

Strontium 87/strontium 86 ratios as tracers in groundwater and surface waters in Mono Basin, California

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Abstract. The $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratios in spring waters in Mono Basin, California, are highly variable and reflect contact with different rock types. Whole rock $^{87}\text{Sr}/^{86}\text{Sr}$ ratios throughout the basin range between 0.7054 and 0.7281. Ratios in surface water samples differ greatly between runoff from the mainly granitic Sierra (0.7094–0.7097) and runoff from the volcanic regions (0.7054–0.7064). The ratio in Mono Lake water (0.7096) is similar to the ratios of streams from the Sierra Nevada. Springs close to the western shoreline have more radiogenic Sr ratios (0.7092–0.7100), while those on the east side have ratios (0.7081–0.7088) indicative of a mixture of water from the volcanic terrain and Mono Lake. Thermal springs at the south side of the lake have $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.7081–0.7089 and might originate in Paleozoic limestones at depth.

Introduction

Within the last three decades the determination of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios has been shown to be a valuable tool in tracing groundwaters. Sr isotopic measurements are very precise, sample preparation is comparatively easy, and the amounts of sample required for measurements are low, unlike lighter isotopes. Sr is not fractionated by physical processes. Therefore Sr in groundwater carries the isotopic signature of the rocks it passed along its flow path. For example, this behavior has been used successfully to determine the origin of water solutes in Antarctica [Jones and Faure, 1967] and Israel [Starinsky *et al.*, 1983], to trace groundwater in Australia [Collerson *et al.*, 1988], and outline mixing processes in playa lakes [Lyons *et al.*, 1995]. Other applications have included the evaluation of hydrothermal processes in France [Stettler, 1977] and the measurement of weathering rates in the Sierra Nevada [Blum *et al.*, 1994]. Mono Basin in California has a number of water types passing through a variety of rock types, and $^{87}\text{Sr}/^{86}\text{Sr}$ ratio measurement promised to be a suitable method to answer questions regarding the basin's hydrogeology.

Site Description

Mono Basin is a tectonic basin, located at the eastern side of the Sierra Nevada in central California (Figure 1). The Sierra Nevada is composed of Mesozoic granites and granodiorites, and of lower Paleozoic metasediments and metavolcanics [Bateman and Wahrhaftig, 1966; Kistler, 1966a, b]. The Sierra Nevada borders Mono Basin to the west and is separated from it by the Mono Lake fault [Bursik and Sieh, 1989]. Rhyolitic, andesitic, and basaltic mountains border the basin to the north, east, and south [Christensen *et al.*, 1969]. The age of the mountains ranges from 28 m.y. in the Bodie Hills to few hundred years at the Mono Craters. The basin is filled with up to

2100 m of Tertiary and Quaternary lacustrine sediments. In the central part of the basin, they consist mainly of diatomaceous silts and diatomites, with some interbedded pumiceous ash layers [Lajoie, 1969]. Along its margins they interfinger with fluvial sediments [Pakiser, 1976].

Mono Lake, located in the western part of the hydrologically closed basin, is a terminal lake. The lower part of the basin lies in the rain shadow of the Sierra Nevada; precipitation is about 150 mm/yr, compared to 1300 mm/yr precipitation in the Sierra Nevada [Vorster, 1985]. Eighty-five percent of the water recharging the basin comes from the Sierra Nevada, mainly from snowmelt, and 7% from the other mountain ranges [Vorster, 1985]. The remaining 8% of the water input is from precipitation on the lake and the lower portion of the basin. The Sierra Nevada portion of the basin is drained by five perennial streams, including Rush Creek and Lee Vining Creek, and several intermittent creeks, including Wilson Creek. Streams from the Sierra Nevada are the only ones that reach the lakeshore. Creeks from the other mountains percolate into the basin fill. Only in years with unusually high precipitation do some of them reach the lake. Since most of the water comes from snowmelt, the discharge of the creeks varies widely over the seasons. One half to two thirds of the annual discharge occurs between May and July [Lee, 1969]. Seventy-five percent of this runoff is carried by two streams, Rush Creek and Lee Vining Creek [Vorster, 1985].

Water loss from the basin occurs via evaporation, evapotranspiration, and water export. Evaporation is the main natural discharge, and evapotranspiration is relatively unimportant. Water is evaporated from the lake and from shallow aquifers along the shoreline. Los Angeles has diverted water since 1940, capturing the flow of Rush and Lee Vining Creeks. This resulted in more than a 12-m drop in the lake level [National Research Council, 1987]. The drop has produced wide areas of exposed lake beds and salt flats on the north-eastern side of the lake. The water export stopped in 1991.

The hydrogeology of the basin is very complex. The basin fill consists of interfingering lacustrine, fluvial, glacial, and volcanic deposits [Lee, 1969]. These different layers create a system of semiconfined to confined aquifers [National Research Council, 1987]. Fluvial gravels and sands are predominant at the

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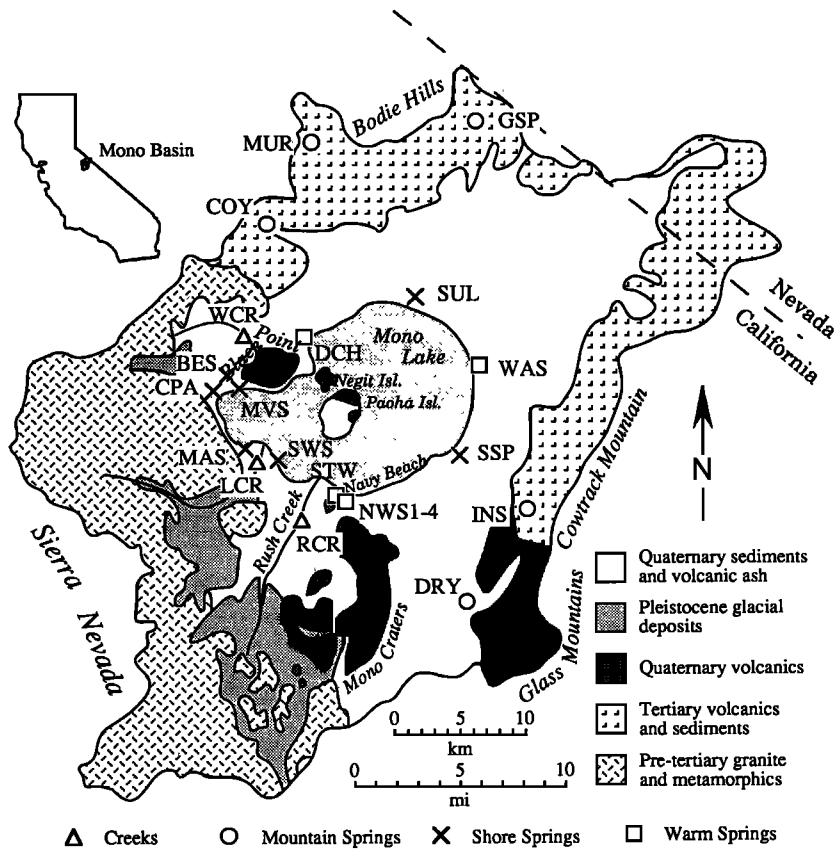


Figure 1. Map of Mono Basin and the sample locations within it. The sample site names and geologic settings are listed in Table 1. Map modified after Rogers *et al.* [1992].

western shoreline. The aquifers in the basin are recharged by the streams via these gravels and via fractures. The tuffs in the basin also contain large amounts of groundwater [Gresswell, 1940]. Along the shoreline the water table is very shallow. It intersects the surface at several locations, forming generally vegetated seep zones. Along the eastern shoreline, springs seem to be located along faults [Basham, 1988]. Along the western and southern shoreline, spectacular tufa towers have formed at former sublacustrine springs. Thermal springs with temperatures of $\sim 35^{\circ}\text{C}$ emanate at two locations at the southern and southeastern shore. The DeChambeau well on the northern shore produces water with temperatures of about 63°C .

The overall objective of this study was to identify the origins of the spring water in the basin, using major ions and Sr isotopes. Specifically this study focused on (1) describing and distinguishing recharge end-members that influence groundwater chemistry, (2) determining the eastward extent into the basin of groundwater originating in the Sierra Nevada, and (3) reevaluating the origin of the thermal waters in the basin.

Sampling and Analytical Methods

Water samples were collected during two trips to Mono Basin, in April and May 1991. Samples come from 23 different locations in the basin (Figure 1, Table 1), which were classified into five groups: (1) springs in the volcanic mountains around the basin (mountain springs); (2) streams flowing into the basin

from the Sierra Nevada (creeks); (3) springs and wells in the sediment-filled part of the basin (shoreline springs); (4) warm springs close to the lake (warm springs); and (5) Mono Lake proper. Temperature, pH, and conductivity were determined at the sampling site. Samples were collected in 500-mL polyethylene bottles which had been soaked in 6 N HNO_3 for several days and rinsed with Milli-Q water. Three samples were taken per site: one for carbonate/bicarbonate determination, one for the other anions, and a third for cations. The anion/cation samples were filtered, and the sample for cation determination was acidified with concentrated HNO_3 to a pH < 2. Three additional creek samples were collected in December 1991. The procedures used were the same as those above, except that one sample for strontium isotope determination was taken additionally from each site.

The analytical methods used and the analytical uncertainties for the major elements are shown in Table 2 and are described in detail elsewhere [Neumann, 1993]. The errors in the charge balances are less than 8%, except for two samples. Eighteen of the 27 analyzed samples have errors less than 5%.

The $^{87}\text{Sr}/^{86}\text{Sr}$ measurements were performed on the VG Sector 54-30 mass spectrometer in the Earth Science Department at the University of California, Santa Cruz. Two hundred and fifty milliliters of the sample were evaporated. The residual was redissolved with ~ 3 mL 2.5 N HCl. Samples with high alkalinities (including all warm springs and Mono Lake water) were precipitated and redissolved in HCl until all the bicar-

Table 1. List of Water Groups, Sample Sites, Abbreviations, and Bedrock Type

Group	Symbol	Name	Bedrock
Mountain springs	COY	Coyote Creek Spring	andesites, undivided volcanic rocks
	MUR	Murphy Spring	undivided volcanic rocks
	GSP	"Get Stuck" Spring	latite
	INS	Indian Spring	basalt
Sierran creeks	RCR	Rush Creek	granite, granodiorite
	LCR	Lee Vining Creek	granodiorite
	WCR	Wilson Creek	granodiorite, undivided volcanic rocks
Shoreline springs	SSP	Simon's Spring	lacustrine deposits
	SWS	South West Spring	lake terrace deposits, tufa
	MAS	Marina Spring	lake terrace deposits, tufa
	CPA	County Park Spring	lake terrace deposits, tufa
	BES	"Blue Eye" Spring	lacustrine deposits
	MVS	Mona Vista Spring	alluvium
	SUL	Sulfur Pond Spring	aeolian deposits
Warm springs	WAS	Warm Spring	lacustrine sediments
	NWS1-4	warm springs at Navy Beach	lacustrine sediments, tufa
	STW	South Tufa West	lacustrine sediments, tufa
	DCH	DeChambeau well	lacustrine sediments
Mono Lake	MLK	Mono Lake	

bonate was replaced by Cl. The samples were centrifuged, and 0.5 mL of the solution was passed through an exchange column. The residual was dried, redissolved in 2-mL Milli-Q water, and loaded on H₃PO₄ primed tantalum filaments. For standardization, the NBS 987 standard was run with each measurement cycle. The ⁸⁷Sr/⁸⁶Sr ratios measured for the standard were 0.710238 and 0.710242.

Results

The results of the major ion analysis are shown in Table 3 and Figure 2. The variety of the water chemistry is clearly apparent in electrical conductivities that range from 56 μS/cm in the creeks to 98,000 μS/cm in the lake. The pH values lie between 6.4 and 9.8. The shoreline springs are all basic, while the warm springs are all slightly acidic, and have the lowest pH values in the basin (pH, 6.3–6.6).

Calcium and Mg concentrations are the dominant cations in creek, mountain spring, and shoreline waters with low pH. However, they are low in the Na-dominated lake and high-pH shoreline springs. In the lake, Na is ~10,000 times more concentrated than in the creeks, while K is only 2000 times more concentrated. The Cl concentration increases by a factor of 3000 from the streams to the lake. Waters are generally HCO₃ dominated, with increased SO₄ and Cl concentrations in the lake and the warm spring water. Mono Lake contains 406 mg/L B, accounting for 7% of its alkalinity.

Table 2. Analytical Methods Used and Uncertainties, Expressed as Percent Standard Deviation

Element	Method	Uncertainty
Na, K	AAS, air/acetylene flame	3.9%, 5.3%
Ca, Mg, Sr	AAS, nitrous oxide/acetylene flame	3.3%, 6.3%, 4.7%
HCO ₃	alkalinity titration	3.1%
Cl	titration, mercuric nitrate	6.3%
SO ₄	liquid chromatograph	2.0%
B	photometric, curcumin method	3.1%
SiO ₂	photometric, molybdate blue	1.0%
⁸⁷ Sr/ ⁸⁶ Sr	thermal ionization mass spectrometry	0.03%

AAS denotes atomic absorption spectrophotometry.

The Sr isotopic distribution in the waters is shown in Figure 3 and Table 3. The creeks have high and uniform ⁸⁷Sr/⁸⁶Sr ratios: 0.7097 for RCR and LCR, and 0.7094 for WCR. The creeks drain granitic/granodioritic and metamorphic terrains and have similar Sr isotopic ratios, despite the different source areas of the streams. The mountain springs have the lowest ratios in the basin, 0.7054–0.7064. INS, located on Cowtrack Mountain in the southern part of the basin, has nearly the same ratios as the springs in the Bodie Hills in the north. DRY is an exception; its ratio of 0.7081 is higher than all the other mountain spring ratios.

The ratios of the shoreline springs show no homogeneous pattern as the two former groups. SWS, MAS, BES, and MVS, the springs along the Sierra Nevada, have ratios close to the Sierran creek compositions. SSP and SUL also have lower ratios (0.7084 and 0.7088, respectively). The four warm springs at Navy Beach have very uniform ratios, 0.7088–0.7089. WAS, at the southeast side of the lake, shows a lower ratio (0.7081). Warm water from DCH has a low ratio of 0.7071, close to the ratios of waters from the Bodie Hills. Mono Lake's ratio of 0.7096 is the same ratio as the Sierran creek waters. The waters in the basin fall into three groups: mountain spring waters with low ⁸⁷Sr/⁸⁶Sr ratios, some shoreline springs and the warm springs with intermediate ratios, and creeks and groundwater from the Sierra with more radiogenic ratios.

Discussion

Although the creeks come from different regions of the Sierra Nevada, their water chemistries are similar. The abundance of cations has the same order: Ca > Na > Mg > K. *Feth et al.* [1964] and *Garrels and MacKenzie* [1967] attributed the cation ratios found in the creeks to the weathering of feldspars to kaolinite and montmorillonite. *Garrels and MacKenzie* [1967] explained high calcium values by dissolution of small amounts of carbonates. The abundance of the anions is HCO₃ > Cl > SO₄. The waters generally follow the same trend as observed by *Feth et al.* [1964], but the Cl and SO₄ concentrations are higher. All creek waters have a Ca/HCO₃ ratio <1 meq/L. This ratio is crucial for the further evolution of the water in the basin. In a process that *Hardie and Eugster* [1970] and *Eugster and Jones* [1979] described as chemical

Table 3. Chemical Composition and Physical Properties of Samples From Mono Basin

Source	pH	T, °C	EC, μS/cm	SiO ₂ , mmol/L	Alk, mmol/L	SO ₄ , mmol/L	Cl, mmol/L	B, mmol/L	Ca, mmol/L	Mg, mmol/L	K, mmol/L	Na, mmol/L	Sr, mmol/L	⁸⁷ Sr/ ⁸⁶ Sr
<i>Mountain Springs</i>														
COY	8.2	7.0	239	0.77	4.53	0.16	0.41	0.018	1.08	1.18	0.10	1.00	0.0087	0.7064
MUR	8.2	13.8	107	0.62	0.93	0.09	0.15	0.011	0.22	0.20	0.06	0.39	0.0009	0.7054
GSP	7.7	9.1	81	0.61	1.02	0.05	0.23	<0.002	0.26	0.35	0.09	0.24	0.0016	0.7057
INS	7.9	10.0	65	0.52	1.37	0.23	0.24	0.008	0.35	0.51	0.08	0.43	0.0025	0.7064
DRY	7.2	6.4	32	0.99	0.45	0.02	0.15	0.008	0.06	0.05	0.10	0.27	<0.0005	
<i>Sierra Nevada Creeks</i>														
RCR	8.0	10.3	67	0.14	0.45	0.04	0.20	<0.002	0.20	0.07	0.02	0.12	<0.0005	
RCRII	6.4	3.0	59	0.10	0.53	0.03	0.23	0.002	0.23	0.09	0.03	0.13	0.0002	0.7097
LCR	6.8	6.8	65	0.15	0.15	0.13	0.24	0.003	0.19	0.06	0.01	0.12	<0.0005	
LCRII	6.6	1.0	57	0.15	0.39	0.05	0.15	0.003	0.14	0.05	0.02	0.09	0.0002	0.7097
WCR	7.8	9.2	73	0.19	0.43	0.13	0.20	<0.002	0.28	0.05	0.03	0.11	<0.0005	
WCRII	6.8	1.0	76	0.14	0.55	0.14	0.20	<0.002	0.33	0.09	0.03	0.11	0.0004	0.7094
<i>Shoreline Springs</i>														
SSP	7.7	15.0	158	0.87	1.37	0.22	0.23	0.004	0.09	0.78	0.12	0.75	<0.0005	0.7084
SWS	7.5	13.0	173	0.86	1.38	0.13	0.23	0.009	0.23	0.26	0.06	0.80	<0.0005	0.7095
MAS	8.1	11.5	178	0.45	1.80	0.09	0.22	0.018	0.70	0.25	0.06	0.38	0.0014	0.7100
CPA	7.5	9.2	193	0.45	1.77	0.11	0.08	0.015	0.68	0.34	0.04	0.23	0.0016	0.7081
BES	8.2	12.8	170	0.29	1.98	0.08	0.16	0.006	0.70	0.15	0.05	0.57	0.0014	0.7092
MVS	9.3	11.0	698	0.23	4.38	0.09	1.46	0.592	0.01	0.05	0.85	5.1	<0.0005	0.7098
SUL	9.6	14.0	768	0.65	9.41	0.98	0.59	1.138	0.03	0.01	1.16	12.2	<0.0005	0.7088
<i>Thermal Springs</i>														
WAS	6.8	30.0	3,446	1.92	26.1	0.91	6.53	0.721	1.27	3.64	1.43	25.4	0.0083	0.7081
NWS1	6.6	35.5	3,303	2.14	30.8	0.39	4.05	0.712	3.61	5.82	1.33	19.7	0.0106	0.7089
NWS2	6.4	23.8	2,700	1.87	23.3	0.34	2.93	0.499	3.82	4.14	0.64	13.1	0.0114	0.7088
NWS3	6.5	29.9	3,550	2.16	30.8	0.54	4.46	0.916	2.39	5.16	1.09	22.8	0.0110	0.7088
NWS4	6.5	33.9	2,701	2.09	25.5	0.36	2.80	0.490	3.39	4.41	0.99	15.5	0.0098	0.7089
STW	6.8	13.8	1,781	1.54	19.2	0.25	1.76	0.287	3.60	1.91	0.56	8.1	0.0083	0.7089
DCH	7.9	63.0	1,880	1.20	6.90	0.99	9.78	0.684	0.37	0.24	0.21	17.1	0.0029	0.7071
<i>Mono Lake</i>														
MLKII	9.8		98,000	0.22	430	139	618	37.554	0.10	1.71	44.1	1490	<0.0005	0.7096

T denotes temperature; EC, electrical conductivity; and Alk, alkalinity.

divides, evaporation and concentration of water of this ratio will lead to calcium carbonate precipitation, resulting in bicarbonate-rich and calcium-poor lake water.

The wide range of Sr isotopic ratios in the waters (0.7054–0.7100) resembles the variety of the bedrock ratios (Figure 4, Table 4). Generally, the ⁸⁷Sr/⁸⁶Sr ratios in basalts and tuffs are low and range from 0.7052 to 0.7068, with few higher exceptions [Kelleher and Cameron, 1990; Halliday et al., 1984]. Granites range from 0.7069 to 0.7074 [Kistler and Peterman, 1973]. More radiogenic values are found in quartz monzonites (0.7160–0.7243 [Evernden and Kistler, 1970]), and Upper Permian metamorphosed rocks (0.7046 and 0.7281 [Kistler, 1966b]).

Creeks

The creeks have very homogeneous ⁸⁷Sr/⁸⁶Sr ratios (0.7097, 0.7097, 0.7094) that are far greater than the ratios measured for Sierran rocks [Kistler and Peterman, 1973], in the range of metamorphic rocks [Kistler, 1966b], and below the ratios of the quartz monzonites [Evernden and Kistler, 1970]. The ratios in the three creeks are very similar, despite the different source areas of the streams.

The Sr isotope ratios found in the creek waters are high, considering that the granodiorites that cover about one half of the area have generally low Sr ratios. The quartz monzonites have high Sr ratios, but are described for the Lee Vining canyon only, and have relatively low Sr concentrations. If they are only locally abundant, monzonite weathering cannot ex-

plain the homogeneous ratios in the creeks. To explain the Sr ratios in the water, selective mineral weathering of the rocks must be occurring. The Sr isotopic ratios are not the same throughout the rock but vary between different minerals [Faure and Powell, 1972]. This is a result of the decay of ⁸⁷Rb and the production of radiogenic ⁸⁷Sr. Rubidium 87 behaves chemically and physically like K and is enriched in micas, e.g., in the abundant biotite and muscovite, and in K-feldspars [Faure and Powell, 1972]. These minerals will have higher Sr isotopic ratios than minerals with low K/Rb ratios. If micas weather faster than the other main rock constituents (quartz and plagioclase), the Sr isotopic ratio in the water will be more radiogenic than the value measured for the whole rock. Biotite tends to weather rapidly [Nesbitt et al., 1980]. Nimz et al. [1992] suggested that relatively high K-feldspar weathering rates produce the high Sr ratios in groundwater in the Wawona Basin on the western side of the Sierra Nevada. Chemical speciation modeling using PHREEQE [Parkhurst et al., 1980] indicates that the creek waters are undersaturated with respect to anorthite and K-feldspar. However, the short residence time and high water/rock ratios may not let the system equilibrate, limiting the use of equilibrium-based thermodynamic modeling.

Meteoric water, assumed to have ⁸⁷Sr/⁸⁶Sr ≈ 0.7091 (ratio of seawater [Jones and Faure, 1972]), is a second potential cause of higher Sr isotope ratios. The creek waters have about 20 times the total dissolved solids (TDS) of rainwater and snowmelt [Feth et al., 1964], so the influence of the rainwater is

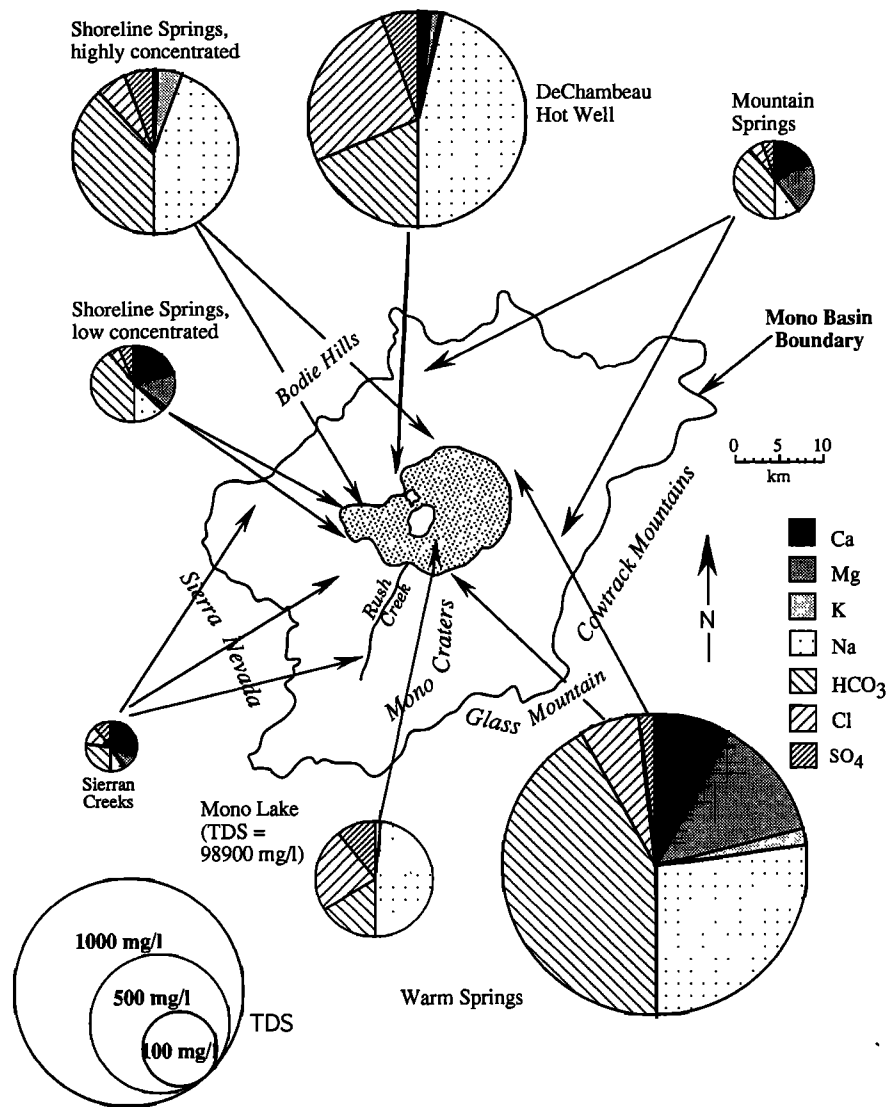


Figure 2. The pie diagram gives an overview of the different water types encountered in Mono Basin. The area of the pies represents the total dissolved solids (in milligrams per liter) of the waters, except for Mono Lake water, which is too highly concentrated to be drawn in scale. The shape of the pie pieces is based on the relative concentration of the cations and anions in milliequivalents per liter.

probably small. For creeks in watersheds of neighboring Yosemite National Park, *Blum et al.* [1994] calculated that rain-water contributes 0.3% of the Sr in the creeks. *Barnes et al.* [1981] gave ratios between 0.7063 and 0.7088 for different possible Paleozoic limestones in the roof pendants in the High Sierran parts of the watershed. These ratios are not radiogenic enough to explain the observed ratios in the creeks. Also, the chemical composition of the creeks measured resembles waters coming from granitic areas, described by *Garrels and MacKenzie* [1967] and *Feth et al.* [1964], thereby making the influence of the limestone weathering to the water questionable. The weathering of monzonites could produce water of very high ratios, but these rocks have been described only in Lee Vining Canyon. Thus preferential weathering, which influences wide areas equally, appears to be the best explanation for the Sr ratios in the creeks.

Mountain Springs

The mountain springs originate in volcanic rocks around Mono Basin and are all located above lake sediments [*Neumann, 1993*]. They show a broader range of ionic concentrations and more diverse chemistries than the Sierran creeks. Conductivities (32–239 $\mu\text{S}/\text{cm}$) and TDS (49–414 mg/L) range over nearly one order of magnitude. A higher Mg relative to Ca concentration is the main difference between the springs in the volcanic area and the granitic Sierra. The mountain springs have the lowest $^{87}\text{Sr}/^{86}\text{Sr}$ values in the basin, 0.7054–0.7064. DRY is an exception: Its ratio of 0.7081 is higher than all the other mountain spring values.

The springs in the volcanic Bodie Hills and Cowtrack Mountain have ratios similar to those in the bedrock. Unlike the Sierran granites the volcanic rocks contain a glassy matrix. The

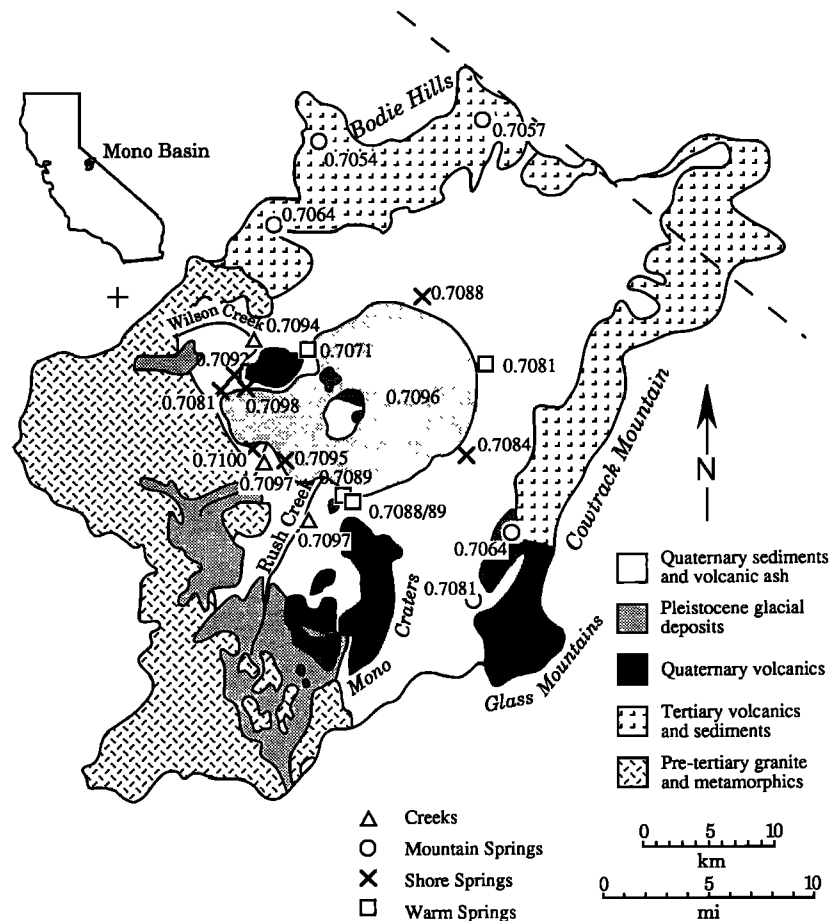


Figure 3. Graphic overview of the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios found in the spring waters. Values are listed in Table 3.

matrix is susceptible to chemical weathering and contains the majority of the Sr [Halliday *et al.*, 1984]. Most importantly, the isotopic composition of the glass and the whole rock is the same. Water reacting with the glassy matrix should yield the whole rock Sr isotopic ratio, which is the case for COY, MUR, GSP, and INS.

It is remarkable that all the springs emanating from volcanic rocks, except DRY, have the same low isotope ratio, regardless of their location in the basin. Unlike the bedrock ratios of the Sierra Nevada rocks, all the bedrock ratios in the volcanic rocks are in the same range. This range is similar to that of the spring waters, and it does not require additional weathering processes to produce the ratios found in the mountain springs. The higher ratio of DRY can be a result of the high part of meltwater contributing to this spring. Mixing of 89% meltwater (data from Feth *et al.* [1964]) and 11% average mountain spring water produces water with the isotopic composition of DRY.

Shoreline Springs

Shoreline springs lie in the lower, sediment-filled part of Mono Basin and, in general, have higher conductivities and TDS than the mountain springs or the creeks (electrical conductivity (EC), 158–768 $\mu\text{S}/\text{cm}$; TDS 143–988 mg/L). This is caused by longer groundwater flow paths, and, for several springs, by mixing with highly concentrated pore waters near the lake. The chemistry of these waters is the most diverse of all the water groups. The shoreline springs fall in two sub-

groups: (1) Na- and K-dominated MVS and SUL and (2) others with a more diverse, Ca- and Mg-dominated composition.

The springs located at the northwestern edge of the lake (MAS, CPA, and BES) have an ionic composition similar to the Sierran creek waters. Water flows through fractures in the granitic bedrock of the Sierra Nevada and then enters the alluvial material that interfingers with lake sediments [Rogers *et al.*, 1992]. *Los Angeles Department of Water and Power* [1984] suggested percolation of streamflow as an additional water source for the springs at the western shore. Irrigation accounts for some of the recharge at CPA. Chemical equilibrium modeling with PHROFITZ [Plummer *et al.*, 1988] reveals that unlike the surface runoff from the Sierra, these three springs are supersaturated with respect to calcite. Very different chemistries are encountered at MVS, a small spring close to Black Point, and SUL, an artesian well on the north side of the lake (Figure 2). Their relatively high pH (9.3 and 9.6, respectively) and high TDS (471 and 987 mg/L, respectively), and a Na-dominated chemistry separate them from the other shoreline springs. Their chemistries resemble lake water chemistry, but the TDS is much lower: Both springs produce a water that is a mixture of 0.3–0.7% lake water and fresh groundwater, based on Na and Cl concentrations. High B concentrations in MVS and SUL water require mixing either with 1.7–3.0% lake water or an additional source, such as groundwater influence from

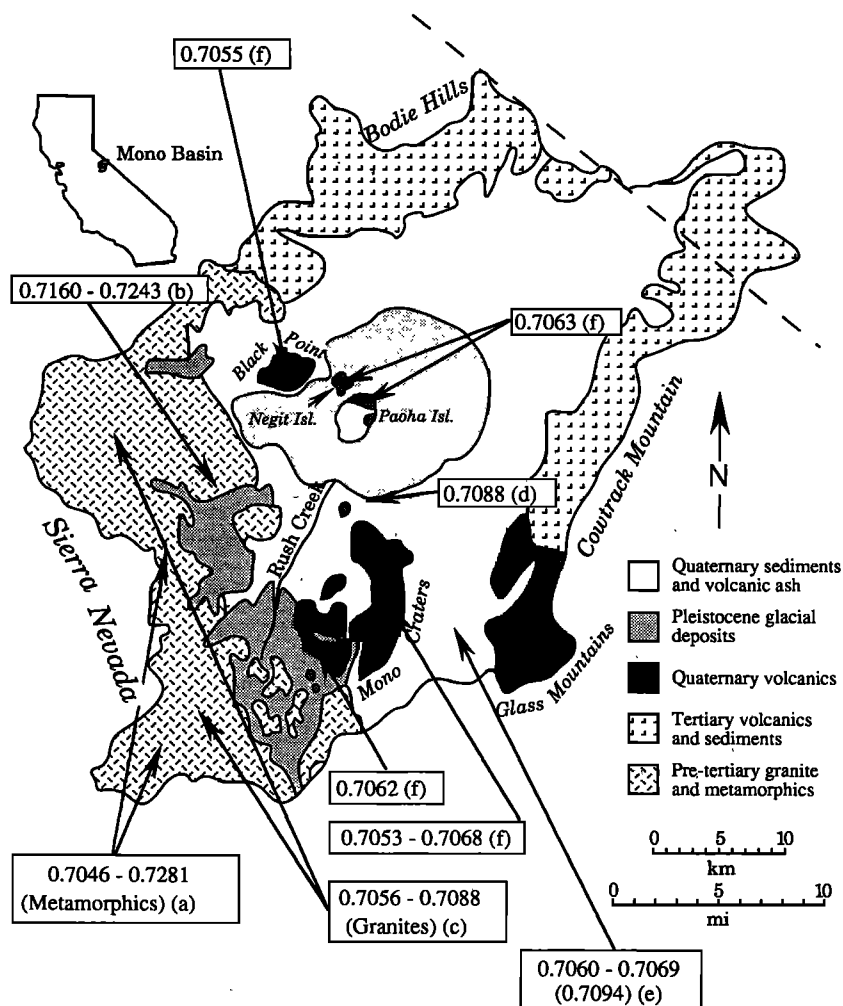


Figure 4. Strontium 87/strontium 86 ratios of the bedrock in Mono Basin. Data from *Kistler* [1966a, b] (sites labeled a), *Evernden and Kistler* [1970] (sites b), *Kistler and Peterman* [1973] (sites c), *Barnes et al.* [1981] (sites d), *Halliday et al.* [1984] (sites e), and *Kelleher and Cameron* [1990] (sites f). Detailed values and bedrock type are listed in Table 4.

the relatively young (13,300 years age, *Bursik and Sieh* [1989]) volcanics at Black Point.

The differing Sr ratios reflect the different geologic and hydrologic settings: springs at the west side of the lake with ratios between 0.7090 and 0.7100 and springs along the other shores with ratios between 0.7080 and 0.7089 (Figure 3). SWS, MAS, BES, and MVS ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7092\text{--}0.7100$) have ratios close to those of the Sierran creeks. The same processes discussed earlier (selective weathering, high-ratio rocks) probably

cause these ratios. The Sr isotopic ratio of CPA (0.7081) is lower than the ratios of the other shoreline springs on the Sierra Nevada side. This indicates mixing with groundwater with low Sr isotopic ratios, as observed in the waters from the volcanic areas.

SUL, the artesian well on the north shore, has a lower ratio of 0.7088. Na and K concentrations suggest SUL is a mixture of ~99% mountain spring water and <1% Mono Lake water. However, this mixing proportion does not result in the ob-

Table 4. Published Whole Rock and Water $^{87}\text{Sr}/^{86}\text{Sr}$ Ratios for Mono Basin

Author	Rock Type	$^{87}\text{Sr}/^{86}\text{Sr}$
<i>Kistler</i> [1966b]	mesozoic metamorphites	0.7046, 0.7081, 0.7116, 0.7105, 0.7281
<i>Evernden and Kistler</i> [1970]	quartz monzonite	0.7160, 0.7211, 0.7243
<i>Kistler and Peterman</i> [1973]	granitic rocks	0.7074, 0.7072, 0.7069, 0.7072, 0.7070, 0.7074, 0.7088, 0.7056, 0.7061
<i>Barnes et al.</i> [1981]	thermal water at South Tufa	0.7088
<i>Halliday et al.</i> [1984]	rhyolite	0.7060, 0.7067, 0.7084, 0.7094, 0.7069, 0.7069
<i>Kelleher and Cameron</i> [1990]	basalt	0.7045, 0.7062, 0.7052
	rhyolite, dacite	0.7063, 0.7063, 0.7068

served Sr ratio and concentration. To obtain the observed $^{87}\text{Sr}/^{86}\text{Sr}$ ratio, the lake water has to be 98%. One process that could cause the observed ratio is precipitation of calcite in the subsurface, resulting in the depletion of Ca and Sr in the mountain spring water. Coprecipitation of Sr as a dilute solid solution in calcite alone should not change the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the water [Pingitore *et al.*, 1992], but Bischoff *et al.* [1993] found at the Navy Beach warm springs that virtually all the Ca of the warm spring water is precipitated when groundwater mixes with lake water. Therefore Sr should be precipitated too. If this is so, nearly all the Sr with mountain spring composition (low $^{87}\text{Sr}/^{86}\text{Sr}$) is removed from the water when calcite is precipitated. Evidence for this Ca precipitation and Sr loss is that the Ca concentration of SUL (1.2 mg/L) is lower than the Ca concentration in the possible mixing end-members (MLK 4.0 mg/L, MUR 8.6 mg/L, COY 43.3 mg/L), and the saturation of SUL with respect to calcite (saturation index, 0.0153, calculated with PHRQPITZ). If all or most of the Sr is removed from the inflowing water, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the remaining solution should be more dominated by lake water than one might expect from the Sr concentration of the lake. The same process could produce the Sr ratios in two other shoreline springs, MVS and SSP. In both cases the amount of lake water needed to obtain the observed Sr ratios would be more than 40%, while using anions like chloride to calculate the mixing does not allow a lake water contribution of more than 1%.

Thermal Springs

The warm springs on the east and the south side of the lake and DCH have electrical conductivities (1780–3550 $\mu\text{S}/\text{cm}$) that are an order of magnitude higher than in the shoreline springs. Except for DCH with its pH of 7.9, the pH values of the creeks (6.4–6.8) are the lowest in the basin. The warm springs on the eastern and southern shore are Na dominated, but have relatively high contents of Ca and Mg, while DCH has a NaK-Cl composition and only traces of Ca. High boron concentrations (5.3–7.7 mg/L) are often measured in thermal springs and are common in other thermal springs in this area [Mariner *et al.*, 1977]. Boron concentrations in the thermal springs measured by us are actually lower than in some shoreline springs and the lake.

The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the four Navy Beach warm springs are nearly identical (0.7088–0.7089). These ratios eliminate heated surface runoff from the Sierra Nevada (~ 0.7096) as a source water for the warm springs. Water coming from the volcanic Mono Craters should have a ratio between 0.7052 and 0.7068 (whole rock composition [Kelleher and Cameron [1990]]). Mixing of Sierran and volcanic waters alone can produce the observed Sr isotopic ratios, but it would not produce water with the high concentration of Na, Ca, Mg, and Sr. Earlier work [Mariner *et al.*, 1977] explained the composition of the Navy Beach warm spring waters by the mixing of recycled lake water and groundwater. This does not appear to be the case as (1) mixing with lake water could account for the high chloride, but not for high Ca, Mg, or bicarbonate [Bischoff *et al.*, 1993]; (2) the radiocarbon age of the warm spring water is $>22,000$ years B.P. [Oremland *et al.*, 1987], too old to allow lake water with its nearly present day ^{14}C age to be largely involved; and (3) $\delta^{13}\text{C}$ of the warm spring water is -0.97‰ [Neumann *et al.*, 1995]. In case of mixing, lake water ($\delta^{13}\text{C}$, $+2.21\text{‰}$) with its high bicarbonate concentration would dominate and produce a heavier $\delta^{13}\text{C}$ than is observed.

Barnes *et al.* [1981] suggested Middle Carboniferous meta-

morphic limestones with strontium isotopic ratios of 0.7088 as a possible source for the Sr and the high Ca concentration in the Navy Beach warm springs. Goff *et al.* [1991] suggested that the dissolution of marble ($^{87}\text{Sr}/^{86}\text{Sr} = 0.70904$) could explain the similar Sr isotopic ratios in thermal waters found in neighboring Long Valley caldera. Middle Carboniferous carbonates have $\delta^{13}\text{C}$ ratios of $+2\text{‰}$ [Lindh, 1983], and dissolution of those rocks, plus mixing with less radiogenic, shallow groundwater could cause the rather heavy $\delta^{13}\text{C}$ ratios in the warm springs, as well as the observed Sr isotopic ratios. Mixing of warm spring water with water from the Sierra Nevada does not significantly influence the Sr isotopic ratio in the warm springs, because the Sr concentrations in the Sierran waters are very low.

In summary, the water in the Navy Beach warm springs (1) is primarily warm, deep circulating groundwater that did not originate in the lake, (2) was probably in contact with Paleozoic carbonates, and (3) is mixed with a small fraction of cold, fresh groundwater from the Sierra Nevada and the Mono Craters.

The Sr isotopic ratio (0.7081) of WAS at the southeastern shore of the lake is significantly lower than at Navy Beach. Mixing $\sim 0.5\%$ lake water with Navy Beach waters increases SO_4 , Cl, and Na concentrations sufficiently to produce WAS water. But both Navy Beach water and MLK have $^{87}\text{Sr}/^{86}\text{Sr}$ ratios higher than WAS. This can be explained by the mixing of a deep source thermal water with a similar composition as Navy Beach warm springs with a small amount of lake water and a significant amount of mountain spring water with its low ratios (0.7064 for INS). Like at CPA, the increasing influence of low-Sr ratio, non-Sierran water can be observed in the change of Sr isotopic ratios.

DCH, with its ratio of 0.7071, is unlike the other warm springs. It has a Na- and Cl-dominated chemistry, the only one collected in this study. NaCl water has also been reported for springs on Paoha Island by Lee [1969], Welhan *et al.* [1988], and Basham [1988]. The high temperature of the water results from the high thermal gradient at the site. At a depth of only 287 m, the water already has a temperature of 63°C [Axtell, 1972].

The Sr ratio of DCH (0.7071) is close to those of the Bodie Hills (0.7054–0.7064), making recharge from this location the most likely option for its source. Rogers *et al.* [1992] proposed that water from the Sierra Nevada might reach this area in the subsurface. Slightly higher Sr isotopic ratios in DCH compared to the Bodie Hill waters support this idea. High Na, Cl, and B concentrations in DCH require mixing with 1.1–1.8% lake water.

Mono Lake

Mono Lake's $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7096 is similar to the ratios of its main water contributors, the Sierra Nevada creeks. This supports the notion that the majority of the water in the lake is from the western part of the basin. Interestingly, the 7% inflow from the volcanic mountains [Vorster, 1985] has no effect on the isotopic composition of the lake. Taking into account this 7% of low-ratio water from the volcanic areas, the expected Sr ratio for the lake would be between 0.7089 (assuming the same Sr concentration in all sources) and 0.7081 (if one considers that the waters from volcanic areas have higher Sr concentrations than the waters from granitic areas). As suggested earlier, much of the Sr in the groundwater from the volcanic mountains to the north, east, and south might be lost via precipitation as CaCO_3 before it reaches the lake. Most water from the

Sierra reaches Mono Lake via streams, which are undersaturated with respect to calcite. Therefore no loss of Ca and Sr on the way to the lake has occurred. Jones and Faure [1972] observed similar processes in their investigation of Sr isotopic ratios in the Great Salt Lake (GSL), Utah, which has a setting like Mono Lake. Located in a desert basin, the GSL receives most of its recharge from the adjacent Wasatch Mountains. The Sr isotopic composition of the Great Salt Lake represents the ratio of the weighted averages of the Sr ratios of the tributaries. Jones and Faure [1972] did not discuss the influence of subterranean inflow. It appears that the Sr ratio of the surface water inflow, rather than that of the total inflow, determines the Sr ratio in hypersaline, bicarbonate-dominated lakes.

Differences in the Sr/Ca ratios in the waters also are influenced greatly by different bedrock types. Mountain springs, originating in volcanic areas, show a distinctly different Sr/Ca ratio than springs fed by Sierran water (Figure 5). The Navy Beach warm springs ratios differ from them but are closer to the Sierran composition (Figure 5). This is in accordance with our conclusion that they are not simply heated, unaltered waters from granitic areas. DCH and WAS, on the other hand, closely resemble the "volcanic" line. One of the Navy Beach warm springs, NWS3, also seems to be influenced by water from volcanic-dominated areas.

A $^{87}\text{Sr}/^{86}\text{Sr}$ versus Sr/Ca plot (Figure 6) emphasizes many of the observed relations between the different waters. The mountain springs cluster in the area of high Sr/Ca and low $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. The Sierran creeks lie close together, marked by low Sr/Ca and high Sr ratios. The shoreline springs of the western part of the basin lie close to the creeks, indicating their common origin in Sierran rocks. CPA lies toward lower Sr isotopic ratios and higher Sr/Ca ratios, demonstrating the possible influence of water from the Bodie Hills. The springs of the northern and eastern sites are not plotted, since their Sr concentrations were below detection limit. NWS1, NWS2, and NWS4 are nearly indistinguishable. NWS3 comes from the same location and has the same Sr isotopic ratio, but has a higher Sr/Ca ratio than can be produced by mixing with water of volcanic composition. WAS on the eastern side of the lake and DCH are shifted even more toward mountain spring com-

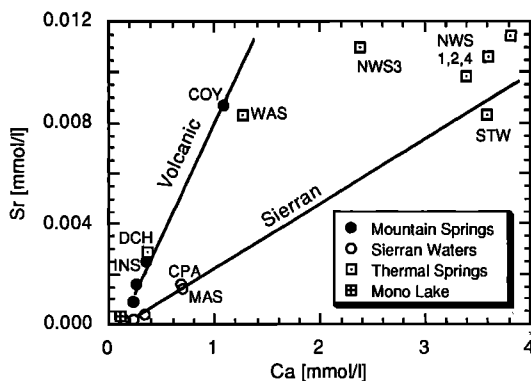


Figure 5. Sr versus Ca plot of Mono Basin waters. GSP, INS, DCH, and COY originate in volcanic bedrock and fall onto the "volcanic" line. The average Sr/Ca ratio is 0.0088. MAS, CPA, and STW waters plot on the "Sierran" line and originate in igneous and metamorphic regions. Their average Sr/Ca ratio is 0.0025.

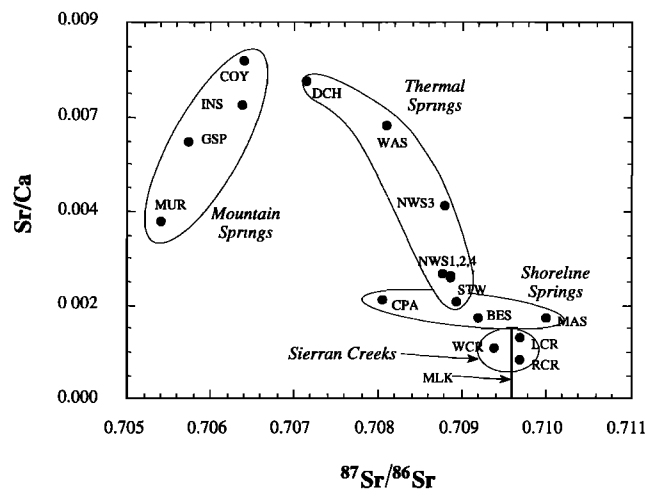


Figure 6. Sr/Ca ratios versus $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for waters of Mono Basin. Mono Lake is plotted as a range of possible Sr concentrations <0.0005 mmol/L. Note the similar location of MLK and its main tributaries.

position. DCH certainly originates in a different setting than the Navy Beach warm springs, while WAS appears to have the same origin but is altered by mixing with other waters. For Mono Lake the range of possible Sr/Ca ratios is shown (Sr, <0.5 mg/L). The range overlaps with the composition of the creeks, the main contributors to the lake.

Conclusions

1. For the waters within the basin, $^{87}\text{Sr}/^{86}\text{Sr}$ ratios prove to be a powerful tool for determining source areas. Groundwater inherits the different Sr isotopic ratios of the bedrocks it flows through.
2. Selective weathering is an important process in determining the Sr isotopic ratio of waters originating in granitic rocks. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the creeks are more radiogenic than the whole rock ratios. In volcanic rocks, such a phenomenon does not need to be invoked as the waters closely resemble the rock ratios.
3. In areas where different types of groundwaters mix, it is possible to calculate the relative amounts of water from each source using Sr isotopic ratios. The change from Sierran-dominated to mixed to volcanic-dominated groundwater can be documented.
4. In the areas close to the lakeshore, where groundwater has high bicarbonate concentrations, extensive Ca and Sr removal from the waters via CaCO_3 precipitation makes the tracing of different waters difficult, if not impossible. To test this hypothesis (i.e., a selective "stripping" of the groundwater Sr), it is necessary to measure Sr ratios in the basin fill, the tufa, and other authigenic Ca precipitates surrounding the lake.
5. The $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{13}\text{C}$ measurements support previously proposed theories in which the dissolution of Paleozoic limestones serves as a source for both Sr and C in the warm springs on the southern shoreline of Mono Lake. This is apparently not the source for DCH at the northern shore.
6. The Sr isotopic composition of Mono Lake represents exclusively the ratios in surface waters entering the lake from the Sierra Nevada. Groundwaters entering the lake seem to have no effect on the ratio in the lake.

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