data. *Azolla*, *Typha*, and *Pediastrum* are common in this interval. Fungal spores are present but rare (Moutoux, 1995; Moutoux & Davis, 1995). This is in partial contrast with the North Basin, where, during the same time interval, *Cyprideis beaconnensis* was the dominant ostracode, overall abundance was higher, and *Pediastrum* was rare or absent. Given the paleoecologic differences between the two basins, either hydrologic systems of the South and North Basins were completely disconnected, or the North Basin may have served as a drainage sump for the South Basin.

Between 0.6 and 0.3 Ma, lacustrine conditions also occurred at the well 'H' site (Figures 7 and 8b-2). The lake was eutrophic, as suggested by higher ostracode abundances, and the ostracode assemblage was more diverse. The dominant species is *Cyprideis beaconensis* (despite a relatively constant sediment accumulation rate). In plant fossil record, we observe a decline in *Typha* and an increase in *Pediastrum*. Also mollusks and brine shrimp fecal pellets are more common.

From 0.3 Ma to the end of the late Pleistocene, lacustrine conditions predominated (Figures 7 and 8b-3). The data indicate, however, that the lacustrine conditions varied greatly through that time interval, from very shallow and saline to deep and freshwater. This is consistent with earlier reconstructions of the late Pleistocene lake history (e.g. Morrison, 1991). Ostracode taxonomic composition varies between samples. However, worth noting is the occurrence of *Limnocythere ceriotuberosa*. Fluctuations in the occurrence of this species, coupled with an overall increase in the ostracode abundance, may reflect the Bonneville cycles. Among aquatic palynomorphs only *Pediastrum* is common, but its abundance decreases in the upper part of the interval. Fungal spores are rare. Values of $\delta^{18}\text{O}$ fluctuate greatly between samples suggesting variable $\delta^{18}\text{O}$ of the host water. Also the covariance between $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ is poor suggesting relatively short residence time water bodies and an open system, with possible drainage to another sump.

At well 'N' fluvial deposition occurred between about 2.3–2.1 Ma. (Figures 7 and 8b-1). Between 2.1 and 0.9 Ma, all data consistently indicate the occurrence of hypersaline ponds and playas. Periods of desiccation and playa formation are marked by evaporites and a poor lacustrine fossil record (Figures 7 and 8b-2).

Between 0.9 and 0.3 Ma, marsh conditions occurred in the extreme south (Figures 7 and 8b-2). The ostracode record is dominated by *Cyprideis beaconensis*. Clastic deposits are similar to those of the prior interval (silt-rich sandstone). This change from playa to marsh conditions was most likely the result of a more constant water supply from ground water, and/or overland flow, and/or lower evaporation rates.

Between 0.3 and 0.2 Ma, lacustrine conditions predominated (Figures 7 and 8b-3). The presence of a variety of *Candona* species and *Limnocythere ceriotuberosa* indicates fresher water lacustrine environments. Similarities of this interval with the corresponding time interval recorded in well 'H' suggests that the widely fluctuating lakes were aerially extensive.

Comparison between the South and North Basins

The substantial differences in the environmental history between the North Basin and the South Basin suggest that there have been only periodic connections between the two basins during the time interval from 5 to 0.1 Ma, but that these became more frequent during the mid-Pleistocene. Although both basins went through similar cycles, from fluvial through ephemeral lacustrine to fully lacustrine conditions, these cycles occurred at different times in the two basins. Moreover, the chemical and physical properties of the lakes were different and they supported different ostracode communities. Notably, the unusual exotic candonids of the North Basin, indicative of hydrologic connection with Snake River Plain lakes during the Pleistocene, are completely absent in the South Basin fossil record, where standing water environments were actually rare until the Pleistocene. In contrast, in the North Basin marsh and lacustrine conditions occurred (intermittently, at least) after 5 Ma.

Comparisons with prior research

Oviatt et al. (1997) have recently reported on Plio-Pleistocene deposits west of the modern Great Salt Lake. Their paleolimnologic interpretations are in excellent agreement with our own major conclusion that large, open lakes were not a common feature of the Great Salt Lake basin landscape prior to the middle Pleistocene. Morrison (1991) presented a very detailed stratigraphic history of the Quaternary period in the Great Basin, in particular the history of Lake Bonneville. Between 0.8 and 0.29 Ma, major environmental fluctuations are marked by a series of four lacustrine intervals divided by five paleosols. Between 0.29 and 0.13 Ma, the proto Great Salt Lake was again fully lacustrine, followed by a nonlacustrine interval from 0.13 to 0.03 Ma. After 0.03 Ma, Morrison distinguished four paleoenvironmental intervals, representing widely fluctuating conditions varying from large and deep lakes (including Lake Bonneville from 30 to 12 Ka) to nonlacustrine conditions.

Our records show that lake conditions had become very common throughout the entire basin by about 0.6 Ma. Morrison's notion of four lake cycles between 0.8 and 0.29 Ma is consistent with our record from the South Basin where we observe temporary lakes. At the North Basin well sites, however we have no record of complete desiccation after 0.6 Ma. Between 0.29 and 0.13 Ma, Morrison again describes fully lacustrine conditions, which agrees with our interpretation,

although the North Basin lakes were very saline and shallow.

Although generally consistent, our interpretation differs in detail from Morrison's reconstruction. Morrison's data for the North Basin region came mostly from outcrops from Little Valley in the southern Promontory Mountains, an area located northeast of our wells. Morrison's interpretations for the younger part of the record is based mainly on the Burmester and especially Saltair cores which were drilled in the southernmost part of the South Basin. The differences between Morrison's and our reconstruction most likely reflect local environmental variation within the Bonneville Basin. Because of the resolution of our record we cannot make comparisons with interpretations provided by Morrison and others for the youngest part of the Quaternary history of the Basin.

Regional paleoclimate reconstructions have been developed by several authors for the Great Salt Lake region (Thompson, 1991, 1996; Moutoux, 1995; Moutoux & Davis, 1995; Davis & Moutoux, 1997). Davis and Moutoux (1997) and Davis (in press) have argued that temperatures increased during the early Pliocene to a maximum about 4 Ma, which they argued was the warmest interval in the Late Tertiary. This was followed by a general decline through the remainder of the Pliocene. Precipitation in their estimates showed a slow but minor increase through the Pliocene, with absolute values drier than today. In contrast, Thompson (1996) has argued that Pliocene climates were moister than at present, with cooler summers and possibly warmer winters, based on palynological evidence from the Snake River Plain. During the late Pliocene, Davis (1997) observes a continuous gradual increase in desert vegetation and a decrease in proportions of pine and *Artemisia* pollen in the Great Salt Lake wells. Paleotemperature estimates continue to decline with an abrupt dip about 2.6 Ma. Davis and Moutoux's (1997) reconstructions show that upland environments in the early Pleistocene were similar to those of the late Pliocene, with a continued gradual increase in chenopods and *Amaranthus* pollen and a decrease in pine and *Artemisia*. Paleotemperature estimates suggest stable or slightly decreasing temperatures through this interval, accompanied by stable or slightly increasing precipitation. After about 0.75 Ma however, the climate rapidly became more humid and colder.

Our paleolimnologic reconstruction can only partially be explained in reference to these reconstructions. Our reconstruction is chronologically inconsistent with a strictly climatic explanation for the history of expansion

and contraction of lakes that occupied the Basin. Neither the gradual Pliocene drying event, nor the abrupt paleotemperature fall and rise at 2.6 Ma is recorded in lake signals. Instead, simultaneous with these increasing indications of aridity in upland signals we observe a surprising expansion of aquatic habitats. This anomaly may result from an expansion of accommodation space extending west from the Carrington Fault, or the development of new drainage interconnections feeding water to the basin, particularly from Lake Idaho, or some combination of the two factors. The abrupt rise in precipitation and decline in temperatures recorded at 0.75 Ma in upland pollen signals occurs significantly before the Middle Pleistocene expansion of lacustrine conditions (at 0.6 Ma in the North Basin and at about 0.3 Ma in the South Basin). It seems likely that alternative explanations involving multiple episodes of drainage capture will have to be invoked to explain these discrepancies between lake and upland records. However our reconstructions are too imprecise to suggest specific stream piracy events as the cause of lake expansion.

Eardley & Gvosdetsky (1960) and Eardley et al. (1973) presented two reconstructions of the Bonneville Basin based on two deep cores taken at the south shore of the Great Salt Lake: the Saltair core (198 m) and the Burmester core (307 m), (Figure 1). Both cores covered a time interval of about 0.8 Ma and include the Lava Creek 'B' ash and Bishop ash. Comparison of these previous records with our record, especially for the most southern Sandbar 'N' well, reveals differences between our work and previous reconstructions. The differences between their and our reconstructions, as with Morrison's reconstruction, most likely reflect environmental variation within the Bonneville Basin. Other minor differences may simply be an artifact of sampling resolution and sampling techniques. The Saltair and the Burmester cores were sampled at intervals less than 1 m, whereas our sampling interval was usually about 9 m. Lake fluctuations shorter than 20 000 yrs, like those recorded by the Saltair and Burmester cores, were not manifested at our sampling resolution of about 30 000 yrs. Another problem is that our samples are from cuttings, with their inherent broad analytical time-averaging problems, whereas Eardley & Gvosdetsky sampled the cores directly. Pluvial cycles are evident in the palynological data from the AMOCO cuttings record (Moutoux & Davis, 1995). There are two possible explanations for discrepancy between our record and Eardley & Gvosdetsky and Moutoux & Davis. First, ostracodes are only abundant at the well sites during

particular phases of a pluvial cycle, and this is reflected in a time-averaged sample. Second, the available ostracode samples were simply too small to discriminate these differences.

Conclusions

1. We have examined five deep wells (including deposits spanning most of the Plio-Pleistocene) from the Great Salt Lake, Utah, using lithological, paleontological, and stable isotope data. Lithological data were compiled from AMOCO well logs. We obtained ostracodes, mollusks and brine shrimp fecal pellets from cuttings samples. Ostracodes were identified and counted.

2. Cuttings samples were collected at ~9 m intervals. The sediment accumulation rates indicate that an average ~9 m interval corresponds to the time-interval of ~30 000 yrs.

3. The well records cover the time-interval from 5 to 0.1 Ma, with the exception of the Sandbar well 'N' (2.3–0.2 Ma).

4. According to our environmental interpretation, marsh and shallow lacustrine conditions began in the North Basin starting from 5 Ma, with a major expansion of open water environments only in the Middle Pleistocene. Lacustrine environments reached their maximum aerial extent at about 0.6 Ma. In the South Basin, however, extensive lakes do not appear until 0.3 Ma.

5. In general, the aquatic palynologic signals from the same wells (Moutoux, 1995; Moutoux & Davis, 1995) are consistent with our interpretations. However, the climatic interpretation from the upland pollen record does not explain some of the major fluctuations in lake level in our record, and support the notion that aerial expansions in aquatic environments the Bonneville Basin prior to the Middle Pleistocene were controlled by a complex combination of drainage diversion events and expansion of accommodation space along major faults. Only after the Middle Pleistocene, with the rapid expansion of open water indicators and disappearance of marsh vegetation is there a strong correlation between upland climate and paleolimnologic signals in the basin.

6. The Quaternary history of the Great Salt Lake Basin was previously reconstructed using surface data and high resolution core samples (Eardley & Gvosdetsky, 1960; Eardley et al., 1972; Morrison, 1991). Our interpretation is consistent with the prior research for the Middle-Late Pleistocene interval (past 0.8 Ma) in the chronology of lacustrine conditions. However, unlike

prior studies, our data suggests that the North and South Basin have differed substantially in their lake cycle history during the middle Pleistocene, and have probably existed as independent hydrologic basins for much of that time interval.

7. Because of our coarse sampling intervals, our data cannot provide conclusive evidence, one way or the other, for dramatic and abrupt lake level fluctuations for the last 32 000 yrs. However, both single sample and synoptic isotopic variability suggest that the hydrology and hydrochemistry of the Great Salt Lake have been variable throughout the Pleistocene.

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