The $^{87}Sr/^{86}Sr$ ratios of lacustrine carbonates and lake-level history of the Bonneville paleolake system

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ABSTRACT

Lakes in the Bonneville basin have fluctuated dramatically in response to changes in rainfall, temperature, and drainage diversion during the Quaternary. We analyzed tufas and shells from shorelines of known ages in order to develop a relation between $^{87}Sr/^{86}Sr$ ratio of carbonates and lake level, which then can be used as a basis for constraining lake level from similar analyses on carbonates in cores. Carbonates from the late Quaternary shorelines yield the following average $^{87}Sr/^{86}Sr$ ratios: 0.71173 for the Stansbury shoreline (22–20 ^{14}C ka; 1350 m), 0.71153 for the Bonneville shoreline (15.5–14.5 ^{14}C ka; 1550 m), 0.71175 for the Provo shoreline (14.4–14.0 ^{14}C ka; 1450 m), 0.71244 for the Gilbert shoreline (~10.3–10.9 ^{14}C ka; 1300 m), and 0.71469 for the modern Great Salt Lake (1280 m). These analyses show that the $^{87}Sr/^{86}Sr$ ratio of lacustrine carbonates changes substantially at low- to mid-lake levels but is invariant at mid- to high-lake levels.

Sr-isotope mixing models of Great Salt Lake and the Bonneville paleolake system were constructed to explain these variations in $^{87}Sr/^{86}Sr$ ratios with change in lake level. Our model of the Bonneville system produced a $^{87}Sr/^{86}Sr$ ratio of 0.71193, very close to the observed ratios from high-shoreline tufa and shell. The model verifies that the integration of the southern Sevier and Beaver rivers with the Bear and others rivers in the north is responsible for the lower $^{87}Sr/^{86}Sr$ ratios in Lake Bonneville compared to the modern Great Salt Lake. We also modeled the $^{87}Sr/^{86}Sr$ ratio of Lake Bonneville with the upper Bear River diverted into the Snake River basin and obtained an $^{87}Sr/^{86}Sr$ ratio of 0.71414. Coincidentally, this ratio is close to the observed ratio for Great Salt Lake of 0.71469. This means that $^{87}Sr/^{86}Sr$ ratios of >0.714 for carbonate can be produced by climatically induced low-lake conditions *or* by diversion of the upper Bear River out of the Bonneville basin. This model result also demonstrates that the upper Bear River had to be flowing into the Bonneville basin during highstands of other late Quaternary lake cycles: carbonates from the Little Valley (130–160 ka) and Cutler Dam (59 ± 5 ka) lake cycles returned $^{87}Sr/^{86}Sr$ ratios of 0.71166 and 0.71207, respectively, and are too low to be produced by a lake without the upper Bear River input.

Keywords: Bonneville, Pleistocene, carbonates, strontium, lake.

INTRODUCTION

The eastern Great Basin consists of a series of topographically closed basins, some of which were filled by large lakes during major Pleistocene pluvial episodes. The largest of these, Lake Bonneville, the predecessor of Great Salt Lake (GSL), was over ~50,000 km^2 in area at its highstand and ~332 m in depth, covering most of western Utah along with smaller areas of eastern Nevada and southern Idaho (Fig. 1). Lake-core records show multiple cycles of lake formation and desiccation during the Quaternary (Eardley and Gvosdetsky, 1960; Eardley et al., 1973; Oviatt et al., 1999). During high-lake episodes the basin was occupied by a single body of water, but as changing climatic conditions caused the lake to recede below internal basin thresholds, the lake segmented into two large basins and several minor ones. Today, the GSL occupies the largest northern basin, and Sevier Lake occupies the largest southern basin (Fig. 1).

The hydrologic budget of the GSL is dominated by discharge from the Bear River, whereas the Sevier River dominates that of Sevier Lake (Waddell and Barton, 1980). Due to differences in provenance (the Bear River flows through volcanics and carbonates while the Sevier flows through sulfate-rich sedimentary rocks) the $^{87}Sr/^{86}Sr$ ratios (87-strontium/86-strontium) of these two rivers are also distinct. When Lake Bonneville was high, both the Bear and Sevier rivers (and many other smaller rivers and creeks) flowed into an integrated lake and should have produced a single $^{87}Sr/^{86}Sr$ ratio for lake waters, provided the lake was well mixed. As the lake level dropped and segmented at the Old River Bed threshold (1390 m) in the central part of the basin, the $^{87}Sr/^{86}Sr$ ratio of lake waters in the newly separated basins should have evolved in the direction of the $^{87}Sr/^{86}Sr$ ratio of their respective tributary rivers. These changes should in turn be reflected in the $^{87}Sr/^{86}Sr$ ratio of lake carbonates formed in the presence of these waters.

Our intent in this paper is to develop the $^{87}Sr/^{86}Sr$ ratio of lake carbonates ($^{87}Sr/^{86}Sr_{carbonate}$) as a new tool for constraining lake depth in

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the Bonneville basin paleolakes, similar to efforts by Benson and Peterman (1995) on the Lake Lahontan system in the western Great Basin. The $^{87}Sr/^{86}Sr_{carbonate}$ ratio appears to vary inversely with lake depth and volume, based on preliminary results from Quade (2000a) and Pedone et al. (2000). We propose that, by analyzing $^{87}Sr/^{86}Sr_{carbonate}$ ratios from shoreline carbonates from known lake elevations, we can develop a relationship that can be used to constrain lake elevations from similar analysis of carbonates in lake cores.

To help explain the causes for the variations observed in the $^{87}Sr/^{86}Sr$ ratios of the carbonates, we have constructed hydrologic models of the strontium (Sr) budget for the modern GSL and the Bonneville system. The expectation is that our model results will assist in distinguishing between climatic and nonclimatic causes for lake-level fluctuations. During the Quaternary the Bear River was diverted two or more times from the Bonneville basin to the Snake River drainage (Bouchard et al., 1998), and it has been suggested that these diversions may have been responsible for the rise of the lakes in Bonneville basin to their late Quaternary highstands. The large Sr flux and distinct $^{87}Sr/^{86}Sr_{river}$ ratio of the Bear River should make its partial diversion clearly visible in the lake carbonate record.

Lake-Level History

Previous lake cycles have been documented in the Bonneville basin (Eardley and Gvosdetsky, 1960; Eardley et al., 1973; Oviatt et al., 1999) from cores where multiple cycles of lake formation and desiccation are recognized. Other work (Scott et al., 1983; McCoy, 1987; Oviatt et al., 1987; Machette et al., 1992; Kaufman et al., 2001) has shown that two of the previous lake cycles, the Little Valley cycle (~130–160 cal ka) and the Dam cycle (~59 ± 5 cal ka) probably correspond to marine oxygen isotope stages 6 and 4, respectively (Fig. 2). Shorelines associated with these and other older lake cycles have not been identified, making exact lake depth determination at these times uncertain (Oviatt and Currey, 1987).

The most recent major transgression and regression of Lake Bonneville spanned ~30–12 ^{14}C ka (Oviatt et al., 1992; Currey and Oviatt, 1985). About 30 ^{14}C ka Lake Bonneville began to rise from levels close to that of the modern GSL. During this rise the lake oscillated at ~22–20 ^{14}C ka, producing the Stansbury shoreline complex (Fig. 2) between 1347 and 1378 m (Oviatt et al., 1990). Following formation of the Stansbury shoreline(s), Lake Bonneville rose to its highest level of 1552 m by ~15.5 ^{14}C ka (the Bonneville stage). At this elevation the lake overflowed

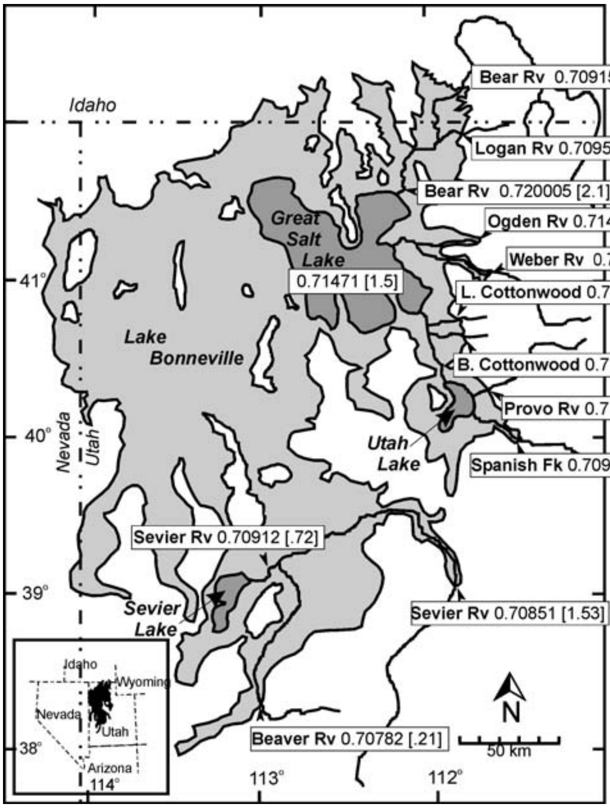

Figure 1. Study area showing locations of river sample collection sites. Area occupied by Lake Bonneville at its maximum (the Bonneville stage) is shaded. Boxes contain river name and associated $^{87}Sr/^{86}Sr_{water}$ ratio and Sr concentration in ppm.

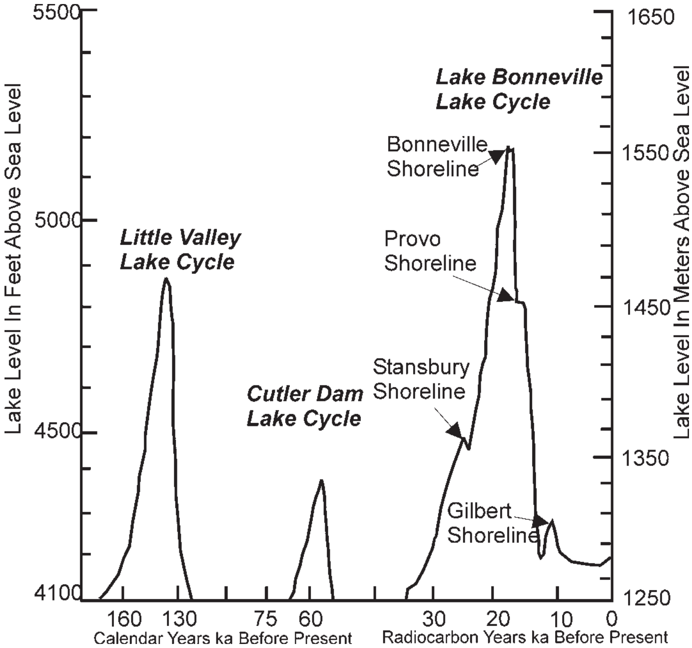

Figure 2. Schematic diagram of reconstructed lake levels in the Bonneville basin during the last 200 ka. Note breaks in temporal scale. Little Valley and Cutler Dam lake cycles ages in calendar ka, Bonneville lake cycle in ^{14}C ka years. Modified from Machette et al. (1992).

intermittently for ~500–1000 yr near Zenda, Idaho, into the Snake River basin, until catastrophic failure of the alluvial threshold dropped the lake level by ~100 m during the Bonneville flood at ~14.5 ^{14}C ka. Immediately following the Bonneville flood, the lake level stabilized at 1450 m by the overflow at the Red Rock Pass bedrock threshold, and the Provo shoreline formed. The lake regressed rapidly from the Provo shoreline sometime between 14 and 12 ^{14}C ka, possibly to levels lower than the modern GSL. As the lake level receded past 1390 m, it separated into two basins (Fig. 3), forming Lake Gunnison in the southern basin. Lake Gunnison apparently continued to overflow along the Old River Bed into the northern basin until ~10 ^{14}C ka (Fig. 4) (Oviatt, 1988). The lake remnant occupying the northern basin transgressed to the Gilbert shoreline (~1300 m) ~10.3 ^{14}C ka (Currey, 1990; Oviatt et al., 2001) before dropping to levels <1287 m throughout the Holocene.

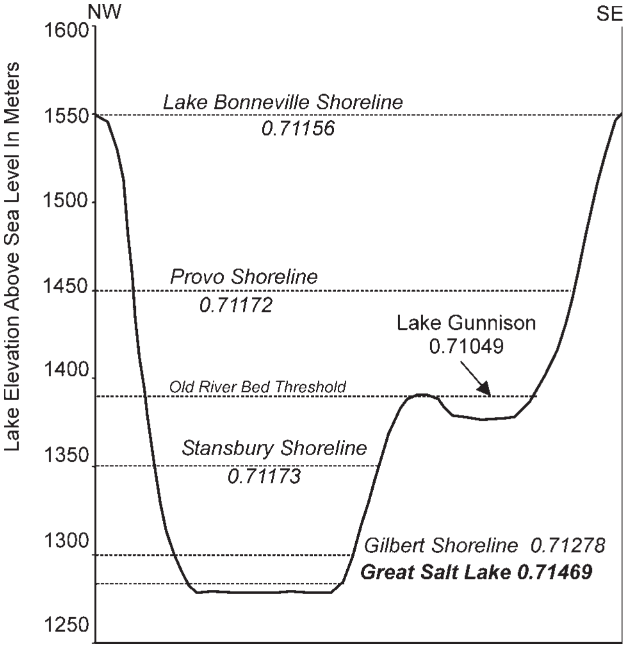

Figure 3. Schematic diagram, not to horizontal scale, showing the Bonneville basin and approximate paleo-shoreline elevations in meters. The average of $^{87}Sr/^{86}Sr$ ratios from all samples at each stage shown at each shoreline altitude. Note the Old River Bed threshold at ~1390 m, which caused the lake to segment as lake level dropped in the latest Pleistocene.

Strontium Isotopes

Large amounts of calcium carbonate (calcite and aragonite) were precipitated in the paleolakes of the Bonneville system as tufas, marls and shells of mollusks and ostracodes. Strontium is found in trace (10s–100s ppm) amounts in these carbonates (and in bioapatites, such as fish bone) since Sr substitutes readily for calcium in the structure of both aragonite and calcite. Two stable isotopes of Sr, ^{87}Sr, and ^{86}Sr are commonly used as tracers in a wide variety of low-temperature geologic contexts (e.g., Banner, 1995; Quade et al., 1997; Capo et al., 1998) The ^{87}Sr to ^{86}Sr ratio in lacustrine carbonate ($^{87}Sr/^{86}Sr_{carbonate}$) provides a useful proxy for changes of $^{87}Sr/^{86}Sr$ ratios of lake waters through time. Because of similar atomic weights, ^{87}Sr and ^{86}Sr do not fractionate measurably during natural chemical reactions or physical transformations. This means that the $^{87}Sr/^{86}Sr$ ratio of any lacustrine carbonate or bioapatite will be the same as the $^{87}Sr/^{86}Sr$ ratio of the water ($^{87}Sr/^{86}Sr_{water}$) in which it formed.

In order to use $^{87}Sr/^{86}Sr_{carbonate}$ ratios as an indicator of lake level and/or river diversion, the following conditions must be satisfied:

(1) The $^{87}Sr/^{86}Sr$ ratios of lake water must be a well-mixed reflection of the differing river and ground-water sources flowing into that lake.

(2) The major tributaries of the lake must have strongly contrasting $^{87}Sr/^{86}Sr_{water}$ ratios.

(3) The lake must segment as lake level decreases, partially or completely isolating subbasins fed by rivers with differing $^{87}Sr/^{86}Sr_{water}$ ratios.

(4) Recycling of carbonates and other salts during each new lake cycle must be limited.

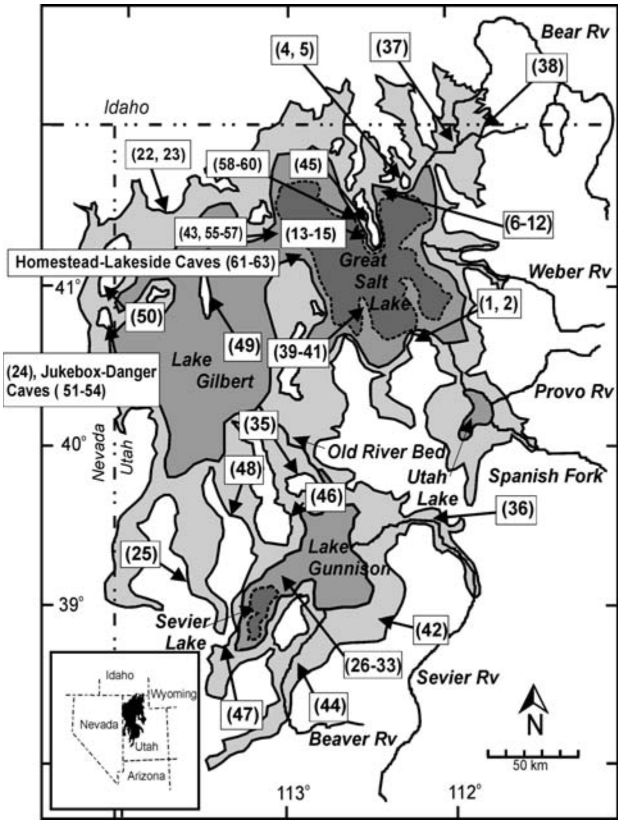

Figure 4. Study area showing approximate shorelines of Lakes Bonneville, Gilbert, Gunnison, and the GSL. Lake Bonneville at its maximum shown shaded; GSL shown with dashed line. Boxes contain site number in parentheses.

(5) The Sr isotopic composition of lacustrine carbonates must not undergo alteration after deposition.

METHODS

Field Methods

Sampled carbonates consisted of mollusks and tufas, including tufa heads and thick carbonate cements on beach gravels (Table 1). Tufa heads and gravel cements were collected from at or just below (0–10 m) major paleolake shorelines. We attempted to collect tufa samples from the protected areas (shallow caves or under ledges) whenever possible to avoid weathered samples. Fossil fish vertebrae were obtained from pack-rat middens found in caves by Dr. Dave Rhode and in excavations at Homestead Cave. In the Sevier basin, we measured and described a section from lake sediments along the Sevier River and obtained gastropods and ostracodes. Living gastropods (Table 1, sample 7) were collected from spring-fed marshes along the northern edge of GSL near the Public Shooting Grounds.

We collected water samples during 1995–1996 and again in July 2001 from all major tributaries entering the Bonneville basin, near the elevation where the modern rivers pass through the Bonneville shoreline (Fig. 1). The Bear River was analyzed in greater detail by collecting samples along most of its length. Surface water samples were also collected from various sites around the GSL (Table 2). We collected 50 ml water samples, which were passed through disposable 0.2 µm glass syringe filters and stored in sealed acid-washed polyethylene bottles.

Lab Methods

Tufas and cements were broken into ~200 mg pieces and then handpicked for the densest fragments. These were reduced to ~100 mg by etching with 10% HCl to reduce the likelihood of secondary cement contamination. Where required, shells were sieved from sediments, then washed in milli-Q (18 MΩ [mega-ohms]) water. Multiple shells were combined for a single Sr analysis. After grinding to powder, all carbonates were pretreated with 10% NaOCl to remove organic matter. Approximately 50 mg of carbonate from each sample was crushed, soaked in 2% NaOCl for about one hour to remove organic matter and dissolved in doubly distilled 1 M acetic acid, placed in an ultrasonic bath for 0.5 h and then allowed to stand for ~8 h. This mild acid treatment was used to prevent Sr leaching from silicate impurities in the carbonates (Asahara et al., 1995).

TABLE 1. SUMMARY OF ^{87}Sr/^{86}Sr ANALYSIS OF BONNEVILLE BASIN CARBONATES AND BIOAPATITES

Sample number/ Lake Phase	^{87}Sr/^{86}Sr (mean ± 1 SE)	Sample material	Sample location
Bonneville Stage			
1b	0.71153 ± 1	Tufa	Oquirrh Mountains
5	0.71149 ± 1	Tufa	Little Mountain
15	0.71151 ± 1	*Stagnicola*	Promontory Mountains
23	0.71147 ± 1	Tufa	Grouse Creek Mountains
35	0.71160 ± 2	marl	Old River Bed
36	0.71131 ± 1	marl	High Crossing of Sevier River
37	0.71184 ± 2	mollusk indet.	Cutler Dam
38	0.71174 ± 1	mollusk indet.	Cache Valley
26	0.71125 ± 1	ostracodes	Sevier River Section
Average	***0.71153 ± 198***		
Provo stage			
2	0.71183 ± 1	Tufa	Oquirrh Mountains
4c	0.71189 ± 1	Tufa	Little Mountain
4n	0.71159 ± 1	Tufa	Little Mountain
4t	0.71186 ± 1	Tufa	Little Mountain
22c	0.71175 ± 1	Tufa	Grouse Creek Mountains
22t	0.71185 ± 1	Tufa	Grouse Creek Mountains
24	0.71185 ± 1	Tufa	Wendover
25c	0.71159 ± 1	Tufa	Confusion Range
25t	0.71185 ± 1	Tufa	Confusion Range
39	0.71177 ± 1	Tufa	Stansbury Mountains
40	0.71171 ± 1	Tufa	Stansbury Mountains
41	0.71180 ± 1	Tufa	Stansbury Mountains
42	0.71159 ± 2	Tufa	Tabernacle Hill
43	0.71174 ± 1	Tufa	Homestead Cave
44	0.71153 ± 2	Tufa	Table Mountain
45	0.71186 ± 1	Tufa	Promontory Mountains
46	0.71183 ± 1	Tufa	Smelter Knoll
47	0.71149 ± 1	Tufa	Pot Mountains
48	0.71158 ± 2	Tufa	Tule Valley
49	0.71195 ± 1	Tufa	Newfoundland Mountains
55	0.71174 ± 2	*Stagnicola*	Homestead Cave
56	0.71182 ± 2	*Stagnicola*	Homestead Cave
57	0.71175 ± 1	mollusk indet.	Homestead Cave
Average	***0.71175 ± 13***		
Stansbury Stage/Oscillation			
3	0.71198 ± 1	Tufa	Oquirrh Mountains
66	0.71178 ± 1	Tufa	Stansbury Mountains
67	0.71144 ± 1	Tufa	Crater Island
Average	***0.71173 ± 27***		
70[†]	0.71200 ± 2	Tufa	Lakeside Cave (1295 m)
Post-Provo regression			
51[‡]	0.71188 ± 1	Tufa	Danger Cave (1325 m)
52[‡]	0.71173 ± 2	Tufa	Danger Cave(1325 m)
54	0.71159 ± 1	Tufa	Jukebox Cave (1338 m)
50	0.71142 ± 5	fish vertebrae	Raven Cave (midden)
53	0.71148 ± 1	fish vertebrae	Triple Barrel Cave (midden)
Gilbert Stage			
58	0.71203 ± 1	Tufa	Promontory Mountains
59	0.71202 ± 2	Tufa	Promontory Mountains
60	0.71194 ± 1	Tufa	Promontory Mountains
61	0.71278 ± 1	fish vertebrae	Homestead Cave
62	0.71264 ± 3	fish vertebrae	Homestead Cave
63	0.71256 ± 3	fish vertebrae	Homestead Cave
64a	0.71268 ± 3	fish vertebrae	Homestead Cave
64b	0.71285 ± 3	fish vertebrae	Homestead Cave
64c	0.71247 ± 3	fish vertebrae	Homestead Cave
Average	***0.71244 ± 35***		
6	0.71371 ± 1	*Pygulopsis*	Public Shooting Grounds (SR 83)
8	0.71387 ± 1	*Pygulopsis*	Public Shooting Grounds (SR 83)
9	0.71341 ± 1	*Pygulopsis*	Public Shooting Grounds (SR 83)
10	0.71265 ± 2	*Stagnicola*	Public Shooting Grounds (SR 83)
11	0.71294 ± 1	*Stagnicola*	Public Shooting Grounds (SR 83)
12	0.71285 ± 1	shell	Public Shooting Grounds (SR 83)
Lake Gunnison			
27	0.70992 ± 1	*Anodonta, Pygulopsis*	Sevier River Section
28	0.70982 ± 1	*Stagnicola*	Sevier River Section
29	0.70970 ± 1	*Anodonta*	Sevier River Section
31	0.70997 ± 1	*Planorbis, Anodonta*	Sevier River Section
32	0.71002 ± 1	*Physa*	Sevier River Section
33	0.70930 ± 1	*Planorbis*	Sevier River Section
65[§]	0.71049 ± 2	*Anodonta*	Sevier Lake Basin
Cutler Dam Cycle			
68	0.71207 ± 2	shell	Cutler Dam
Little Valley Cycle			
13	0.71156 ± 1	*Pygulopsis*	Promontory Mountains
14	0.71165 ± 1	*Pygulopsis*	Promontory Mountains
69	0.71178 ± 2	shell	Cache Valley
Great Salt Lake			
7	0.71261 ± 1	*Stagnicola*	Public Shooting Grounds (SR 83)

[†] 21,390 ± 170 ^{14}C yr B.P. (AA-20955).

[‡] 13,245 ± 80 ^{14}C ^{14}C yr B.P. (AA-20954).

[§] 11,270 ± 110 ^{14}C yr B.P., from Oviatt (1988).

TABLE 2. SUMMARY OF STRONTIUM ANALYSIS OF RIVERS AND LAKES

Sample number	^{87}Sr/^{86}Sr	Sr (ppm)	Sample location	Date collected
1	0.70851 ± 6	1.53	Sevier River	7-08-01
2	0.70857 ± 1	1.44	Sevier River, Yuba State Park	7-08-01
31	0.70912 ± 1	0.72	Sevier River, Gunnison section	7-13-01
32	0.70782 ± 1	0.21	Beaver River	7-13-01
3	0.70937 ± 1	0.40	Spanish Fork	7-08-01
4	0.71020 ± 1	0.37	Provo River	7-08-01
5	0.71027 ± 1	1.80	Jordon River	7-08-01
6	0.71022 ± 1	0.11	Little Cottonwood Creek	7-08-01
7	0.71258 ± 1	0.20	Big Cottonwood Creek	7-08-01
9	0.70990 ± 1	0.34	Weber River	7-08-01
21	0.70957 ± 1	0.13	Logan River	7-09-01
10	0.71426 ± 1	0.13	Ogden River	7-08-01
11	0.71910 ± 1	0.71	Malad River	7-09-01
19	0.71090 ± 1	0.16	Little Bear River, Hyrum Reservoir	7-09-01
20	0.71115 ± 1	0.08	Blacksmith Fork	7-09-01
12	0.71478 ± 1	0.86	Bear River Refuge	7-09-01
13	0.71661 ± 1	2.20	Bear River Refuge	7-09-01
14	0.72000 ± 1	2.10	Bear River, Corrine	7-09-01
15	0.71395 ± 1	0.73	Bear River, Bear River City	7-09-01
16	0.72341 ± 1	36.00	Crystal Hot Springs	7-09-01
17	0.71327 ± 1	0.62	Bear River, Deweyville	7-09-01
18	0.71367 ± 1	0.67	Bear River, Riverside	7-09-01
22	0.71225 ± 1	0.13	Bear River, Smithfield	7-09-01
23	0.71463 ± 1	0.68	Bear River, Preston, Id	7-09-01
24	0.70915 ± 1	0.44	Bear River, Oneida Narrows	7-09-01
25	0.70900 ± 1	0.33	Bear River, Grace, Id	7-09-01
26	0.70903 ± 1	0.35	Bear River, Georgetown, Id	7-09-01
27	0.70918 ± 1	0.30	Bear Lake outflow	7-09-01
28	0.71282 ± 1	1.90	GSL, Public Shooting Grounds	7-10-01
29	0.71464 ± 1	1.20	GSL, North of causeway	7-11-01
30	0.71472 ± 1	2.90	GSL, South of causeway	7-11-01
8	0.71471 ± 1	1.50	GSL, Great Salt Lake State Park	7-08-01
	0.72190		Bear River, Corrine†	9-2-66
	0.71398 ± 2		Bear Biver, Corrine	10-94
	0.71290		Weber River†	8-30-66
	0.71002 ± 2		Weber River	10-94
	0.74153 ± 2		Ogden River	10-94
	0.72060 ± 3		Jordan River	10-94
	0.70933 ± 2		Spanish Fork	10-94
	0.70703 ± 3		Sevier River	10-94
	0.70785 ± 3		Beaver River	10-94
	0.71740		Great Salt Lake†	5-66
	0.71350		Western Desert†	5-66

†Jones and Faure (1972).

Sufficient Sr was present in single fish vertebrae for analysis. Ground fish bone was pretreated with 2% NaOCl followed by 1 M acetic acid (30 min each at room temperature), then dissolved in ~50% ultrapure nitric acid.

Acid supernatants from dissolution of carbonates and fish bone and water samples were evaporated, redissolved in 2.5 N HCl, centrifuged, and aliquots drawn off for Sr separation using either cation-exchange or ion-specific resins. ^{87}Sr/^{86}Sr ratios for this study and in Bouchard (1997) were measured on a Micromass Sector 54 thermal ionization mass spectrometer at the University of Arizona. The ^{87}Sr/^{86}Sr ratios were checked by analysis of the NBS-987 standard on each turret run, which yielded a mean ratio of 0.710236 ± 0.000010 (±1 SE; n = 11; 72–75 ratios per sample). The ^{87}Sr/^{86}Sr ratios were normalized for variable mass discrimination to a ^{86}Sr/^{88}Sr ratio of 0.1194. All uncertainties are reported as ± 1SE. Strontium concentrations [Sr], expressed throughout the paper in ppm (±3%), were measured at the University of Arizona with atomic absorption spectroscopy.

RESULTS

Petrographic thin sections of sampled tufas revealed that, in general, they contained abundant primary textures with little or no evidence of secondary addition or alteration. Most tufas are spongy and porous with a radiating fabric and a popcorn structure overall. In thin section (Fig. 5A and 5B), clotted micrite (Demicco and Hardie, 1994) and microspar are intermingled with spar around tubular molds, some of which are open or filled with calcite. These molds generally range in length from tens of micrometers to 1 mm but may be up to several millimeters long. The calcite spar tends to radiate outward and have euhedral terminations on crystals that can be tens of micrometers long. Larger voids are lined with a combination of clotted micrite and spar, in intergrowth patterns that show both textures developed contemporaneously. In hand sample, the tufas are consistent in texture with those typically described from lacustrine environments (Demicco and Hardie, 1994; Ku et al., 1998). The sampled tufas show little or no evidence of post-lacustrine cementation or alteration.

The three samples from the Little Valley cycle (130–160 ka) obtained from the Little Valley in the Promontory Mountains (McCoy, 1987) yielded ^{87}Sr/^{86}Sr$_{\mathrm{carbonate}}$ ratios ranging from 0.71156 to 0.71178 and produced an average ^{87}Sr/^{86}Sr$_{\mathrm{carbonate}}$ ratio of 0.71166 ± 0.00011. The sample from the Cutler Dam cycle (59 ± 5 ka) exposed near Cutler Dam produced an ^{87}Sr/^{86}Sr$_{\mathrm{carbonate}}$ ratio of 0.71207 (Bouchard, 1997).

Most of our analyses come from materials associated with the major stages of the Bonneville cycle. Three tufa samples from the Stansbury shoreline (1347–1378 m; 22–20 ^{14}C ka) at Crater Island and in the Stansbury Mountains and the Oquirrh Mountains produced ^{87}Sr/^{86}Sr$_{\mathrm{carbonate}}$ ratios ranging from 0.71144 to 0.71198 and a mean of 0.71173 ± 0.00027. A single tufa sample from Lakeside Cave (1295 m) yielded an ^{87}Sr/^{86}Sr$_{\mathrm{carbonate}}$ ratio of 0.71200 and date of 21,390 ± 170 ^{14}C yr B.P. (Table 1). Nine carbonates from the Bonneville stage (1550 m; 15.5–14.5 ^{14}C ka), consisting of tufas, mollusk shells, and deep-water marls were analyzed. They yielded ^{87}Sr/^{86}Sr$_{\mathrm{carbonate}}$ ratios ranging from 0.71131 to 0.71184 and a mean of 0.71153 ± 0.00019 (Table 1). The two marls come from the Old River Bed described in Gilbert (1890) and Oviatt (1987) and from the High Crossing of the Sevier River and are inferred to be deep-water deposits from the Bonneville stage. The three shell samples were collected from Bonneville shoreline deposits. Twenty-three tufa and mollusk samples (Table 1) from the Provo stage (1450 m; 14.0–14.4 ^{14}C ka) yielded ^{87}Sr/^{86}Sr$_{\mathrm{carbonate}}$ ratios ranging from 0.71149 to 0.71195, with an average ^{87}Sr/^{86}Sr$_{\mathrm{carbonate}}$ ratio of 0.71175 ± 0.00013.

Samples dating to the post-Provo stage regression include fish vertebrae and tufas. The fish vertebrae, obtained from pack-rat middens dated to 13,470 ± 100 ^{14}C ka at Triple Barrel and to 12,910 ± 50 ^{14}C ka at Raven Cave (Rhode and Madsen, 1995), produced ^{87}Sr/^{86}Sr$_{\mathrm{bioapatite}}$ ratios ranging from 0.71142 to 0.71148. Tufas from Danger Cave (1325 m) dated at 13,245 ± 80 ^{14}C yr B.P. (Table 1, footnote) and from Jukebox Cave (1338 m) yielded ^{87}Sr/^{86}Sr$_{\mathrm{bioapatite}}$ ratios ranging from 0.71159 to 0.71188 (Table 1).

Fifteen samples possibly associated with the Gilbert stage (1295 m; ~10.3 ^{14}C ka) or some

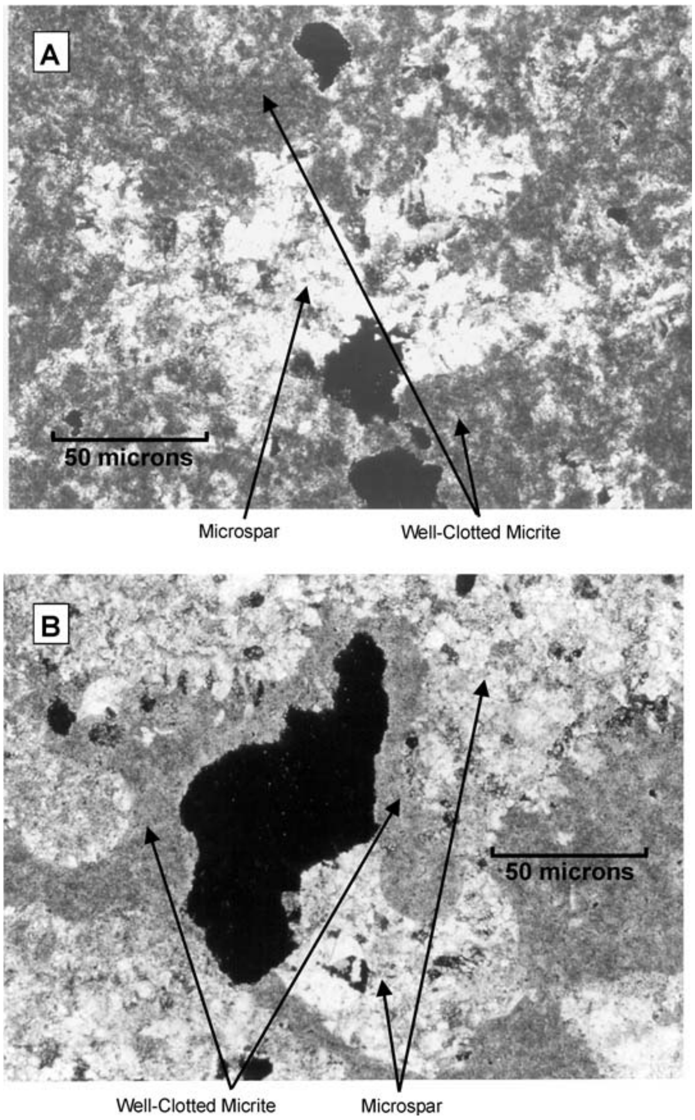

Figure 5. (A and B) Photographs of tufa thin section showing void surrounded by a combination of clotted micrite and spar; these patterns imply that both textures developed contemporaneously and show no sign of recrystallization.

other late-lake stage in the GSL basin produced a range of $^{87}\text{Sr}/^{86}\text{Sr}_{\text{carbonate}}$ ratios from 0.71194 to 0.71341. Three tufas from at or just below the Gilbert shoreline produced $^{87}\text{Sr}/^{86}\text{Sr}_{\text{carbonate}}$ ratios ranging from 0.71194 to 0.71203. Six fish vertebrae from middens in Homestead Cave dated (from associated rat feces) between 11.3 and 10.2 ^{14}C ka (Broughton et al., 2000; Quade, 2000b) yielded $^{87}\text{Sr}/^{86}\text{Sr}_{\text{bioapatite}}$ ratios ranging from 0.71256 to 0.71278. Combined tufa and fish samples produced an average $^{87}\text{Sr}/^{86}\text{Sr}_{\text{carbonate}}$ ratio of 0.71244 ± 0.00035 (Fig. 4). Six mollusk shell samples, all from Gilbert-related deltaic and marsh deposits of the Bear River, yielded $^{87}\text{Sr}/^{86}\text{Sr}_{\text{carbonate}}$ ratios ranging from 0.71265 to 0.71387. These values are elevated compared to those from more open-lake tufas and fish, probably due to the local influence of the Bear River and discharging springs.

In the southern basin we analyzed samples from the Lake Gunnison shoreline and from a stratigraphic section interpreted by Oviatt (1988; locality 4) to record the transition from Lake Bonneville to Lake Gunnison (Fig. 6). The shoreline sample was a single *Anodonta* valve that yielded an $^{87}\text{Sr}/^{86}\text{Sr}_{\text{carbonate}}$ ratio of 0.71049. The base of the sampled section (Fig. 6, Unit I) consists of gray, marly, partly reworked lake sediments of the Bonneville regressive phase, which contain lacustrine ostracodes that yielded $^{87}\text{Sr}/^{86}\text{Sr}_{\text{carbonate}}$ ratios of 0.71125 (Fig. 6, sample 26). These are overlain by ~1.5 m of sediment interpreted to represent deposition in Lake Gunnison (Units E–H). These consist of light gray clayey silt, interlayered with silty yellow sand containing abundant whole mollusk shells and fragments yielding $^{87}\text{Sr}/^{86}\text{Sr}_{\text{carbonate}}$ ratios ranging from 0.70992 (Fig. 6, sample 27) near the bottom of the unit to 0.70970 (Fig. 6, sample 29) near the top. These are overlain by ~3 m of alluvium deposited by the Sevier River (Oviatt, 1988), consisting of interbedded silty clays and fine to medium sands that are well to poorly sorted. Alluvial and eolian units (Units A and B) capping this section contain very fragmented and likely reworked mollusks that produced $^{87}\text{Sr}/^{86}\text{Sr}_{\text{carbonate}}$ ratios of 0.70997 (Fig. 6, sample 31).

We analyzed all the major tributaries of the Bonneville basin for $^{87}\text{Sr}/^{86}\text{Sr}_{\text{river}}$ ratios and [Sr] in order to model Sr budgets of the lake system at its various stages. Discharge into the northern basin is dominated by the Bear River, which shows considerable downstream variation. Where the Bear River passes the Bonneville shoreline near Grace, Idaho, the $^{87}\text{Sr}/^{86}\text{Sr}_{\text{river}}$ ratio is 0.70900. At Corrine, Utah, near the inlet to the GSL, the $^{87}\text{Sr}/^{86}\text{Sr}_{\text{river}}$ ratio increases to 0.72000 (Fig. 7). This increase in $^{87}\text{Sr}/^{86}\text{Sr}_{\text{carbonate}}$ ratios is due to spring and ground-water additions to the Bear River, such as Crystal Hot Springs, which yielded a $^{87}\text{Sr}/^{86}\text{Sr}_{\text{spring}}$ ratio of 0.72341, and [Sr] of 36 ppm (Fig. 7). Along the same transect, [Sr] of the Bear River ranges from [0.30] at Bear Lake outflow to [2.1] at Corrine, Utah. Other measured (Table 2) tributaries that provide significant discharge into the GSL include the Weber, Ogden, and Provo rivers. Less significant tributaries included in the sample are Spanish Fork, Big Cottonwood Creek, Little Cottonwood Creek, the Logan River, and others.

Discharge in the southern basin is dominated by the Sevier River with an $^{87}\text{Sr}/^{86}\text{Sr}_{\text{river}}$ ratio of 0.70851, [1.53]. The Beaver River, $^{87}\text{Sr}/^{86}\text{Sr}_{\text{river}}$ 0.70782, [0.21], only provides discharge during times of high flow, due to extensive irrigation diversion.

The GSL was analyzed at several nearshore locations. Sheltered marsh-water sites include the Public Shooting Grounds with an $^{87}\text{Sr}/^{86}\text{Sr}_{\text{lake}}$ ratio of 0.71282 and the Bear River Refuge with an $^{87}\text{Sr}/^{86}\text{Sr}_{\text{lake}}$ ratio of 0.71661 (Table 2, samples 12, 13, 28). Three other sites were from areas of open shoreline such as the Great Salt Lake State Park in the southern basin and from the northern and southern sides of the causeway near the southern tip of the Promontory Mountains; these yielded $^{87}\text{Sr}/^{86}\text{Sr}_{\text{lake}}$ ratios ranging from 0.71464 to 0.71478 (samples 8, 29, 30).

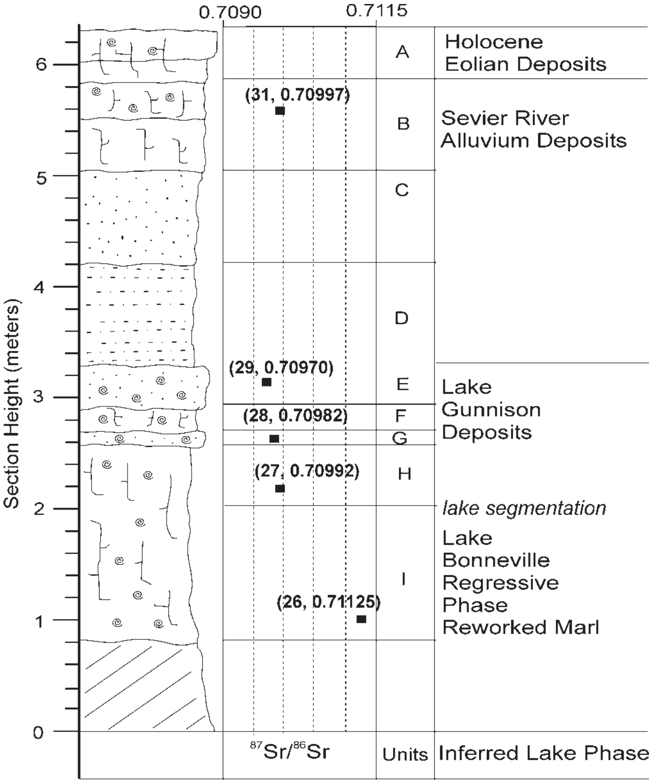

Figure 6. Stratigraphic section exposed along the Sevier River, near that reported in Figure 4 of Oviatt (1988). ^{87}Sr/^{86}Sr ratios (black squares) of fossil mollusks (see Table 1). Stratigraphic units and inferred lake phases following Oviatt (1988). The marked shift in ^{87}Sr/^{86}Sr ratios at ~2 m coincides with lake segmentation as lake level dropped below 1390 m and Lake Gunnison occupied the Sevier Lake basin. See Figure 9 for expanded view of ^{87}Sr/^{86}Sr evolution of paleo-lake waters.

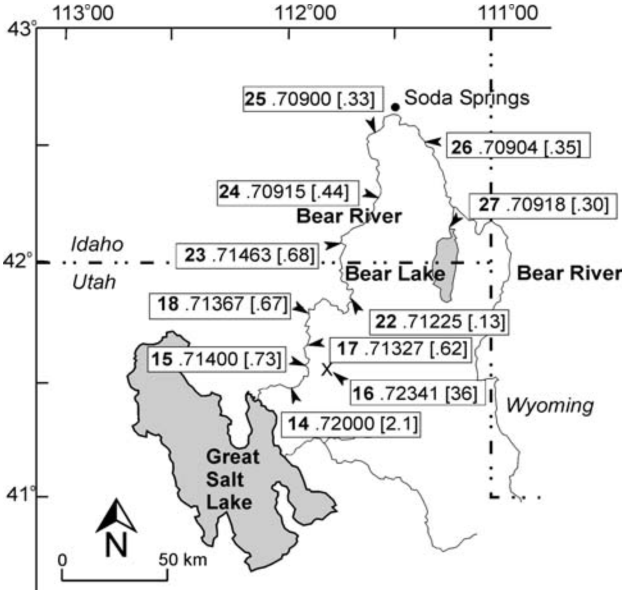

Figure 7. Map of Bear River (map adapted from Bouchard et al., 1998), showing approximate sample locations and analytical results from this study. Boxes show sample number in bold, ^{87}Sr/^{86}Sr$_{water}$ ratios, and Sr concentration in ppm in brackets. The Crystal Hot Springs site is noted with an X. Note the sharp increase in ^{87}Sr/^{86}Sr$_{water}$ ratios between sites 24 and 23, probably due to addition of groundwater with high ^{87}Sr/^{86}Sr$_{water}$ ratios and high [Sr].

DISCUSSION

We examined the mixing of Sr in the lake as a function of lake level by a comparison of the ^{87}Sr/^{86}Sr$_{carbonate}$ ratios of individual sites at the Bonneville and Provo stages to the average ^{87}Sr/^{86}Sr$_{carbonate}$ ratio for each respective stage. We found that Bonneville-stage sites with ^{87}Sr/^{86}Sr$_{carbonate}$ ratios above and below the average (0.71153) are scattered randomly throughout the basin (Table 1 and Fig. 4). This indicates that the waters of the lake were well mixed with respect to Sr during the highest stage.

We also compared the ^{87}Sr/^{86}Sr$_{carbonate}$ ratios of all the Provo stage sites to the average Provo stage ratio of 0.71175 (Table 1 and Fig. 4). In general, sites with ^{87}Sr/^{86}Sr$_{carbonates}$ ratios above the average come mainly from the northern GSL basin, whereas sites with ^{87}Sr/^{86}Sr$_{carbonate}$ ratios lower than the stage average are found in the southern Sevier basin. This contrast makes sense given the higher ^{87}Sr/^{86}Sr$_{water}$ ratio of the Bear River and northern groundwater compared to that of the Sevier River, and indicates that lake waters at the Provo stage are not as completely mixed as waters at the Bonneville stage, perhaps due to topographic sills that inhibited complete mixing across the individual basins. Despite the modest variability, ^{87}Sr/^{86}Sr$_{carbonate}$ ratios of Provo-age tufas at all locations are still clearly distinguishable from those of low (<1325 m) lake levels.

Our analysis of ^{87}Sr/^{86}Sr$_{carbonate}$ ratios for the northern basin yielded a nonlinear inverse relation between ^{87}Sr/^{86}Sr ratios and lake elevation (Fig. 8). The range of ^{87}Sr/^{86}Sr$_{carbonate}$ ratios for the Bonneville (0.71153 ± 0.00019), Provo (0.71175 ± 0.00013), and Stansbury (0.71173 ± 0.00027) shorelines display little, if any, change over an elevation difference of ~200 m (1550–1350 m). This similarity shows that ^{87}Sr/^{86}Sr ratios are essentially invariant across the mid- to high-lake levels. The results from the Stansbury tufas are interesting because the Stansbury shoreline complex from 1347 to 1378 m lies below the Old River Bed at 1390 m, the elevation below which the high lake would have segmented. The low ^{87}Sr/^{86}Sr$_{carbonate}$ ratios from the Stansbury tufas in the northern basin therefore indicate that the southern basin must have overflowed into the northern basin at that time, a conclusion supported by stratigraphic evidence (Oviatt, 1987).

From the Stansbury shoreline(s) (~1347–1378 m) to the Gilbert shoreline (~1300 m) to the GSL (~1280 m), the ^{87}Sr/^{86}Sr ratios change dramatically from averages of 0.71173 ± 0.00027 (Stansbury) to 0.71244 ± 0.00035 (Gilbert tufas and fish) to 0.71469 ± 0.00004 (GSL). The shift toward higher ^{87}Sr/^{86}Sr$_{carbonate}$ ratios associated with the Gilbert shoreline is further constrained between 1300 and 1325 m based on our results from Danger Cave (1325 m; 0.71173–0.71188) (Table 1).

The results from Lakeside Cave tufa at 1294 m, if dated correctly, may yield a new constraint on the magnitude of the Stansbury oscillation. The ^{87}Sr/^{86}Sr$_{\text{carbonate}}$ ratio of 0.71200 is consistent with the low elevation (1294 m) of the cave at or near the Gilbert shoreline (1300 m in this area). The date of the tufa at 21,390 ^{14}C yr B.P. falls within the age range estimated by Oviatt (1988) for the Stansbury oscillation, but suggests that the oscillation was as much as twice the amplitude of the previous ~45 m estimate. A key uncertainty is with the dating of the tufa, as the magnitude of the ^{14}C reservoir effect is unknown for this stage of the lake.

The ^{87}Sr/^{86}Sr$_{\text{bioapatite}}$ ratios of fish remains from cave middens provide some new constraints regarding the nature and timing of post-Provo stage lake declines, a thinly documented period of the lake history. The remains come from a variety of freshwater fish harvested from Lake Bonneville by raptors living in the caves. The low ^{87}Sr/^{86}Sr$_{\text{bioapatite}}$ ratios (0.71142–0.71148) of Triple Barrel and Raven Cave fish show that the lake was no lower than 1325 m (the elevation of Danger Cave, see above) at 13,470 and 12,190 ^{14}C yr B.P. This would appear to constrain the pre–Gilbert-age, near-drying of the lake suggested by Currey and Oviatt (1985) and Oviatt et al. (1992) to after 12,190 ^{14}C yr B.P.

Fish remains from Homestead Cave (Fig. 1; 1406 m) (discussed also in Broughton et al., 2000) offer an important new perspective on lake-level changes around the time of the Gilbert stage. The fish-bearing layers are well dated, contain 11 species of fish (Madsen, 2001) and show that an intermittently freshwater lake must have existed within the raptor foraging radius (6–10 km) of the cave between 11.3 and ~10.3 ^{14}C ka B.P. The ^{87}Sr/^{86}Sr$_{\text{bioapatite}}$ ratios of the six fish remains analyzed by us fall in a narrow range of 0.7125 and 0.7129 (Quade, 2000a; Table 1). These ratios overlap those from carbonates of the Gilbert stage from elsewhere in the basin. Although the lake from which the fish came was shallow (around 1295 m), it was also at times very fresh and cold, based on the types of fish present (Madsen, 2001). This points to major pulse(s) of fresh water entering the basin during the latest glacial that created transiently freshwater lakes capable of supporting large fish populations.

We tested the newly developed relationship between ^{87}Sr/^{86}Sr$_{\text{carbonate}}$ and lake level on a stratigraphic section with a known history in the Sevier basin. We analyzed carbonates from deposits along the Sevier River previously

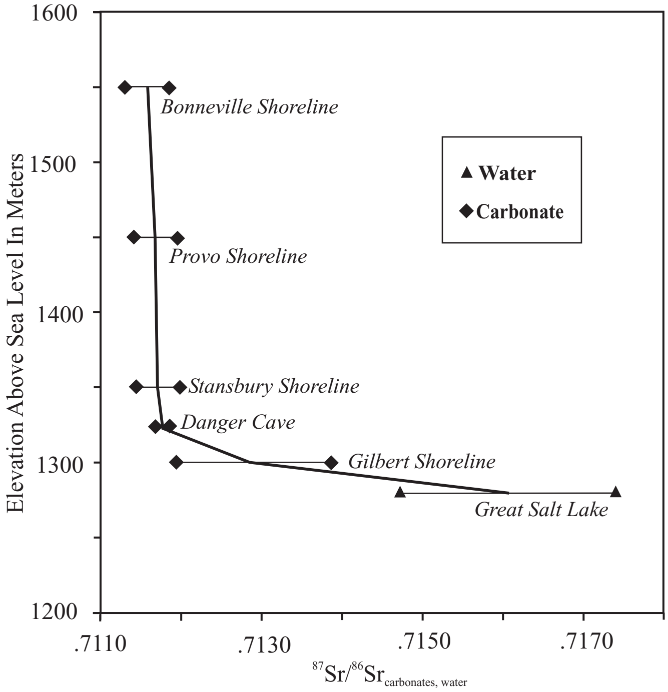

Figure 8. Diagram showing the inverse relationship between ^{87}Sr/^{86}Sr ratios (of water and carbonate) and lake elevation. The ranges of ^{87}Sr/^{86}Sr ratios overlap at elevations above 1325 m, but below 1325 m the ^{87}Sr/^{86}Sr ratios change dramatically.

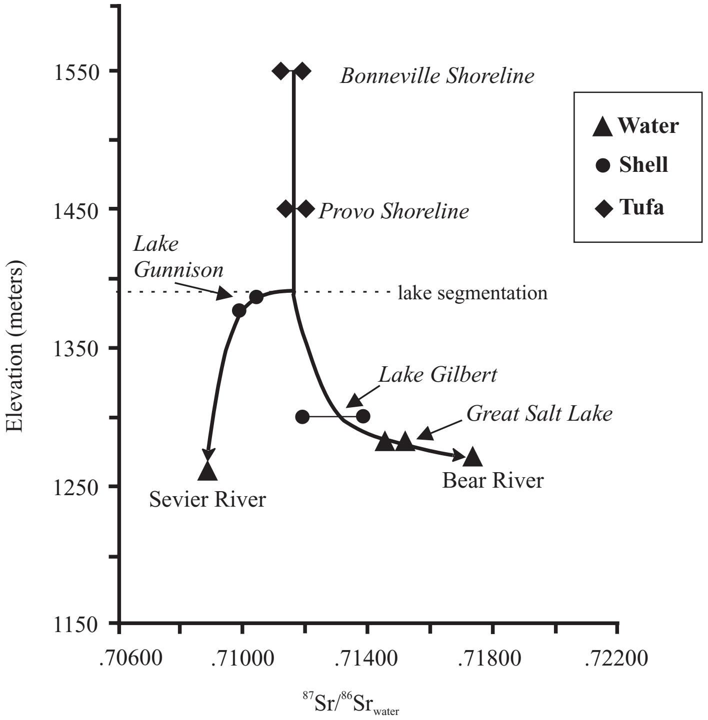

Figure 9. Diagram showing the evolution of ^{87}Sr/^{86}Sr ratios as Lake Bonneville regresses and segments at 1390 m. The rapid rate of change of ^{87}Sr/^{86}Sr ratios of the isolated Lake Gunnison is due to the influx of low ^{87}Sr/^{86}Sr$_{\text{water}}$ from the Sevier and Beaver rivers. Meanwhile, overflow of Lake Gunnison into the northern basin would have slowed the shift in ^{87}Sr/^{86}Sr$_{\text{water}}$ ratios away from the ratios of integrated lake toward ratios similar to that of the modern GSL.

studied by Oviatt (1988) and interpreted to represent the transition of Lake Bonneville to Lake Gunnison (Fig. 6). The Bonneville-cycle sediments (21–13 ^{14}C ka) yield an $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{carbonate}}$ ratio (0.71125; Table 1, sample 26) that is consistent with a high lake but slightly influenced by the lower $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{river}}$ ratio of the southern rivers. $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{carbonate}}$ ratios decrease upsection in sediments deposited in Lake Gunnison, consistent with the lower $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{carbonate}}$ ratios of the southern lake system. Lake segmentation, as indicated by the Sr isotopes, occurred sometime prior to the deposition of unit E (Fig. 6), dated at 10,070 ± 130 ^{14}C yr B.P. (Oviatt, 1988). The uppermost $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{carbonate}}$ ratio from alluvium near the top of the section is on a probable reworked shell (Fig. 6, sample 31).

Our $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{carbonate}}$ results from the various shorelines provide the basic outline of the evolution of $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{water}}$ as the lake hydrography changed (Fig. 9). As the lake dropped from its highest level, the $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{lake}}$ ratio remained relatively constant until the Old River Bed threshold was reached at 1390 m. At this point lake segmentation began and the $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{water}}$ ratio of each basin evolved toward the $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{river}}$ ratio of the major tributaries for that basin. The $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{water}}$ of Lake Gunnison probably evolved quickly because, after lake segmentation, the southern basin was fed only by the Sevier and Beaver rivers. The northern basin $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{lake}}$ ratios did not change as rapidly due to continued overflow of waters from the southern basin into the northern basin until ~10 ^{14}C ka (Oviatt, 1988; Oviatt, unpublished).

Lake Models

We modeled the Sr mass balance of GSL and the Bonneville system to try to explain the systematic patterns of change in $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{carbonate}}$ with lake level. Our model required knowledge of the Sr flux into the system from every major source, which includes surface runoff, groundwater, and rainfall. The low [Sr] in rainfall makes its contribution negligible (Grautstein and Armstrong, 1983; Gosz and Moore, 1989). The runoff terms were estimated for discharge, [Sr] and $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{river}}$ data on modern rivers. The input of Sr from groundwater is a major unknown that cannot be realistically sampled. However, we can constrain the $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ ratio input of groundwater by knowing the other parameters of the modern system.

Great Salt Lake Model

For our model of the GSL system we used the following input parameters: annual average discharge, [Sr], and the $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{river}}$ ratio of each river flowing into the basin. The average annual discharge for each river was obtained from the USGS water resource website (http://water.usgs.gov/ut/nwis/annual/calendar_year), and is based on daily flow measurements. The length of these records varies considerably, from 1 yr for the Big Cottonwood Creek, to 93 yr for the Bear River at Colliston, Utah. We have an average of 71+ years for all the major rivers in our model.

The [Sr] and $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{river}}$ ratios needed for the model were obtained from our 2001 sampling campaign (Table 2). We also have comparative data for some of the sites from our previous work and that of others (Jones and Faure, 1972; Bouchard, 1997). These data sets come from different years and seasons but the results do not differ greatly, suggesting our results are representative of the present-day Bonneville hydrologic system.

The Bear River is the largest source of water into the GSL basin (Waddell and Barton, 1980; Arnow and Stephens, 1990) and likely the largest source of Sr to the lake. Because of this, the Bear River is also the largest source of potential error in our models and deserves closer investigation along its course. Our results show a large increase in the $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{river}}$ ratios of the Bear River downstream along our transect (Fig. 7). However, most of the change is along the river downstream of the Oneida Narrows, 0.70915 [0.44] to 0.72000 [2.1], whereas the section upstream of Oneida Narrows has a relatively constant $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{river}}$ ratio range of 0.70900–0.70918 and [Sr] ranging from 0.44 to 0.33 ppm. Below Oneida Narrows a large increase in the $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{river}}$ ratio of the Bear River is due to the increased contribution of springs, both cool and thermal, which tend to have high $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ and high [Sr] (Table 2). The addition of the Malad River with its high [Sr] and high $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{river}}$ ratio also increases the $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{river}}$ ratio of the Bear River.

The Bear River contributes ~56% of the total present-day discharge into the GSL basin (Waddell and Barton, 1980). Our sampling of the Bear River at Corrine, Utah, took place at a time of low flow and thus may not be a good representation of annual Sr flux past this point. Examination of water quality data from the USGS water site shows that the [Sr] negatively covaries with discharge. This means the 2.1 ppm we observed in July 2001 (Table 2) at a flow rate of 2.6 m^3/sec is most likely too high to use as representative of the annual flux. A compilation of 22 years of stream quality data (http://water.usgs.gov/ut/nwis/annual/calendar_year) shows that the Bear River has an average annual discharge of 51 m^3/sec. Based on linear regression of discharge and [Sr], the estimated mean concentration is 0.5 ppm. For all the other rivers discharging into the basin, a lack of year-round data required us to use only the [Sr] from July 2001 (Table 2).

Modeling of the lake $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{lake}}$ ratio was estimated by using a simple mass balance:

$$^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{lake}} = f_{\mathrm{Sr\ River\ 1}}\,(^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{River\ 1}}) + f_{\mathrm{Sr\ River\ 2}}\,(^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{River\ 2}}) \ldots + f_{\mathrm{Sr\ groundwater}}\,(^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{groundwater}}) + f_{\mathrm{Sr\ precipitation}}\,(^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{precipitation}}). \quad (1)$$

Here $f_{\mathrm{Sr\ River\ 1,\ River\ 2,\ etc.}}$ = the fraction of Sr from each of the major rivers entering the GSL, and $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{River\ 1,\ River\ 2,\ etc.}}$ = the $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ ratio for each of the major rivers.

We applied equation (1) to the Sr composition data we collected from the seven major tributaries that flow toward the GSL today (Table 2) in order to calculate the $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{lake}}$ ratio of the lake-water mixture. However, the groundwater contribution to lake budgets is impossible to sample, and analysis of some of the springs by us (Table 2) and others (Jones and Faure, 1972; Bouchard, 1997) shows them to vary widely in concentration and isotopic ratio.

We estimated the unknown ground-water Sr contribution by:

(1) using the known GSL $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{lake}}$ ratio of 0.714–0.715,

(2) using the known river inputs into GSL,

(3) neglecting rainfall,

(4) using spring discharge estimates from Waddell and Barton (1980), and

(5) using a range of $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{springs}}$ ratios and [Sr] of analyzed springs.

Because of the complicated hydrology of the lower Bear River, we chose to combine the $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{river}}$ ratio of the springs of the lower Bear River with the basin-wide ground-water system. To do this we used the $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{river}}$ ratios and [Sr] of the Bear River from Oneida Narrows but retained the discharge values from Corrine on the assumption that groundwater adds negligible flow to the lower Bear River (but high Sr).

Using our model (Table 3), a large range of combinations of ground-water [Sr] values and $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ can be used to produce the $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ ratio observed in the modern GSL of 0.71462. The exact combination is irrelevant as long as a good fit is obtained. We combined 10 ppm for [Sr] with 0.72160 to produce the observed GSL ratio. This is not an implausible choice as it fits values observed in some thermal springs in the lower Bear River drainage. Our model results show that the groundwater discharge and the Bear River are the largest sources of Sr into the present-day system, accounting for 80% of the total Sr flux into the GSL.

Great Salt Lake Model with Irrigation

To apply our GSL model to paleolake systems we had to correct for anthropogenic diversion. Irrigation diversions above our sampling points

TABLE 3. HYDROLOGIC MODELS

River	Average discharge† (m^3/s)	Fraction total discharge	Sr concentration (mg/l)	Sr input (mg/yr)	Fraction of Sr input	^{87}Sr/^{86}Sr	Contribution to Lake Sr
Great Salt Lake Strontium Budget							
Provo	10.2	0.100	0.37	1.19E + 11	0.055	0.7102004	0.0393675
Weber	18.1	0.178	0.34	1.94E + 11	0.090	0.7099022	0.0641211
Ogden	2.8	0.027	0.13	1.14E + 10	0.005	0.7142623	0.0037922
Spanish Fork	7.8	0.076	0.40	9.80E + 10	0.046	0.7093732	0.0323325
Little Cottonwood Creek	1.7	0.017	0.11	6.07E + 09	0.003	0.7102193	0.0020075
Big Cottonwood Creek	1.4	0.014	0.20	8.76E + 09	0.004	0.7125816	0.0029037
Bear River‡	56.7	0.558	0.44	7.88E + 11	0.366	0.7091518	0.2598937
Groundwater§	2.9	0.029	10.00	9.24E + 11	0.430	0.7216000	0.3102661
						Resulting lake ^{87}Sr/^{86}Sr	**0.7146843**
Great Salt Lake Strontium Budget with Diversion Corrections							
Provo	14.4	0.090	0.37	1.68E + 11	0.058	0.7102004	0.0411427
Weber	32.1	0.200	0.34	3.43E + 11	0.118	0.7099022	0.0840723
Ogden	2.8	0.017	0.13	1.14E + 10	0.004	0.7142623	0.0028106
Spanish Fork	10.8	0.067	0.40	1.36E + 11	0.047	0.7093732	0.0331733
Little Cottonwood Creek	1.7	0.011	0.11	6.07E + 09	0.002	0.7102193	0.0014879
Big Cottonwood Creek	1.4	0.009	0.20	8.76E + 09	0.003	0.7125816	0.0021521
Bear River‡	93.9	0.587	0.44	1.30E + 12	0.449	0.7091518	0.3185205
Groundwater§	2.9	0.018	10.00	9.24E + 11	0.319	0.7216000	0.2299521
						Resulting lake ^{87}Sr/^{86}Sr	**0.7133113**
Lake Bonneville Strontium Budget							
Provo	14.4	0.077	0.37	1.68E + 11	0.041	0.7102004	0.0293735
Weber	32.1	0.171	0.34	3.43E + 11	0.085	0.7099022	0.0600228
Ogden	2.8	0.015	0.13	1.14E + 10	0.003	0.7142623	0.0020066
Spanish Fork	10.8	0.057	0.40	1.36E + 11	0.033	0.7093732	0.0236838
Little Cottonwood Creek	1.7	0.009	0.11	6.07E + 09	0.001	0.7102193	0.0010623
Big Cottonwood Creek	1.4	0.007	0.20	8.76E + 09	0.002	0.7125816	0.0015364
Bear River‡	93.9	0.500	0.44	1.30E + 12	0.321	0.7091518	0.2274055
Sevier	23.5	0.125	1.53	3.57E + 11	0.279	0.7085139	0.1975099
Beaver	4.5	0.024	0.21	7.67E + 09	0.007	0.7078217	0.0051604
Groundwater§	2.9	0.016	10.00	9.24E + 11	0.288	0.7216000	0.1641727
						Resulting lake ^{87}Sr/^{86}Sr	**0.7119340**
Lake Bonneville with Bear River Diversion into Snake River Basin							
Provo	14.4	0.098	0.37	1.68E + 11	0.044	0.7102004	0.0313380
Weber	32.1	0.217	0.34	3.43E + 11	0.090	0.7099022	0.0640371
Ogden	2.8	0.019	0.13	1.14E + 10	0.003	0.7142623	0.0021408
Spanish Fork	10.8	0.073	0.40	1.36E + 11	0.036	0.7093732	0.0252678
Little Cottonwood Creek	1.7	0.012	0.11	6.07E + 09	0.002	0.7102193	0.0011333
Big Cottonwood Creek	1.4	0.009	0.20	8.76E + 09	0.002	0.7125816	0.0016392
Bear River‡	53.6	0.363	0.62	1.05E + 12	0.275	0.7169100	0.1972038
Sevier	23.5	0.159	1.53	1.13E + 12	0.297	0.7085139	0.2107192
Beaver	4.5	0.030	0.21	2.96E + 10	0.008	0.7078217	0.0055055
Groundwater§	2.9	0.020	10.00	9.24E + 11	0.243	0.7216000	0.1751524
						Resulting Lake ^{87}Sr/^{86}Sr	**0.7142554**
Lake Gunnison							
Sevier	23.5	0.840	1.53	1.13E + 12	0.975	0.7085139	0.6904566
Beaver	0.4	0.160	0.21	2.96E + 10	0.025	0.7078217	0.0180396
						Resulting lake ^{87}Sr/^{86}Sr	**0.7084963**

†See text for discharge estimations.

‡ ^{87}Sr/^{86}Sr ratio and [Sr] at Oneida Narrows with Corrine discharge value.

§Waddell and Barton, 1980.

complicated our discharge estimates as they significantly alter the current discharge of every major tributary of the modern GSL. Estimates of tributary diversion and water use from the EPA website (http://cfpub.epa.gov/surf/locate/map2.cfm) were used to estimate the extent of these diversions. We added the water use from each of the basins to each of the lower basins along the entire reach of the Bear River, to produce a total water loss estimation at each gauge site used in our model. The same method was used on every other basin with substantial water use and discharge. For the Weber-Ogden system we applied the correction to the Weber River only. Most of the diversion occurs along the Weber River since it is the larger and more open basin. Our irrigation-corrected estimates increase the Bear River discharge by 65% (from 56.7 m^3/sec to 93.9 m^3/sec), and increase the Provo, Weber, and Spanish Fork basin discharges by 41%, 77%, and 38%, respectively (Table 3). In the southern basin, irrigation corrections are much larger and increase Sevier River discharge by 217% and Beaver River discharge by 286%.

The irrigation-corrected GSL model (Table 3) was based on the same parameters as the GSL model already presented, except that we used the new, irrigation-corrected discharge estimates. As in the previous model the Bear River and the basin groundwater were the major contributors of Sr (77%). In the irrigation-corrected model the relative discharge of the Bear River increased from 56% to 59% while the relative Sr input increased from 37% to 45%. The relative flux of Sr from the springs decreased from 43% to 32%, accompanied by a decrease in the fraction of relative discharge from 3% to 2% (Table 3). The model yielded an ^{87}Sr/^{86}Sr$_{\text{lake}}$ ratio of 0.71331 for a lake that is corrected for irrigation diversions and would presumably be ~2 m higher in elevation than the modern lake (Arnow, 1980). This result matches with the inverse correlation of ^{87}Sr/^{86}Sr$_{\text{lake}}$ ratios observed in recent lake-level changes discussed by Pedone et al. (2000).

Lake Bonneville Model

Vegetation reconstruction of the eastern Great Basin during the late Pleistocene indicates that the climate was cooler and moister than today (Rhode and Madsen, 1995; Madsen, 2001), possibly due to a southward shift of the jet stream during the full glacial (Antevs, 1948; Thompson et al., 1983; COHMAP, 1988). During this time of increased moisture, pluvial lakes throughout the Great Basin experienced significant rises in lake elevation. Lake Bonneville of this time was ~400 times larger in volume than the modern GSL.

Our model of the Lake Bonneville Sr budget (Table 3) used the same parameters as the diversion-corrected GSL model with two significant changes. First, the addition of the two rivers in the southern basin, the Sevier and the Beaver, accounts for ~15% of the total discharge into the Bonneville basin. Both of these rivers have a low ^{87}Sr/^{86}Sr$_{\text{river}}$ ratio (Table 2), which would tend to decrease the ^{87}Sr/^{86}Sr$_{\text{lake}}$ ratio of the overall lake. Second, we assumed each tributary to paleo-Lake Bonneville makes the same relative contribution to the total discharge and Sr as its modern counterpart, even though the total runoff was much higher. The Bonneville model produced an ^{87}Sr/^{86}Sr$_{\text{lake}}$ ratio of 0.71193, which is slightly higher than the average ^{87}Sr/^{86}Sr$_{\text{carbonate}}$ ratio of the high-lake stages (0.71170), but within the total range (0.71125–0.71195) (Figs. 8 and 9). Our Bonneville hydrologic model shows that the Bear and Sevier Rivers along with the groundwater are the major contributors of Sr flux to the Bonneville basin at 32%, 28%, and 29%, respectively. These systems account for ~90% of the Sr flux but only 64% of the total discharge. The key difference of this model from the models discussed above is the addition of the Sevier River system, with its high [Sr] and low ^{87}Sr/^{86}Sr$_{\text{river}}$ ratio (Table 2), providing 28% of the Sr flux. The close correspondence between modeled and observed ^{87}Sr/^{86}Sr$_{\text{carbonate}}$ results from tufas also suggests that recycling of carbonate and other salts was not a major source of Sr in the deep-lake Sr budget.

Lake Bonneville with Upper Bear River Diversion into the Snake River Drainage

Several times in the Quaternary, lava flows near Grace, Idaho, diverted the upper Bear River between the Snake River drainage to the Bonneville basin. Although the Bear River below these lava dams still discharged into the Bonneville basin, at certain times the upper Bear River was diverted into the Snake River drainage, depriving the Bonneville basin of a significant discharge with a low ^{87}Sr/^{86}Sr ratio. Such diversions of the upper Bear River would produce an increase in the ^{87}Sr/^{86}Sr$_{\text{lake}}$ ratio of the overall Lake Bonneville system. As such, the ^{87}Sr/^{86}Sr$_{\text{lake}}$ ratio of lake carbonates potentially could be used as a means to determine whether the upper Bear River flowed into the Bonneville basin during previous lake cycles.

We therefore modeled Lake Bonneville with the upper Bear River diverted into the Snake River drainage basin using the same equation and parameters as the previous model, but with several important changes to the Bear River parameters (Table 3). First, we had to account for the difference in discharge with the upper Bear River flowing into the Snake River basin. Using irrigation-diversion-corrected values, the average annual discharge at the upstream site (Alexander, Idaho; 40.3 m^3/sec) was subtracted from the average annual discharge at the downstream site (Corrine, Utah; 93.9 m^3/sec) to produce a discharge rate for the lower Bear River drainage of 53.6 m^3/sec, or ~40% of the annual discharge rate at Corrine. We used mass balance considerations again to calculate a new ^{87}Sr/^{86}Sr$_{\text{river}}$ ratio for the lower Bear River after diversion of the upper Bear River:

$$^{87}\text{Sr}/^{86}\text{Sr}_{\text{lower Bear}}\,(1-f_{\text{upper Bear}}) + {}^{87}\text{Sr}/^{86}\text{Sr}_{\text{upper Bear}}\,(f_{\text{upper Bear}}) = {}^{87}\text{Sr}/^{86}\text{Sr}_{\text{Bear River composite}} \qquad (2)$$

Here $f_{\text{upper Bear}}$ is the fractional discharge of the upper Bear River, represented here by the discharge at Alexander, Idaho, divided by the discharge at Corrine, Utah.

In equation (2) the ^{87}Sr/^{86}Sr$_{\text{Bear River composite}}$ ratio is problematic. If we used the ^{87}Sr/^{86}Sr$_{\text{river}}$ ratio we observed at Corrine, the equation yielded an ^{87}Sr/^{86}Sr$_{\text{lower Bear}}$ ratio that was unreasonably high. However, our results and those of Bouchard (1997) show that the river at this point is heavily influenced by thermal spring input just downstream of the discharge sites. The combination of low river discharge at the time of sample collection and proximity to thermal springs input magnifies the runoff/groundwater ratio effect at Corrine (Fig. 7, sample 14), resulting in a seasonally high ^{87}Sr/^{86}Sr$_{\text{river}}$ ratio. Instead, we took the ^{87}Sr/^{86}Sr ratio (0.71327) and [Sr] (0.62 ppm) from Site 17 (Fig. 7) as representative of the lower Bear River ^{87}Sr/^{86}Sr$_{\text{river}}$. The ^{87}Sr/^{86}Sr$_{\text{Upper Bear}}$ ratio used in the equation is from site 25 near Grace, Idaho (Fig. 7). Using these parameters, equation (2) produced an ^{87}Sr/^{86}Sr$_{\text{river}}$ ratio of 0.71691 for the lower Bear River input.

We therefore used the same parameters as the previous Bonneville model but with three changes to the resulting Bear River:

(1) average annual discharge is 53.6 m^3/sec
(2) [Sr] is 0.62 ppm, and
(3) ^{87}Sr/^{86}Sr$_{\text{river}}$ is 0.71691.

The modeled ^{87}Sr/^{86}Sr$_{\text{lake}}$ increased to 0.71426 (Table 3) as a result of the diversion of the upper Bear River with its low ^{87}Sr/^{86}Sr$_{\text{river}}$ ratio out of the Bonneville basin.

The key difference between the two Bonneville models (Tables 3C, D) is that geological diversion of the upper Bear River causes a decrease of surface flow into the lake while spring discharge along the lower Bear River remains unaffected. As a result, the fractional discharge of the Bear River into the Bonneville basin drops by 15%, and the ^{87}Sr/^{86}Sr$_{\text{river}}$ ratio of a "beheaded" Bear River increases substantially (0.70915–0.71648), due to a decrease in the runoff/groundwater ratio.

The resulting modeled ^{87}Sr/^{86}Sr ratio of 0.71426 for Lake Bonneville with a diverted upper Bear River is quite close to the ^{87}Sr/^{86}Sr$_{\text{lake}}$ ratio of the present GSL of 0.71472. Therefore, high ^{87}Sr/^{86}Sr$_{\text{carbonate}}$ ratios >0.714 indicate "low" lake conditions but for different underlying causes. Climate change (less moisture) can produce higher ^{87}Sr/^{86}Sr$_{\text{lake}}$ ratios as the lake decreases in size and elevation, as can diversion of the upper Bear River to the Snake River basin. These similar results may prevent the use of ^{87}Sr/^{86}Sr$_{\text{carbonate}}$ ratios for identifying diversions of the upper Bear River in the >50 ka Bonneville lake record.

Sevier Lake Model

Our attempt to model Sevier Lake in the southern Bonneville basin was complicated by several factors. First, we have no isotopic analysis of the actual lake itself, and second, measurements of groundwater inflow for the Sevier basin are unavailable. Today, only the Sevier River discharges into the terminal Sevier Lake basin, but prior to the establishment of irrigation in the basin, the Beaver River also contributed a minor amount (Oviatt, 1988). At our sample locations near the Bonneville shoreline, the Sevier River has approximately five times the average annual discharge and [Sr] seven times higher than the Beaver River, making the Sevier River the dominant contributor of Sr into the system. Our model of Sevier Lake thus used equation (1) without the groundwater input, and predicted an $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{lake}}$ ratio of 0.70850 (Table 3).

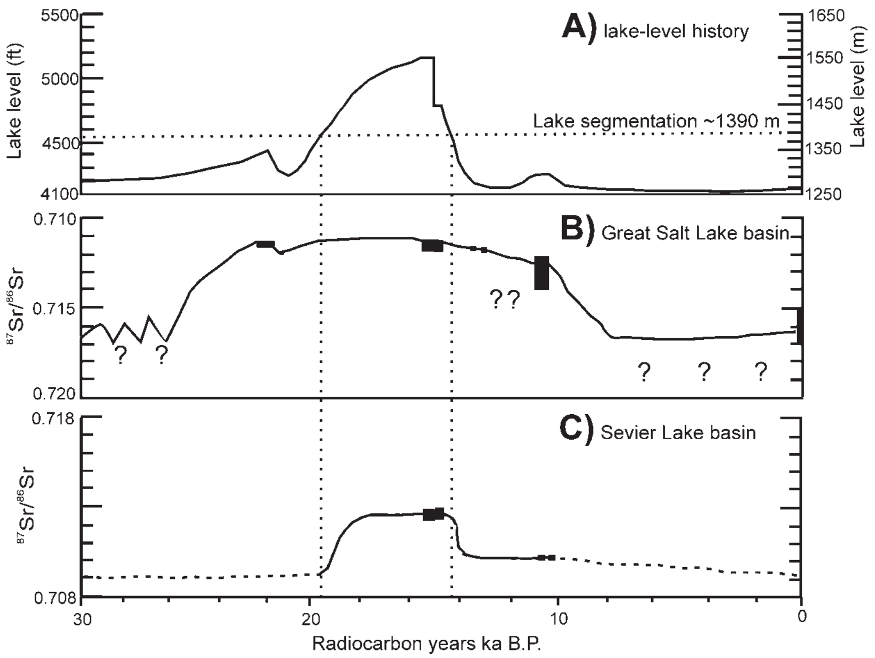

Figure 10. (A) The history of lake elevation changes in the GSL basin compared to the changes in the $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{carbonate}}$ ratio in (B) the GSL Basin, and (C) the Sevier Lake basin. In (B) and (C) the boxes encompass actual data points, whereas the lines are hypothetical and those predicted by current views of the timing and extent of lake-level fluctuations summarized in Currey and Oviatt (1985) and Oviatt et al. (1992). The jagged character of the hypothetical curve at low lake levels in (B) and (C) might be expected given the small lake volume and fluctuations (at some time scale) in the runoff/groundwater ratio. Dashed line denotes lake segmentation events at 1390 m. Analysis of the $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{carbonate}}$ ratios from cores from both basins should provide important additional constraints on the timing of the lake rise and fall across the ~1300–1325 m level in the last 50 ka.

Synthesis of Models and Carbonate Analyses

Our results set the stage for reconstructing and interpreting lake-level changes using $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{carbonates}}$ ratios from surface exposures and cores (Fig. 10). For the northern basins, low $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{carbonates}}$ ratios in the range of 0.7113–0.7119 indicate the presence of a lake at a level no lower than ~1325 m (the elevation of tufa at Danger Cave, Table 1) between the Gilbert shoreline (1300 m) and the base of the Stansbury shoreline complex (1347 m). These low ratios also indicate that the upper Bear River was flowing into the Bonneville system. High $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{carbonates}}$ ratios of >0.7130 indicate lowlake conditions, which prior to 50 ka can be produced in two ways: (1) climatically, due to lower effective moisture, as in the case of modern GSL, or (2) topographically, by diversion of the upper Bear River into the Snake basin. After 35 ka, during the Bonneville lake cycle, we can safely assume that $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{carbonates}}$ ratios of >0.7130 imply a low lake for climatic reasons only. A detailed interpretation of $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{carbonates}}$ ratios at low lake levels also may be complicated by isotopic heterogeneities in the shallower, poorly mixed lake, as in the Gilbert stage. More sampling of materials deposited during episodes of lowlake levels are needed to better resolve these heterogeneities. For the Bonneville lake cycle, in which upper Bear River diversion is not involved, $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{carbonates}}$ ratios in the 0.7120–0.7130 range appear most consistent with a moderately developed lake similar to the Gilbert stage. These intermediate ratios probably reflect some input from Lake Gunnison overflowing across the Old River Bed threshold. $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{carbonates}}$ ratios ranging from 0.7146 to 0.7170 characterize the GSL of the last several decades. During this period, $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{water}}$ ratios are also inversely correlated with lake level, which can be explained by changes in the proportion of runoff (with lower $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ ratios) to groundwater (with higher $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ ratios) input into the lake (Pedone et al., 2000).

For the southern basin and Lake Gunnison, the lowest $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{carbonates}}$ ratios observed are <0.7105 (Fig. 10). The complete isolation of Lake Gunnison once the lake dropped below 1390 m at the Old River Bed threshold should result in a shift of $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{carbonates}}$ ratios in cores from high-lake ratios >0.7112 to lowlake ratios close to that of the Sevier River of 0.70851. This should be readily recognizable in core carbonates, as it was in our sampled section along the Sevier River. Alternating $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{carbonates}}$ ratios of >0.7112 and <0.7105 in a deeper core would denote alternating cycles of deeper (>1390 m) lake and shallower (<1390 m) conditions.

The upper Bear River was once thought to have been diverted into the Bonneville basin ~34 ^{14}C ka (Bright, 1963). More recently, Bouchard et al. (1998) suggested that the upper Bear River flowed into the basin after 50 ka, and perhaps at 140 ka, whereas in the intervening period the Bear River was diverted into the Snake River system (140–50 ka). Our results partially agree with those of Bouchard et al. (1998), suggesting that the Bear River must have flowed into the Bonneville basin during the Little Valley cycle (160–130 ka), but also during the Cutler Dam cycle (59 ± 5 ka). During the Little Valley cycle, a lake nearly as deep as Lake Bonneville occupied the basin, and the Sevier and GSL basins were integrated. During the Cutler Dam cycle, however, the lake does not appear to have attained the elevation to overtop the threshold at the Old River Bed. Further sampling of the Cutler Dam lake phase in locations away from the paleo-Bear River delta is needed to test these conclusions.

CONCLUSIONS

In this paper we have developed the $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{carbonates}}$ ratio as a tool for lake-level reconstruction and interpretation in the Bonneville system. To use $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{carbonates}}$ ratios in this manner, the lake had to be well mixed with respect to Sr, a precondition verified by basin-wide analysis of carbonates from a single shoreline. We found that $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{carbonate}}$ ratios vary inversely with increased lake level, and that the $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{carbonate}}$ ratios are relatively insensitive to lake-level change when the lake is at middle to high (>1390 m) levels. In contrast, the $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{carbonates}}$ ratios are sensitive to changes in lake level in the Sevier Lake basin below 1390 m and in the GSL basin below ~1325 m.

Our hydrologic models of the GSL and Bonneville systems largely account for the systematic changes in $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_{\mathrm{carbonate}}$ ratios with lake level. Our models show that the Bear River and ground water dominate the Sr budget of the GSL basin, while the main Sr contributors to paleo-Lake Bonneville were the Bear and Sevier rivers, as well as groundwater. The Bonneville model verifies that the addition of the Sevier and Beaver rivers flowing into the southern basin is responsible for the low $^{87}\text{Sr}/^{86}\text{Sr}_{\text{carbonates}}$ ratios we observe in the highlake carbonates. Our model shows that taking the Sevier River out (by lake segmentation) or the upper Bear River out (by diversion) of the larger lake system has a similar isotopic effect. Thus, lowlake conditions in the GSL basin can be inferred from high $^{87}\text{Sr}/^{86}\text{Sr}_{\text{carbonates}}$ ratios, but the causes (topographic versus climatic) may not be. The diversion model shows that the upper Bear River was flowing into the Bonneville basin during the two lake cycles prior to the Bonneville cycle, since the $^{87}\text{Sr}/^{86}\text{Sr}_{\text{carbonate}}$ ratios we observed from Little Valley and Cutler Dam cycles are too low to be produced by a lake without the upper Bear River input.

A stratigraphic section in the Sevier basin provided a key test of our predictions for using the $^{87}\text{Sr}/^{86}\text{Sr}_{\text{carbonate}}$/lake-level relationship in the Sevier Lake basin. This exercise verified the usefulness of $^{87}\text{Sr}/^{86}\text{Sr}_{\text{carbonates}}$ ratios in differentiating an integrated (deep) lake from a segmented (shallow) lake. Our results set the stage for a similar but more detailed approach to tracking lake-level changes using the $^{87}\text{Sr}/^{86}\text{Sr}_{\text{carbonates}}$ ratios of carbonates in sediment cores.

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