

# Isotopic and geochemical evidence of palaeoclimate changes in Salton Basin, California, during the past 20 kyr: 2. $^{87}\text{Sr}/^{86}\text{Sr}$ ratio in lake tufa as an indicator of connection between Colorado River and Salton Basin

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## Abstract

As a part of the Colorado River drainage system, Southern California's Salton Basin has two major tributaries: Colorado River and Whitewater River. Interpretations on palaeoclimatic records from the basin strongly depend on the Colorado River inflow to the basin. In this study, we have used the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio in lacustrine deposits to identify the time and duration of the Colorado River input. Our measurements of  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios made on water samples collected from Salton Basin indicate that the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio (0.710169) of the Colorado River input is identical to that of Salton Sea (0.710105), implying little change in the lake water ratio since 1905 when Salton Sea formed and began receiving water mostly from Colorado River; and the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of Colorado River is much lower than that of Whitewater River (0.715960). These results enable us to trace past changes in the Colorado River input using  $^{87}\text{Sr}/^{86}\text{Sr}$  in lake carbonates. Using a two-end-member mixing model, we discuss the major factors that control the  $^{87}\text{Sr}/^{86}\text{Sr}$  variation of Lake Cahuilla, which was an ancient lake in the Salton Basin between 400 and 20,500 yr BP. Thirty measurements of  $^{87}\text{Sr}/^{86}\text{Sr}$  were made on AMS- $^{14}\text{C}$ -dated tufa carbonates in two slabs from Lake Cahuilla. The results show relatively constant  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios throughout the past 20 kyr, ranging from 0.709944 to 0.710140. The average of these  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios,  $0.710060 \pm 0.000049$  ( $n=30$ ), is very close to that of the Colorado River input. Our results indicate that (1) the Colorado River input was the dominant water source for Lake Cahuilla at least during 800–20,500 yr BP when the tufa grew in the basin, and (2) the provenance of run-off to the Colorado River did not change significantly during 800–20,500 yr BP. Hence, the palaeoclimatic proxies retrieved from the Lake Cahuilla tufas in the Salton Basin can decipher the discharge and flood history of the Colorado River under the influence of climate variability in the Colorado River drainage basin.

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## 1. Introduction

Deposited in fresh or brackish water, tufa is the product of calcium carbonate precipitation under ambient temperatures, and is often associated with the remains of micro-and macrophytes, invertebrates and bacteria (Ford and Pedley, 1996; Smith et al., 2004). Although “tufa” is used as a general name, it covers a wide variety of carbonates, and has also been used for the evaporative travertine deposits on the shorelines of ephemeral or dried-up lakes in the Great Basin of Western USA (Newton and Grossman, 1988; Rieger, 1992; Benson et al., 1995). These tufas are normally considered as carbonates precipitated from saline and alkaline lakes through microbial and physico-chemical processes (Scholl and Taft, 1964; Osbourne et al., 1982; Benson, 1994). In the Salton Basin of Southern California (Fig. 1), such carbonates formed in ancient lakes during the past 20 kyr BP (Li et al., 2008-this issue). The palaeohydrological and palaeoclimatic potential of the tufa deposits at this site has drawn little attention compared to other sites in the Great Basin due to changes in the connection between the Salton Basin and Colorado River (e.g., Water, 1983). Geographically speaking, Salton Basin is located in the southwest corner of the Colorado River drainage basin. When the Colorado River is connected with Salton Basin, one should consider that the river discharge is tied to climatic changes in the entire Colorado River drainage basin, which includes the upstream states of Colorado, Utah, and Wyoming, and downstream states of California, Nevada and Arizona.

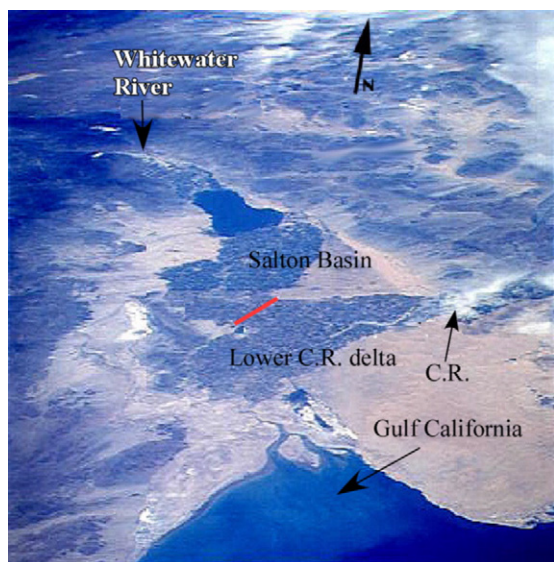


Fig. 1. Satellite image of Salton Trough, with Salton Basin in the north and Lower Colorado River delta in the south (<http://www.sci.sdsu.edu/salton/SaltonBasinHomePage.html>).

When the Colorado River is not connected with the Salton Basin, surface run-off to the lakes in Salton Basin is limited to the catchment area of the basin in southeastern California. Thus, the climatic information recorded in the tufa then mainly reflects climate changes of southeastern California rather than the Colorado River drainage basin (Fig. 1). Therefore, understanding how the Colorado River–Salton Basin connection evolved is a key for deciphering the hydrological changes, hence the palaeoclimatic history, of Salton Basin.

Our recent study on the  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  time series in a 60-cm-thick tufa slab (LC-1) from the Salton Basin shows that the tufa appears to record changes in relative humidity and in discharge or flood frequencies of the Colorado River, which are related to climate variations in the Colorado River drainage basin (Li et al., 2008-this issue). The climate variations could be strongly affected by the summer monsoon strength and by position and strength of the Westerlies. However, the detailed hydrological history and interpretation of the stable-isotope records rely on how the Colorado River was connected to the Salton Basin during the past, as mentioned earlier.

In this study, we use the strontium isotopic composition of tufa deposits for tracing water source and hydrologic state of the Salton Basin. We have measured  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of surface waters in the Salton Basin, and found a means for assessing past changes in the Colorado River input using  $^{87}\text{Sr}/^{86}\text{Sr}$  in lake carbonates. Using a Sr isotope mass-balance model we discuss the controlling factors of  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio in the lake with two major water sources from Colorado River and Whitewater River. Finally, we have obtained information on past shifts of Colorado River input to the basin between 800 and 20,500 yr BP, by measuring  $^{87}\text{Sr}/^{86}\text{Sr}$  time-series in tufas LC-1 and SST-1.

## 2. Background and previous work

Strontium isotopes have been used in studies of Sr mixing processes from different sources in Earth systems (Condie, 1993; Quade et al., 1995; Capo et al., 1998; Capo and Chadwick, 1999; Kurtz et al., 2001; Stewart et al., 2001; Dalai et al., 2003; Banner, 2004; Li et al., 2005). For example, Van der Hoven and Quade (2002) conducted a study of strontium isotopes in soil as a tracer for identifying Ca in pedogenic carbonates from two different sources. Flecker et al. (2002) reconstructed palaeosalinity in marginal marine systems of the Mediterranean based on a simple two-end-member mixing model of Sr isotopes in river and ocean water. Dogramaci and Herczeg (2002) developed a mixing model of Sr isotopes to study carbonate-solution interactions and inter-aquifer

mixing in groundwaters of Murray Basin, Australia. In lake studies, [Katz and Bullen \(1996\)](#) applied  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios along with stable isotopes of D, O and C to study the interaction between groundwater, lake water and aquifer minerals near Lake Barco in Florida. [Anadon et al. \(2002\)](#) used  $\delta^{18}\text{O}$ ,  $^{87}\text{Sr}/^{86}\text{Sr}$ , Sr/Ca and Mg/Ca ratios of fossil ostracod and mollusc shells from a lacustrine sequence in the Velona Basin, Italy, to detect the water source and to obtain palaeoenvironmental reconstructions. [Ojiambo et al. \(2003\)](#) employed  $\delta^{18}\text{O}$ ,  $\delta\text{D}$ , Sr and He isotopes, as well as rare-earth element (REE) data, for investigating groundwater–lake water interactions in the Naivasha watershed, Kenya. The Sr isotope compositions of lake and groundwater were used to detect seepage of lake water into the underlying aquifer and to provide additional insight into the geochemical evolution of waters of the Lake Naivasha watershed. Using a two-component mixing model between seawater and river water, [Israelson and Buchardt \(1999\)](#) studied mixing processes between river water and seawater in East Greenland by measuring  $^{87}\text{Sr}/^{86}\text{Sr}$  in bivalve shells.

Strontium isotopic compositions in tufa and fossil shells have been used for tracing water source and hydrologic state of a drainage system because the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of dissolved Sr in a stream reflects the  $^{87}\text{Sr}/^{86}\text{Sr}$  of rocks being weathered in a given catchment ([Blum et al., 1994](#); [Ingram and DePaolo, 1994](#); [Benson and Peterman, 1995](#); [Katz and Bullen, 1996](#); [Stein et al., 1997](#); [Bain et al., 1998](#); [Jacobson et al., 2002](#)). Changes in input water source to a lake may cause changes in lake water  $^{87}\text{Sr}/^{86}\text{Sr}$ . Since the residence time of Sr in a lake is relatively short (e.g., 3–4 yr in Pyramid Lake) and little Sr isotopic fractionation occurs during carbonate precipitation, carbonate sediments record past changes of  $^{87}\text{Sr}/^{86}\text{Sr}$  in the lake. For example, using  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios in tufas of various ages from Lake Lahontan shorelines, [Benson and Peterman \(1995\)](#) and [Lin \(1996\)](#) studied past changes in the hydrologic state and river inflow to the Lahontan basin.

As a part of the western Sonoran Desert, climate and vegetation of Salton Basin belong to the extremely arid Lower Colorado River Valley subdivision ([Fig. 1](#)). The weather records of the basin between 1915 and 1995 show that monthly temperatures range from 10 to 35 °C. The maximum recorded temperature was 51 °C. The yearly precipitation is at ~8 cm against an evaporation rate of ~180 cm/yr ([Arnal, 1961](#)). At present, the basin is occupied by the Salton Sea, the third-largest salt-water lake in North America created accidentally in 1905. In 1905, heavy snowpacks in the Rocky Mountains engendered by violent winter storms from the Pacific Ocean produced greater-than-normal spring run-off. The enormous flash floods of the Colorado River went over the river bank and

broke through the temporary gates of irrigation canals built for farms in the Imperial Valley, creating the Salton Sea (<http://www.saltonsea.ca.gov/>). Salton Sea currently has a volume of 9.14 km<sup>3</sup>, a surface area of 960 km<sup>2</sup>, an average depth of ~6.5 m, and a maximum depth of 16.5 m ([Arnal, 1961](#)). Its current elevation is about -75 m. Presently, 85% of its water supply comes from Colorado River (mainly through Alamo River and New River) in the form of agricultural, municipal and industrial wastewaters ([Fig. 2](#)). The remaining inputs are from Whitewater River to the sea's northern end (7%), surface precipitation (~3%) and groundwater (~4%).

Historic records, archaeology and shoreline features show that the last lake cycle in the Salton Basin was Lake Cahuilla ([Fig. 2](#)) ([Weide, 1976](#); [Wilke, 1978](#); [Water, 1983](#)). This lake reached an elevation of 12 m a.s.l., which was the highest level during the Late Pleistocene, and sometimes overflowed to the lower Colorado delta. At the highest lake stand, the lake had a surface area of over 5700 km<sup>2</sup> and a maximum depth of 95 m. It became dry before 1700 AD according to historic documents ([McCown et al., 2001](#)). The palaeohydrology of the lake was explored using sediment trenches on lake shorelines, showing the lake existed at highstands between 700 and 6000 yr BP ([Water, 1983](#); [Whistler et al., 1995](#)). [Rinehart and McFarlane \(1995\)](#) used pollen and macrofossils in <sup>14</sup>C-dated packrat



**Fig. 2.** Sampling locations. The contour (thick line) of 12 m elevation approximates the inundated limit of Colorado River. The 12-m-high sill at Cerro Prieto separates the Salton Basin from the lower Colorado River delta. Three open triangles denote three major locations of tufa deposits in the basin: Cahuilla County Park, Old Pacific Railroad Station and Travertine Point (from north to south). The numerical numbers denote sampling locations of the water samples listed in [Table 1](#).

middens to establish the early Holocene vegetation history in the Salton Basin. However, no continuous record throughout the Holocene existed in the area.

Because the Colorado River can switch in and out from Salton Basin, climatic interpretation of the palaeolake records encountered two problems: (1) non-climatic reasons, such as tectonic events or natural meandering, might lead to the Colorado River switch; and (2) the influences of climatic conditions from Salton Basin (local) versus the Colorado River drainage basin (regional) on the palaeoclimatic records. Since the Colorado River drainage basin is much larger than Salton Basin, geographically speaking, the two basins have different climatic conditions. Compared with the Colorado River drainage basin, Salton Basin is influenced more by tropical monsoon than by the Westerlies. Without connection to the Colorado River, the hydrological budget of Salton Basin would only reflect climatic conditions in the arid desert environment of southern California, which are more controlled by the variability of the tropical monsoon strength. With connection to the Colorado River, Salton Basin becomes a small part of the Colorado River drainage basin. The climatic records retrieved from the Salton Basin would then represent the climatic conditions of the entire Colorado River drainage basin, which are also affected by the Westerlies. Therefore, it is important to understand whether and how the Colorado River connected with Salton Basin during the past.

Based on systematic studies of AMS  $^{14}\text{C}$  dating and stable-isotope analyses on tufa and fossil shells, Li et al. (2008-this issue) demonstrated that the lake existed in the basin between 1300 and 20,500 yr BP. The first high-resolution  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  records from the Salton Basin,

established from a 60-cm-thick tufa slab (LC-1), allowed Li et al. (2008-this issue) to decipher lake history and estimate changes in relative humidity. The study showed that the Colorado River has probably always been connected with the Salton Basin between 1300 and 20,500 yr BP, implying that lake-level fluctuations were not caused by non-climatic forcing on course shifts of the Colorado River, and that the lake-level record should reflect changes in discharge or flood frequencies of the Colorado River. The implication of the Colorado River always having been connected with the Salton Basin between 1300 and 20,500 yr BP, however, needs to be confirmed. Furthermore, in order to quantitatively model lake-level (or volume) change in the past, it is necessary to understand the inputs from all sources to the basin. Therefore, we attempt to find a way for detecting past connections of the Colorado River with Salton Basin with the use of Sr isotope analysis. No previous study on Sr isotopes in the Salton Basin exists in the literature.

### 3. Samples and analytical methods

#### 3.1. Water samples

To investigate the Sr isotopic composition and Sr/Ca ratios of different water sources, samples were collected from Salton Sea, the Colorado River, New and Alamo Rivers, and other tributary streams in the Salton Basin in November 2003 (Fig. 2). The  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of the water samples were analyzed using a Thermo Finnigan TRITON TIMS instrument at the National Cheng-Kung University (NCKU), Taiwan, with an external precision of 0.000005. The standard for Sr isotopic measurements is NIST SRM 987. The average value of 92 measurements on the standard

Table 1

Strontium isotopic compositions, concentrations of Ca, Mg and Sr, and Mg/Ca and Sr/Ca ratios of water samples in the Salton Sea and input waters

Sample	$^{87}\text{Sr}/^{86}\text{Sr}$	Ca (ppm)	Mg (ppm)	Sr (ppm)	Mg/Ca	Sr/Ca
Salton Sea water: -8=north shore, -9=northwest shore, -10=southwest shore						
SBW-8	0.710101	562	1098	24.6	1.954	0.044
SBW-9	0.710108	620	1077	25.0	1.738	0.040
SBW-10	0.710105	556	902	21.4	1.623	0.038
Average	0.710104	579	1026	23.6	1.771	0.041
Colorado River water: -6=Colorado River, -7=New River, -1=Alamo River						
SBW-6	0.710429	49	21	1.2	0.437	0.025
SBW-7	0.709848	142	66	3.9	0.466	0.027
SBW-1	0.710230	130	65	3.1	0.499	0.024
Average	0.710169	107	51	2.7	0.467	0.025
Whitewater River water						
SBW-5	0.715960	24	9	0.2	0.388	0.008
Stream water: -2=Jim Folgor Creek, -3=Bombay Beach, -4=San Felipe Creek						
SBW-2	0.711112	103	29	3.6	0.280	0.035
SBW-3	0.708830	195	55	10.4	0.282	0.053
SBW-4	0.709306	312	188	9.2	0.602	0.030
Average	0.709749	203	91	8.3	0.388	0.039



Fig. 3. Picture of tufa deposits near Old Pacific Railroad Station, about 3.5 km south of the Cahuilla County Park. The deposits formed over a vertical distance of  $>20$  m.

is  $0.710260 \pm 0.000009$  ( $2\sigma$  external reproducibility) in the lab of NCKU.  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios are normalized to  $^{88}\text{Sr}/^{86}\text{Sr} = 0.1194$ . For concentrations of Ca, Mg and Sr, about 5 ml of each water sample were used and analyzed by a Finnigan Element II Inductive Coupled Plasma Mass Spectrometer (ICPMS) at NCKU. The measurements have a precision of  $\pm 1\%$ . Table 1 lists the sample locations,  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios and concentrations of these alkaline-earth elements.

### 3.2. Tufa deposits

The tufa deposits in Lake Cahuilla generally contain  $>80\%$   $\text{CaCO}_3$ , and are distributed on ancient shorelines of Lake Cahuilla. They can be up to  $\sim 1$  m thick. The most abundant tufa deposits are located along the northwestern shore of Salton Basin. Fig. 3 shows massive tufas deposited over a vertical distance of  $\geq 20$  m at a location 3.2 km south of the Lake Cahuilla County Park. In a previous study, Li

et al. (2008-this issue) introduced tufa LC-1 from the northeast side of Santa Rosa Mountains ( $33^\circ 24' \text{ N}$ ,  $116^\circ 3' \text{ W}$ ), at Travertine Point. The elevation of tufa LC-1 is 24 m a.s.l., which is  $\sim 36$  m below the highest Holocene lake-level stand. Here we present a 19.5-cm-thick tufa, SST-1, collected in 2003 from Lake Cahuilla County Park, about 25 km away from the north end of Salton Sea ( $33^\circ 38' \text{ N}$ ,  $116^\circ 17' \text{ W}$ ) (Fig. 4). This sampling site is at a much higher elevation than that of LC-1 and is close to the mouth of Whitewater River. There, the highest shoreline (12 m a.s.l.) of Lake Cahuilla can be clearly identified (Fig. 4). We expect tufas at the site to inherit a minimal reservoir effect on radiocarbon dating. SST-1 formed on a granite rock about 4 m below the 12 m shoreline (Fig. 5). It was removed from the granite rock and cut into a 4-cm-thick slab along the growth axis for sub-sampling.

The tufa slabs have lots of pore spaces, filled with detritus such as mud, clay, quartz sand, and gastropod



Fig. 4. The highest shoreline of Lake Cahuilla at the Cahuilla County Park in the north end of Salton Basin. The shoreline at 12 m can be clearly identified.



Fig. 5. Tufa deposits formed over granitic rocks on the ancient lake shoreline. A 19-cm-thick tufa slab SST-1 was cut from the tufa head.

shells (Figs. 6 and 7). The lithological features of the tufa thin-section slides, shown in Fig. 6, indicate that carbonate continuously precipitated when the tufa grew in the lake water. Fig. 7 shows that although abundant open pore spaces exist (Fig. 7a and c), carbonate deposition is still dense (Fig. 7b). No dissolution and diagenesis is visible in the pictures. However, the pore space is filled with detrital material and gastropod shells (Fig. 7d). Thus, the detritus in the pore spaces must be avoided when taking samples along the growth axis of tufa. We used de-ionized water to remove detritus in the pore spaces as much as possible, and then drilled samples from the dense and solid part by using a 3-D

micro mill. The powder samples are very pure carbonate, containing >95%  $\text{CaCO}_3$ . XRD analyses on carbonate samples indicate that the tufa contains almost pure calcite. Dissolution of the samples in acid for isotopic and elemental analyses also shows that little or no residues can be found in the solution. Therefore, it can be concluded that the detrital material in the tufa has little influence on radiocarbon dating and on isotopic analyses of O, C, and Sr. (Table 2).

### 3.3. Chronology of SST-1

Li et al. (2008-this issue) present ten AMS  $^{14}\text{C}$  dates from LC-1. For SST-1 we sub-sampled the tufa slab at intervals of 1 mm and selected five samples for AMS  $^{14}\text{C}$  dating. The radiocarbon analyses were carried out by a 0.5 MV Accelerator Mass Spectrometer (NEC comparative model 1.5 SDH-1) in the Keck AMS Laboratory at the University of California, Irvine (UCI). All  $^{14}\text{C}$  dates have been converted to calendar years before 1950 AD (Stuiver et al., 1998). The dates are in stratigraphic order, ranging from  $1365 \pm 20$  yr BP at 1.1 cm depth to  $4790 \pm 25$  yr BP at 17 cm depth (Table 3). The chronology of SST-1 was determined by a polynomial fitting of the five dates, giving the growth of SST-1 from 800 to 6110 yr BP (Fig. 8).

The  $^{14}\text{C}$  dates shown in Fig. 8 indicate that the  $^{14}\text{C}$  reservoir effect appears to be negligible, because the ages of tufa SST-1 are very close to the age of Lake Cahuilla documented by previous studies (Weide, 1976; Wilke, 1978; Water, 1983), not to mention the fact that the dates are all in stratigraphic order. Since the reservoir effect changes with lake salinity and alkalinity, the large salinity fluctuations of Lake Cahuilla shown by the  $\delta^{18}\text{O}$  profile of LC-1 and by abundant shorelines indicate that the reservoir effect in the lake should not have been constant during the past 20 kyr. If the reservoir effect would have

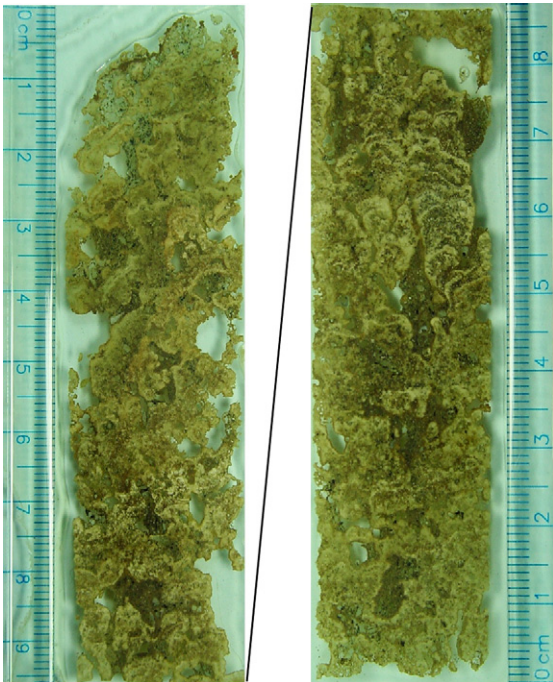


Fig. 6. Photo pictures of the thin section slides of SST-1 slab.

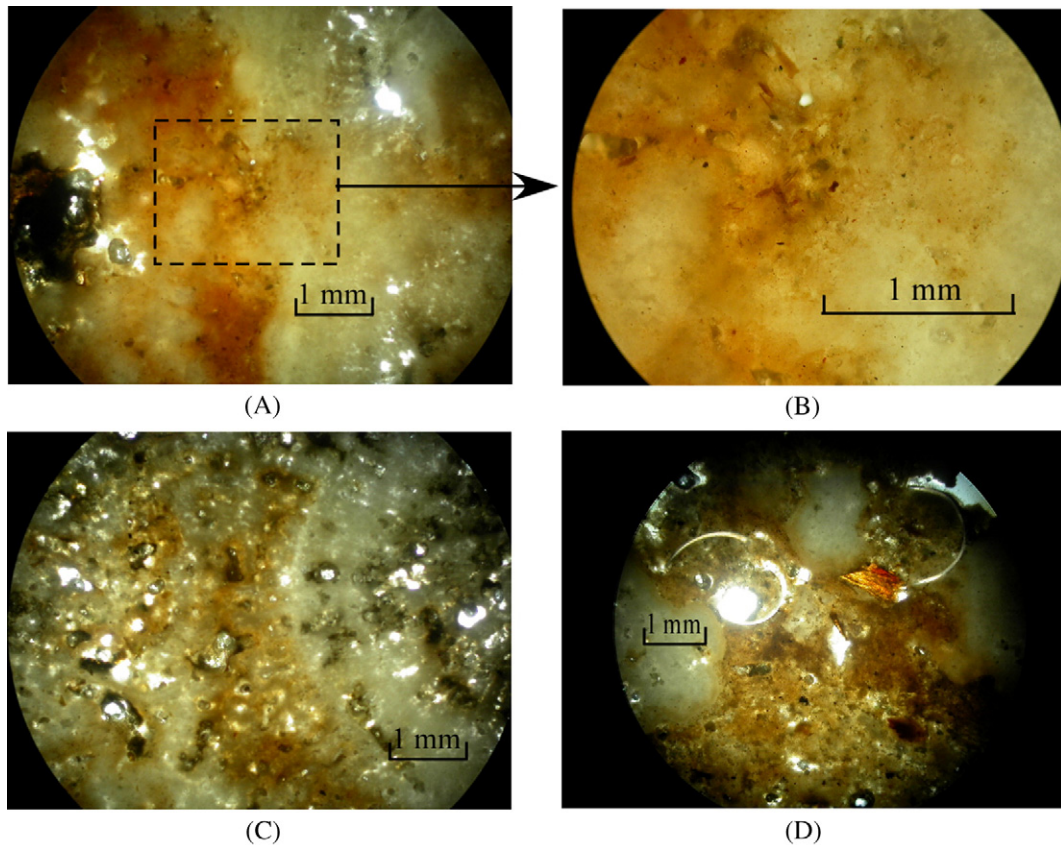


Fig. 7. Photo images of the thin sections made on SST-1.

been significant, this would not have produced  $^{14}\text{C}$  ages in stratigraphic order. A modern barnacle shell deposited in Salton Sea has a  $^{14}\text{C}$  age of 160 yr, indicating very small reservoir effect in Salton Sea. We expect that tufa growing in Lake Cahuilla experienced a much smaller reservoir effect due to lower salinity and alkalinity. As mentioned earlier, SST-1 is located at a higher elevation than that of LC-1 and is close to the mouth of Whitewater River near the highest lake-level stand of Lake Cahuilla. Carbonates formed in the lake water at that location should have minimal reservoir effect on radiocarbon dating. The age of SST-1 overlaps with the younger part of LC-1, beginning

at about 6110 yr BP. When tufa LC-1 stopped growing at ca. 1300 yr BP, SST-1 continued to grow until 800 yr BP. The discrepancy in growth durations between LC-1 and SST-1 may be due to different microbial and physico-chemical conditions at each site. Combining the two tufa slices, we are thus able to detect Sr isotope variations of Lake Cahuilla between 800 and 20,500 yr BP.

### 3.4. $^{87}\text{Sr}/^{86}\text{Sr}$ and Sr/Ca in tufa

Samples for  $^{87}\text{Sr}/^{86}\text{Sr}$  and Sr/Ca analyses were selected from stable-isotope samples, which were sub-sampled

Table 2  
AMS radiocarbon dates of tufa deposits and carbonate shells from Lake Cahuilla in the Salton Basin

Sample	Fraction of modern std	$\delta^{14}\text{C}$	$^{14}\text{C}$ age (yr BP)	Calibrated $^{14}\text{C}$ age	$\delta^{13}\text{C}$ (PDB)	$\delta^{18}\text{O}$ (PDB)	Depth (cm)
SST-183	0.8308±0.0019	-169.2±1.9	1490±20	1365±20	1.69	-8.57	1.1
SST-144	0.7284±0.0017	-271.6±1.7	2545±20	2735±20	1.69	-7.93	5.0
SST-82	0.6767±0.0017	-323.3±1.7	3140±25	3370±25	1.49	-7.25	11.2
SST-54	0.6389±0.0016	-361.1±1.6	3600±20	3890±20	1.66	-7.80	14.0
SST-24	0.5979±0.0015	-402.1±1.5	4130±25	4790±25	2.01	-7.56	17.0

Radiocarbon concentrations are given as fractions of the modern standard,  $\delta^{14}\text{C}$ , and conventional radiocarbon age, following the conventions of Stuiver et al. (1998). Sample preparation backgrounds have been subtracted, based on measurements of  $^{14}\text{C}$ -free coal.

Table 3  
 $^{87}\text{Sr}/^{86}\text{Sr}$  of tufa samples from LC-1 and SST-1, and Sr concentration and Sr/Ca ratios of tufa samples in LC-1

Sample	Depth (mm)	Age (yr BP)	$^{87}\text{Sr}/^{86}\text{Sr}$	Sr (ppm)	(Sr/Ca) <sub>c</sub>	(Sr/Ca) <sub>w</sub>	[Sr] <sub>L</sub> (ppm)
LC-1 from Travertine Point (33°24' N, 116°3' W)							
LCTE-1	4	1524	0.710078	2665	0.00675	0.061	35.5
LCTE-11	44	3030	0.710073	2355	0.00596	0.054	31.4
LCTE-21	84	4492	0.710125	1761	0.00446	0.041	23.5
LCTE-41	164	6959	0.710137	2340	0.00592	0.054	31.2
LCTE-61	244	8582	0.709989	2100	0.00532	0.048	28.0
LCTE-81	324	9489	0.709965	1265	0.00320	0.029	16.9
LCTE-101	404	10278	0.709987	1733	0.00439	0.040	23.1
LCTE-121	484	12019	0.710025	1719	0.00435	0.040	22.9
LCTE-131	524	13710	0.709944	1603	0.00406	0.037	21.4
LCTE-141	564	16253	0.710056	1277	0.00323	0.029	17.0
SST-1 from Lake Calhoun County Park (33°38'N, 116°17'W)							
SST-193	1	799	0.710140				
SST-182	12	1422	0.710119				
SST-177	17	1663	0.710041				
SST-173	21	1838	0.710093				
SST-164	30	2179	0.710048				
SST-159	35	2340	0.710110				
SST-141	53	2775	0.710103				
SST-131	63	2940	0.710096				
SST-122	72	3054	0.710044				
SST-115	79	3127	0.710092				
SST-109	85	3182	0.710072				
SST-97	97	3282	0.710032				
SST-85	109	3388	0.710025				
SST-70	124	3561	0.710056				
SST-53	141	3862	0.710043				
SST-39	155	4236	0.710070				
SST-23	171	4850	0.710035				
SST-13	181	5357	0.710051				
SST-6	188	5776	0.710044				
SST-1	193	6111	0.710104				

The calculated Sr/Ca ratios of the lake water in the second last column are based on the measured (Sr/Ca)<sub>c</sub> ratios and an assumed  $K_d=0.11$ . The last column contains the calculated Sr concentrations of the lake water assuming a constant Ca concentration of 579 ppm (Table 1).

along the growth-axis of LC-1 and SST-1 at 1 mm intervals using a computer-aided tri-axial sampler. About 50 mg of each carbonate sample was dissolved in 6 N HNO<sub>3</sub>. The solutions were passed through TRUE SPEC ion-exchange resin for purification. The pure Sr solution was then placed on a filament for analysis of the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio using a Thermo Finnigan TRITON TIMS instrument at NCKU. A total of 30 samples, with 20 samples from SST-1 and 10 samples from LC-1, were analyzed for  $^{87}\text{Sr}/^{86}\text{Sr}$ . Table 3 lists the results of the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios, in which Sr concentrations and Sr/Ca ratios of LC-1 samples are also given.

In order to use the Sr mass-balance model described later, information of Sr/Ca on waters and tufas is needed. We have carried out measurements of elemental concentrations including Mg, Sr, Mn and Fe in tufa LC-1 by using ICP-AES at the University of Southern California (USC). Working standard curves for the above elements were established for the ICP-AES analyses

during the sample run. A total of 152 samples from LC-1 were measured for the above elements. Here we only report Sr concentrations of the samples which have  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios (Table 3). The Sr/Ca ratio is calculated by the measured Sr concentration divided by the estimated Ca concentration of 394,000 ppm assuming >95% CaCO<sub>3</sub> content in the samples as no visible insoluble material was in the sample solution (Table 3).

## 4. Results and discussions

### 4.1. $^{87}\text{Sr}/^{86}\text{Sr}$ and Sr/Ca of surface waters in Salton Basin

In Table 1,  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of three Salton Sea waters are between 0.710101 and 0.710108 (with analytical errors about  $\pm 0.000005$ ). The  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of Alamo River and New River are 0.710230 and 0.709848, respectively. The

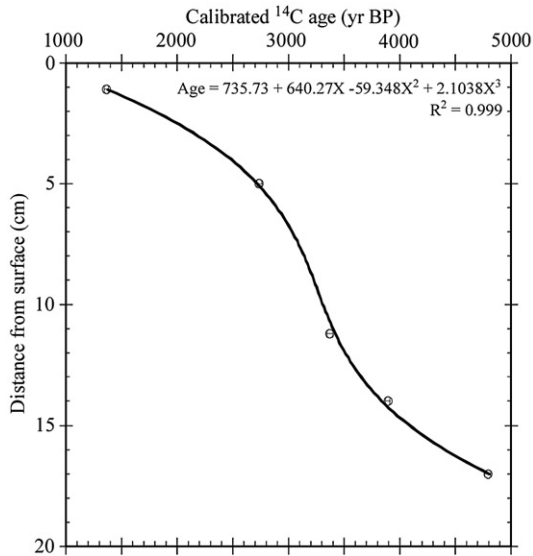


Fig. 8. AMS  $^{14}\text{C}$  chronology of SST-1.

Colorado River near Salton Basin has  $^{87}\text{Sr}/^{86}\text{Sr}$  of 0.710429, whereas Whitewater River near Salton Basin has  $^{87}\text{Sr}/^{86}\text{Sr}$  of 0.715960. Waters from three creeks around Salton Sea have  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios from 0.708830 to 0.711112. The above results indicate the following:

- First, the ratios of three samples from Alamo River, New River and Colorado River are very close, showing the same water source with an average  $^{87}\text{Sr}/^{86}\text{Sr}$  of 0.710169.
- Second, the  $^{87}\text{Sr}/^{86}\text{Sr}$  of Colorado River input is identical to that of Salton Sea (Fig. 9). As most of Salton Sea water comes from Colorado River since 1905 when the Salton Sea formed, the ratio of the lake water seems to remain unchanged regardless of evaporation and mixing.
- Third, the Colorado River water has  $^{87}\text{Sr}/^{86}\text{Sr}$  that is distinctly different from that of the Whitewater River (Fig. 9). If the Colorado River input to the Salton Basin ceases, input from Whitewater River would be dominant. In this case,  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of Salton Sea would increase rapidly. If such a change would occur, it should be recorded in the carbonates precipitated from the lake water.

Thus, one may use the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio in lacustrine deposits to identify the time and duration of the Colorado River input.

Concentrations of Ca, Mg and Sr in the water samples of Salton Basin are shown in Table 1. These results are very similar to the previous results reported

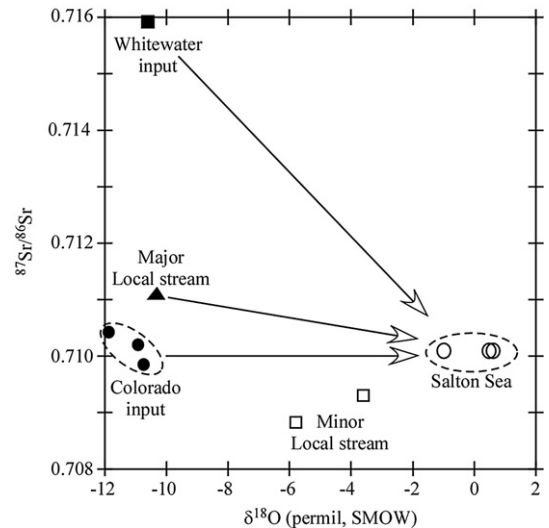


Fig. 9. Variations of Sr isotopic ratios and  $\delta^{18}\text{O}$  values in water samples from Salton Basin potentially provide a means to identify changes in source water during the past.

by Holdren and Montaña (2002). From Table 1, we can summarize the following:

- First, the Salton Sea waters have higher concentrations than the input waters, implying both the effects of strong evaporation of the sea and salt dissolution from the lake bed. Fig. 10 shows strong correlations between Na concentration and concentrations of Mg, Sr and Ca, illustrating such effects. Relatively high Ca and Mg concentrations of the Salton Sea water compared with

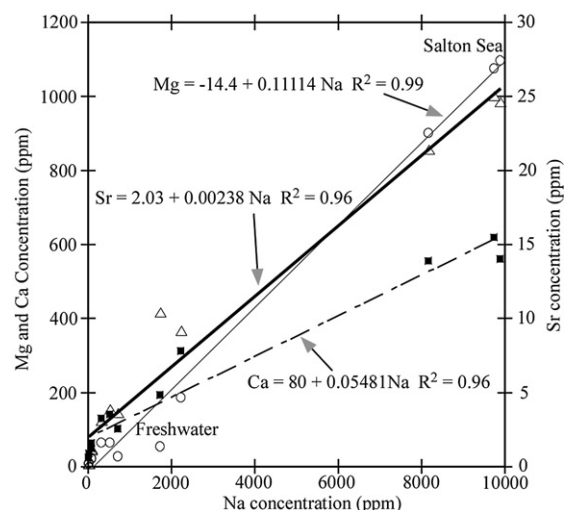


Fig. 10. Plots show positive correlations between concentrations of earth alkaline elements and Na concentration in water samples. Open circles, open triangles and solid squares denote Mg–Na, Sr–Na and Ca–Na relationships, respectively.

other closed-basin lakes in the Great Basin probably reflect relatively low alkalinity of the sea.

- Second, Mg concentrations are higher than Ca concentrations in the Salton Sea water but opposite in the fresh waters, pointing out that Mg residence time in this marine-like lake is longer than that of Ca.
- Third, a strongly linear correlation ( $R^2=0.97$ ) between Sr and Ca concentrations of all water samples illustrates that the Sr behaves much like Ca.
- Finally, although the Sr concentration of the Salton Sea is much higher than that of the Colorado River input, the differences of Sr/Ca ratios between the two waters are relatively small. Since we have only one sample from Whitewater River, which shows a much lower Sr/Ca ratio than the other water samples, we are not confident to interpret this as a true phenomenon. Data from [Holdren and Montañó's report \(2002\)](#) gave Sr/Ca ratios of Salton Sea, Alamo River, New River and Whitewater River of 0.023, 0.017, 0.018 and 0.016, respectively. Their samples of the river waters were taken very close to the sea, and the Salton Sea samples were from the center of the sea. Therefore, if the Sr/Ca in our sample of Whitewater River represents the Sr/Ca ratio of the river without alteration of the Sr dissolution from the ancient lake sediments, it means that a large discrepancy of Sr/Ca between Whitewater River and Colorado River exists. This discrepancy may also be used for detecting shifts of Colorado River from the Salton Basin.

#### 4.2. Sr isotopic mass-balance model for Lake Cahuilla

The  $^{87}\text{Sr}/^{86}\text{Sr}$  of Lake Cahuilla can be considered as two-end-member mixing of Colorado River input and Whitewater River input. As the  $^{87}\text{Sr}/^{86}\text{Sr}$  of Colorado River is much smaller than that of Whitewater River ([Table 1](#) and [Fig. 9](#)), changes in input water source to Lake Cahuilla will cause changes in lake water  $^{87}\text{Sr}/^{86}\text{Sr}$ . To illustrate this situation, we can use a Sr mass- and isotope-balance model for Lake Cahuilla.

Assuming the Colorado River and Whitewater River are the only two significant water sources for Lake Cahuilla, as other input waters account for only 8% of the total input at the present, input water from the two rivers into Lake Cahuilla over time will lead to a change in  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of lake water. Adopting the delta-notation ( $\delta^{87}\text{Sr}=10^3 [(^{87}\text{Sr}/^{86}\text{Sr})_{\text{sample}}/(^{87}\text{Sr}/^{86}\text{Sr})_{\text{seawater}}-1]$ ) and letting  $\delta \equiv \delta^{87}\text{Sr}$ , a Sr isotopic balance can be described as follows:

$$\delta_L = \delta_{LO} \cdot f_{LO} + \delta_a \cdot f_a \quad (1)$$

In Eq. (1),  $\delta_L$ ,  $\delta_{LO}$  and  $\delta_a$ , are  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of the lake water after mixing with the input water, the lake

water before mixing, and the input water, respectively. Further,  $f_{LO}$  is the fraction of dissolved Sr in the original lake water,  $f_a$  is the fraction of dissolved Sr from input water, and

$$f_{LO} + f_a = 1 \quad (2)$$

$$f_a = V_a \cdot [\text{Sr}]_a / V_L \cdot [\text{Sr}]_L \quad (3)$$

where  $V_a$  and  $V_L$  are the volumes ( $\text{km}^3$ ) of input water and the lake after mixing, respectively.  $[\text{Sr}]_a$  and  $[\text{Sr}]_L$  are concentrations of dissolved Sr (ppm) of the input water and the lake water after mixing, respectively. For  $V_a$  and  $[\text{Sr}]_a$ , we have

$$V_a = V_{\text{CR}} + V_{\text{WR}} \quad (4)$$

and

$$V_a \cdot [\text{Sr}]_a = V_{\text{CR}} \cdot [\text{Sr}]_{\text{CR}} + V_{\text{WR}} \cdot [\text{Sr}]_{\text{WR}} \quad (5)$$

where  $V_{\text{CR}}$  and  $V_{\text{WR}}$  are the volume of input water that comes from Colorado River and Whitewater River, respectively.  $[\text{Sr}]_{\text{CR}}$  and  $[\text{Sr}]_{\text{WR}}$  are concentrations of dissolved Sr of Colorado River and Whitewater River, respectively. If we write Eq. (1) as follows:

$$\begin{aligned} \delta_L &= \delta_{LO} \cdot (1 - f_a) + \delta_a \cdot f_a \\ &= \delta_{LO} - \delta_{LO} \cdot f_a + \delta_a \cdot f_a \end{aligned} \quad (6)$$

then

$$\begin{aligned} \delta_L - \delta_{LO} &= \Delta\delta_L = (\delta_a - \delta_{LO}) \cdot f_a \\ &= ((\delta_a - \delta_{LO}) \cdot V_a \cdot [\text{Sr}]_a) / (V_L \cdot [\text{Sr}]_L) \end{aligned} \quad (7)$$

For the  $^{87}\text{Sr}/^{86}\text{Sr}$  of input water,  $\delta_a$ , we also have

$$\begin{aligned} \delta_a &= \delta_{\text{CR}} \cdot (V_{\text{CR}} \cdot [\text{Sr}]_{\text{CR}}) / (V_a \cdot [\text{Sr}]_a) + \delta_{\text{WR}} \\ &\quad \cdot (V_{\text{WR}} \cdot [\text{Sr}]_{\text{WR}}) / (V_a \cdot [\text{Sr}]_a) \end{aligned} \quad (8)$$

where  $\delta_{\text{CR}}$  and  $\delta_{\text{WR}}$  are the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of the Colorado River and Whitewater River, respectively.

Substituting Eqs. (5) and (8) into Eq. (7), we have:

$$\begin{aligned} \Delta\delta_L &= (\delta_{\text{CR}} \cdot V_{\text{CR}} \cdot [\text{Sr}]_{\text{CR}} + \delta_{\text{WR}} \cdot V_{\text{WR}} \cdot [\text{Sr}]_{\text{WR}}) \\ &\quad / (V_L \cdot [\text{Sr}]_L) - (\delta_{LO} \cdot (V_{\text{CR}} \cdot [\text{Sr}]_{\text{CR}} + V_{\text{WR}} \\ &\quad \cdot [\text{Sr}]_{\text{WR}})) / (V_L \cdot [\text{Sr}]_L) \\ &= (\delta_{\text{CR}} \cdot V_{\text{CR}} [\text{Sr}]_{\text{CR}} + \delta_{\text{WR}} \cdot V_{\text{WR}} \cdot [\text{Sr}]_{\text{WR}}) \\ &\quad / (V_L \cdot [\text{Sr}]_L) - (\delta_{LO} \cdot (V_{\text{CR}} \cdot [\text{Sr}]_{\text{CR}} + V_{\text{WR}} \\ &\quad \cdot [\text{Sr}]_{\text{WR}})) / (V_L \cdot [\text{Sr}]_L) \end{aligned} \quad (9)$$

Eq. (9) is the mass balance model of Sr isotopic compositions for Lake Cahuilla. In the equation,  $\delta_{\text{CR}}$  and  $\delta_{\text{WR}}$  are measurable constants, being 0.710169 and

0.715960, respectively, at the present.  $[\text{Sr}]_{\text{CR}}$  and  $[\text{Sr}]_{\text{WR}}$  are also measurable values, being 2.7 and 0.2 ppm, respectively, today (Table 1). Since there is little Sr isotopic fractionation between lake water and the carbonate precipitated from the water,  $\Delta\delta_{\text{L}}$  and  $\delta_{\text{LO}}$  can be estimated from the measurements of  $^{87}\text{Sr}/^{86}\text{Sr}$  in tufa carbonates at a given time interval. Concentration of Sr in the lake water,  $[\text{Sr}]_{\text{L}}$ , can be evaluated from Sr/Ca ratio measured in tufa carbonate (see next section). If we assume  $\delta_{\text{CR}}$ ,  $\delta_{\text{WR}}$ ,  $[\text{Sr}]_{\text{CR}}$  and  $[\text{Sr}]_{\text{WR}}$  remain constant through time, and the calculation of  $[\text{Sr}]_{\text{L}}$  through time is feasible, then the ratios of  $V_{\text{CR}}/V_{\text{L}}$  and  $V_{\text{WR}}/V_{\text{L}}$  are the two unknowns in the equation. Below we discuss several cases of Lake Cahuilla for changes in the Colorado River input.

#### 4.3. Model evaluation

For the case of the modern Salton Sea, the Colorado River input accounts for 85% of the total inflow, whereas Whitewater River accounts for 7%. The Sr concentration of Whitewater River is also lower than that of the Colorado River. Therefore, although the  $^{87}\text{Sr}/^{86}\text{Sr}$  of Whitewater River is much larger than that of the Colorado River, its impact on the lake's  $^{87}\text{Sr}/^{86}\text{Sr}$  is strongly reduced. For example, the current volume of the Salton Sea is  $9.25 \text{ km}^3$  (7,500,000 ac ft). The total current inflow to the Salton Sea is about  $1.6 \text{ km}^3/\text{yr}$  (1,300,000 ac ft), in which  $1.36 \text{ km}^3/\text{yr}$  comes from the Colorado River and  $0.112 \text{ km}^3/\text{yr}$  comes from Whitewater River. Given  $\delta_{\text{CR}}=0.710169$ ,  $\delta_{\text{WR}}=0.715960$ ,  $\delta_{\text{LO}}=0.710104$ ,  $[\text{Sr}]_{\text{CR}}=2.7 \text{ ppm}$ ,  $[\text{Sr}]_{\text{WR}}=0.2 \text{ ppm}$ ,  $[\text{Sr}]_{\text{L}}=23.6 \text{ ppm}$ , and  $V_{\text{L}}=9.25 \text{ km}^3$ , we can calculate how many years it takes to make significant change in the lake's  $^{87}\text{Sr}/^{86}\text{Sr}$ . The calculation shows that for every 30 yr the lake's  $^{87}\text{Sr}/^{86}\text{Sr}$  will increase 0.000051, assuming the input rates and lake volume keep constant. In fact, the volume of Salton Sea was much larger than current volume, being  $18.9 \text{ km}^3$  (15,326,500 ac ft) in 1907 (Thomas et al., 1954). During that time, the ratio of  $V_{\text{CR}}/V_{\text{WR}}$  was also higher than today's ratio. These situations would reduce the rate of changes in lake  $^{87}\text{Sr}/^{86}\text{Sr}$ .

If we keep all above parameters unchanged but use a lake volume of  $3705 \text{ km}^3$  for Lake Cahuilla at the highest stand ( $5700 \text{ km}^2$  surface area and a mean depth of 65 m), then the Colorado River input should be at least  $18.1 \text{ km}^3/\text{yr}$  (14,700,000 ac ft) in order to maintain the level of Lake Cahuilla. The lake's  $^{87}\text{Sr}/^{86}\text{Sr}$  will change only 0.000005 for every 100 yr.

Assuming the Colorado River shuts down its input to the Salton Basin, the first term on the right-hand side of

Eq. (9) is eliminated. The input from Whitewater River would then have to become  $1.472 \text{ km}^3/\text{yr}$  in order to keep the Salton Sea at the present level. Otherwise, the lake would dry out in 5 yr due to evaporation ( $1.8 \text{ m}/\text{yr}$ ). In this case, the lake's  $^{87}\text{Sr}/^{86}\text{Sr}$  would increase 0.000237 for every 30 yr. Similarly, for the given volume of Lake Cahuilla ( $3,705 \text{ km}^3$ ) and input rate of Whitewater River at  $18.1 \text{ km}^3/\text{yr}$ , the increase of the lake's  $^{87}\text{Sr}/^{86}\text{Sr}$  will be 0.000025 for every 100 yr. Therefore, in each of the cases when the Colorado River input is shut down, the lake's  $^{87}\text{Sr}/^{86}\text{Sr}$  should increase rapidly. Such increases can be recorded in the tufas deposited in the lake.

#### 4.4. $^{87}\text{Sr}/^{86}\text{Sr}$ and Sr/Ca in tufa carbonates as proxy of Colorado River–Salton Basin connection

As the residence time of Sr in a lake is on the order of a few years and little Sr isotopic fractionation occurs during carbonate precipitation, lake carbonates record past changes of  $^{87}\text{Sr}/^{86}\text{Sr}$  in the lake. Using Sr isotopic compositions in tufa deposited from Lake Cahuilla, we can trace the water source and the hydrologic state of the Salton Basin.

Table 3 lists all measured  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios in tufa slices LC-1 and SST-1. The Sr concentrations and Sr/Ca ratios of tufa carbonates,  $(\text{Sr}/\text{Ca})_{\text{c}}$ , shown in Table 3 are measured on LC-1. The calculated Sr/Ca ratios of the lake water,  $(\text{Sr}/\text{Ca})_{\text{w}}$ , listed in the second last column of Table 3 are determined by  $(\text{Sr}/\text{Ca})_{\text{w}}=(\text{Sr}/\text{Ca})_{\text{c}}/K_{\text{Sr}}$ , where  $K_{\text{Sr}}$  is the partition coefficient of Sr co-precipitating with Ca in carbonate minerals. In our study, the tufas are calcite.

Although many studies have been carried out on the determination of  $K_{\text{Sr}}$ , estimates have shown large variations. For example,  $K_{\text{Sr}}$  values derived from laboratory precipitation experiments range in the order of 0.14 (Kinsman, 1969), 0.05–0.058 (Katz et al., 1972), 0.027–0.1 (Lorens, 1981), 0.146 (Mucci and Morse, 1983), 0.06 (Pingitore and Eastman, 1986), 0.046–0.068 (Malone and Baker, 1999), and 0.057–0.081 (Huang and Fairchild, 2001). Some  $K_{\text{Sr}}$  values have been derived from studying natural speleothems: e.g., 0.09–0.3 (Holland et al., 1964; Gascoyne, 1983) and 0.15–0.16 (Huang and Fairchild, 2001). The experimental studies also show that  $K_{\text{Sr}}$ , while hardly affected by changes in temperature and ionic strength, may depend on calcite precipitation rate (Pingitore and Eastman, 1986; Malone and Baker, 1999; Huang and Fairchild, 2001). It has been shown that  $K_{\text{Sr}}$  increases about 10% when the calcite precipitation rate increases one order of magnitude (Tesoriero and Pankow, 1996;

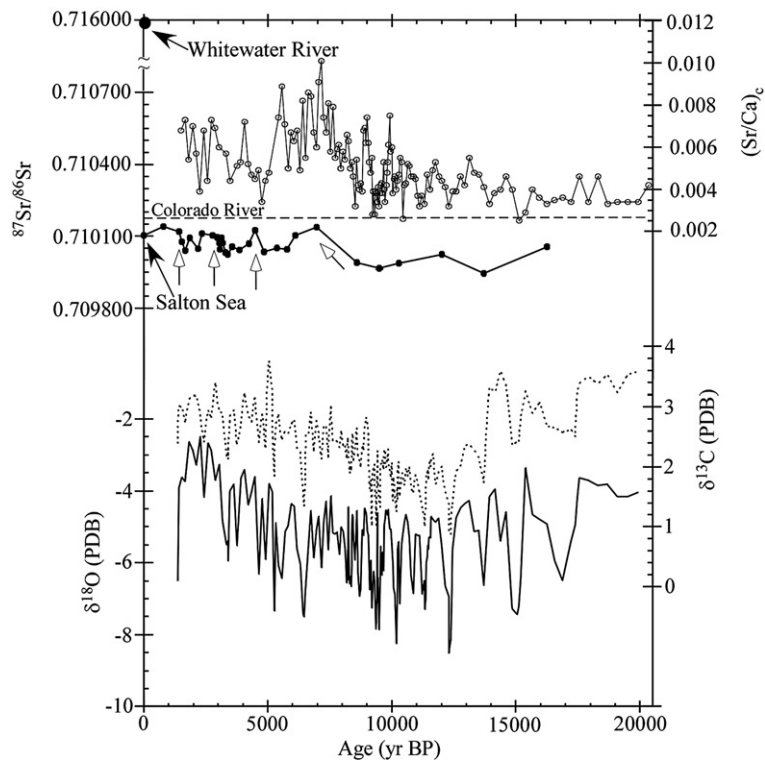


Fig. 11. Comparisons of  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $(\text{Sr}/\text{Ca})_c$  in LC-1 and SST-1 with the  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  records in LC-1. The solid curve with solid dots denotes the  $^{87}\text{Sr}/^{86}\text{Sr}$  profile, whereas the line with open circle presents  $(\text{Sr}/\text{Ca})_c$  variations. In the upper panel, the horizontal broken line indicates the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of the modern Colorado River; and the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of the Salton Sea and Whitewater River are also pointed out. In the lower panel the solid and dashed curves are for  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ , respectively. Open arrows denote the time intervals when the Colorado River inflow to the Salton Basin was reduced significantly.

Huang and Fairchild, 2001). As the growth rates of LC-1 and SST-1 vary less than one order of magnitude (Fig. 6, and Li et al., 2008-this issue), the variation of  $K_{\text{Sr}}$  should be less than 10%. In the future, we will collect modern carbonate deposits in Salton Sea to determine the  $K_{\text{Sr}}$ . Currently, we use a  $K_{\text{Sr}}$  value of 0.11, averaged from previous studies (Li et al., 2005).

With the calculated  $(\text{Sr}/\text{Ca})_w$ , we may estimate the influence of changes in Sr concentrations of the lake water at different times on the Sr mass balance model. Currently, we have not found a way to obtain the Ca concentrations of the lake water with time during the past. If we use the measured  $[\text{Ca}]_L$  of Salton Sea, being 579 ppm (Table 1), which is relatively constant since 1920 (Holdren and Montañó, 2002), the calculated  $[\text{Sr}]_L$  ranges from 16.9 to 35.5 ppm with an average of 25.1 and a standard deviation of 6.2 ppm ( $n=10$ ) (Table 3). The average value is close to the Sr concentration of modern Salton Sea water (23.6 ppm), implying the  $K_{\text{Sr}}$  value we selected is reasonable. We realize that this estimation of  $[\text{Sr}]_L$  may have large uncertainties, however, these uncertainties should not bias the model

results too much as the  $[\text{Sr}]_L$  is a common factor for both terms on the right-hand side in Eq. (9).

Fig. 11 shows the comparisons of  $^{87}\text{Sr}/^{86}\text{Sr}$  in LC-1 and SST-1 with the  $\delta^{18}\text{O}$ ,  $\delta^{13}\text{C}$  and  $(\text{Sr}/\text{Ca})_c$  records in LC-1. The results shown in Fig. 11 indicate the following:

- First, relatively constant  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios occurred throughout the past 20,500 yr BP, ranging from 0.709944 to 0.710140. The average of these  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios,  $0.710060 \pm 0.000049$  ( $n=30$ ), is very close to that of the Colorado River input. As we discussed earlier, if the Colorado River input to Lake Cahuilla were to shut down, an increase of at least 0.000025 in the lake's  $^{87}\text{Sr}/^{86}\text{Sr}$  would be shown in an interval of 100 yr. In Fig. 11, only three intervals have  $^{87}\text{Sr}/^{86}\text{Sr}$  increases greater than 0.000025 per 100 yr, at ca. 3050 (0.000066), 2180 (0.000039) and 1660 yr BP (0.000030). Another major increase of the  $^{87}\text{Sr}/^{86}\text{Sr}$  occurred from 8000 to 7000 yr BP, though the increasing rate did not exceed 0.000025 per 100 yr probably due to sparse data measurements. During these periods, the  $\delta^{18}\text{O}$  values also were relatively

- heavy and had increasing trends, indicating that the Colorado River input was relatively low. In addition, increasing trends in Sr/Ca ratios may also point out increases in the lake salinity during these periods. During these periods, Lake Cahuilla might have become a closed-basin lake, but the Colorado River input may still have been dominant as the magnitude of  $^{87}\text{Sr}/^{86}\text{Sr}$  increases were not large and the tufas continued to grow. Therefore, we conclude that the Colorado River input has been the dominant water source for Lake Cahuilla at least during 800–20,500 yr BP, when the tufas LC-1 and SST-1 grew in the basin.
- Second, the large fluctuations in the  $\delta^{18}\text{O}$  values cannot be explained by changes in the shift of the Colorado River into or out from the Salton Basin. Hence, the palaeoclimatic proxies retrieved from the Lake Cahuilla tufas in the Salton Basin can decipher the discharge and flood history of the Colorado River under the influence of climate variability in the Colorado River drainage basin.
  - Third, a general increase in both  $^{87}\text{Sr}/^{86}\text{Sr}$  and Sr/Ca ratios occurred from the early Holocene toward the late Holocene, perhaps reflecting either slightly decreases in the Colorado River inflow or slightly changes in the provenance of run-off in the Colorado River drainage basin during the Holocene.
  - Finally, all tufa  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios are smaller than that of the modern Colorado River (the broken line in Fig. 11). Three reasons may explain this phenomenon: (a) the Colorado River may have had a lower  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio in the past as carbonate minerals have lower  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios in general and are easier to be weathered in earlier time; (b) more inputs came from the local streams, which have lower  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios, e.g., San Felipe Creek; and (3) human influence during the recent centuries elevated the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of the Colorado River.

## 5. Conclusions

The large difference of Sr isotopic compositions between Colorado River and Whitewater River, which are two major inflows to the Salton Basin, California, allows us to trace the input source and to detect connection of the Colorado River to the basin. A two-end-member mass-balance model has been established to evaluate the controlling factors of the lake's  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio. The volume ratio of input water to the lake and the difference of  $^{87}\text{Sr}/^{86}\text{Sr}$  values between the input water and the lake are the two major factors. A total of 30 measured  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios in two AMS  $^{14}\text{C}$  dated tufa slabs collected from the ancient shorelines of Lake Cahuilla in the Salton Basin provide evidence that the Colorado River input has been

the dominant water source for Lake Cahuilla at least during 800–20,500 yr BP. This evidence allows us to interpret the palaeoclimatic proxies retrieved from the Salton Basin for deciphering changes in relative humidity and the discharge/flood history of the Colorado River under the influence of climate variability in the Colorado River drainage basin.

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