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Geochemical and statistical evidence of deep carbonate groundwater within overlying volcanic rock aquifers/aquitards of southern Nevada, USA

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Abstract

Samples collected from springs and wells in southern Nevada were analyzed for major solutes and trace elements as part of a larger study to characterize the geochemical signatures of these groundwaters. In this study, principal component analysis (PCA) was used to reduce the large data sets, including the four major cations (Ca, Mg, Na, K) and 27 trace elements, analyzed in these groundwater samples. Principal components analysis of the major cation data indicates that groundwaters from Cenozoic felsic volcanic rock aquifers/aquitards of southern Nevada exhibit strong chemical associations to each other but weak relationships to groundwaters from the regional carbonate aquifer (which were instead chemically similar to each other). However, PCA of the trace element data demonstrates that some groundwaters from the volcanic aquifers/aquitards are chemically similar to those of the underlying regional carbonate aquifer. The PCA also reveals that these groundwaters from the volcanic aquifers/aquitards have significantly different trace element compositions than perched groundwaters contained within similar felsic volcanic rocks. Moreover, rare earth element (REE) data from groundwaters collected from wells finished in the volcanic aquifers/aquitards of southern Nevada have similar concentrations and similar shale-normalized patterns to the carbonate aquifer groundwaters as well as local carbonate rocks. These same southern Nevada well waters do not exhibit REE concentrations or shale-normalized signatures that resemble the perched volcanic groundwaters or the tuffs of southern Nevada. The REE data and trace element PCA, along with previous carbon isotope analyses, water temperature data, hydraulic head relations, and results of a recent pump test of a well near Yucca Mountain, suggest close contact of the regional carbonate groundwaters and groundwaters from the overlying volcanic rocks of southern Nevada and possible upwelling of the carbonate groundwaters into the overlying volcanic rock units in the vicinity of Yucca Mountain. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Groundwater; Water–rock interaction; Trace elements; Multivariate statistics; Carbonate aquifer; Volcanic aquifer

1. Introduction

In apparent contrast to the arid climate, there are many large discharge springs in southern Nevada, including those located in Pahranagat (Valley) National Wildlife Refuge, Ash Meadows National Wildlife Refuge, and Death Valley National Park in California (Fig. 1). Previous investigators argued that the waters discharging from these springs reflect inter-basin flow of groundwaters from neighboring basins as well as basins and mountain ranges as far north as

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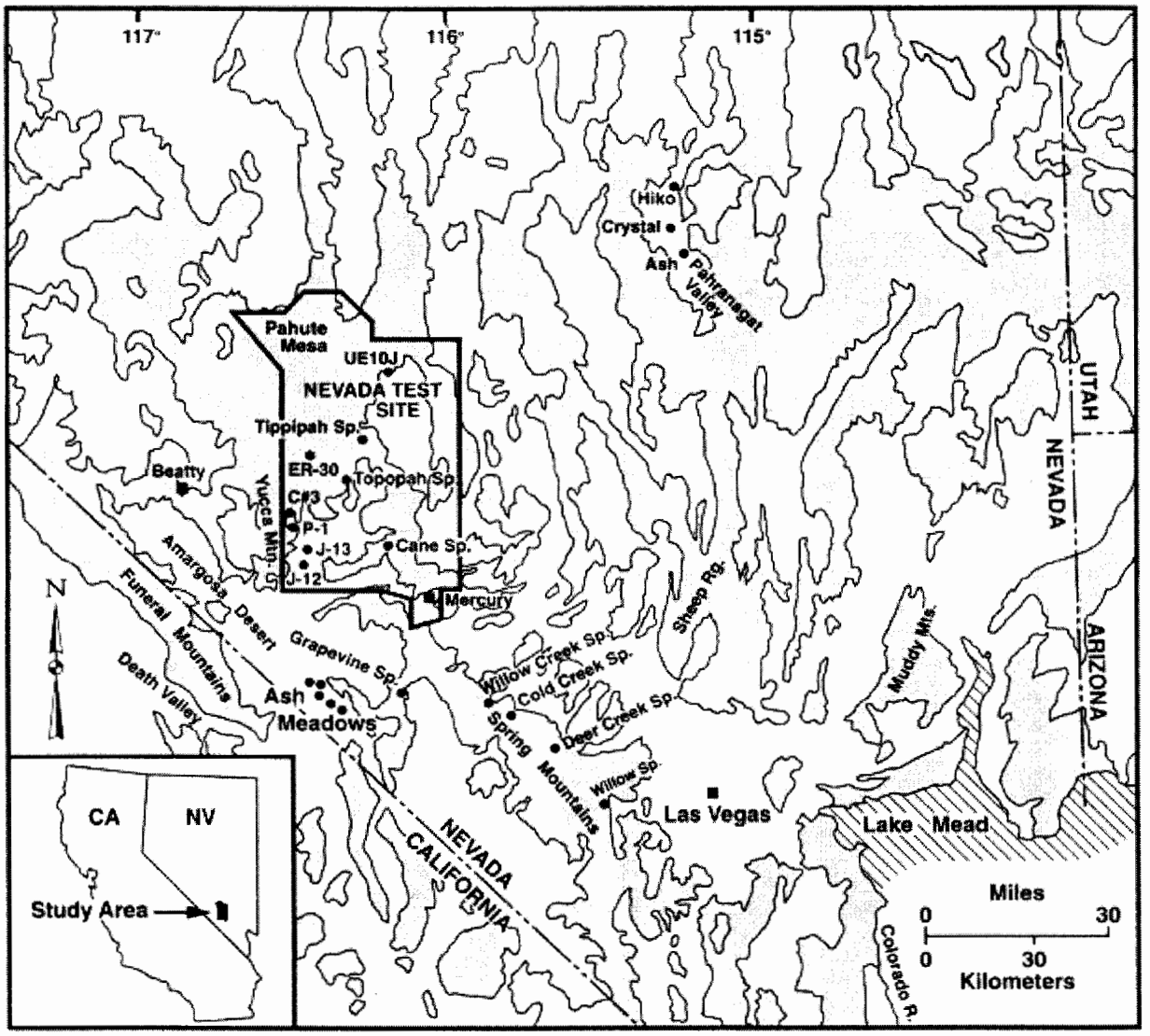

Fig. 1. Map of the study area in southern Nevada showing the locations of springs and wells examined in the current study. In addition, the regions from which groups of samples were collected (Ash Meadows, Spring Mountains, Nevada Test Site/Yucca Mountain, and Pahranagat Valley) are also shown on the map. Mountains and highlands are shown as shaded regions, whereas intermontane basins are unshaded. Wells shown on the map as C#3 and P-1 are UE-25c #3 and UE-25p-1, respectively. For a detailed map of the geographic distribution of the springs within Ash Meadows, see Dudley and Larson (1976) and Hodge et al. (1996).

central Nevada (Eakin, 1966; Winograd and Friedman, 1972; Winograd and Thordarson, 1975; Dudley and Larson, 1976; Winograd and Pearson, 1976; Claassen, 1985; White and Chuma, 1987; Thomas, 1988; Peterman et al., 1992; Thomas et al., 1996; Davisson et al., 1999). Groundwaters issuing from springs in Ash Meadows, for example, are believed to consist of local recharge from the Spring Mountains and interbasin flow from Pahranagat Valley, more than 100 km to the northeast (Fig. 1; Winograd and Friedman, 1972; Cowart, 1980; Osmond and Cowart, 1982). In general, the interbasin groundwater flow is postulated to occur chiefly within aquifers composed of Paleozoic carbonate rocks that underlie the mountains and alluvial/lacustrine deposit-filled basins of eastern and southern Nevada (Winograd

and Thordarson, 1975; Dettinger et al., 1995; Thomas et al., 1996). On the other hand, intrabasin groundwater flow includes both lateral flow and downward percolation of water within overlying Cenozoic felsic volcanic rocks of the region, as well as shallow groundwaters associated with the Quaternary basin-fill deposits, to the underlying Paleozoic carbonate aquifer, which subsequently contributes to the regional flow (Winograd and Thordarson, 1975; Dettinger, 1989; Laczniak et al., 1996). However, the groundwater flow regime is inherently complex and, consequently, poorly understood. Nonetheless, determining the groundwater flow patterns in southern Nevada is important and has been the focus of numerous investigations owing to the proximity of the Nevada Test Site (NTS), the proposed high-level radioactive waste repository at Yucca Mountain (Fig. 1), and the city of Las Vegas, which is one of the fastest growing metropolitan areas in the USA and a city with serious water supply issues (Winograd and Thordarson, 1975; Winograd and Pearson, 1976; Thomas, 1988; Dettinger et al., 1995; Laczniak et al., 1996; Thomas et al., 1996). The poor grasp on the flow regime is exacerbated by the large distances between wells and springs in the region that lead to large spatial gaps in the hydrogeologic data like potentiometric head levels, as well as in the groundwater chemistry data.

The current study is part of a larger project to examine the geochemistry of southern Nevada groundwaters in order to help develop a better understanding of the associated groundwater flow regime. We measured major and trace element concentrations in southern Nevada groundwaters in order to more fully characterize their compositions and to trace the aquifer rocks with which these groundwaters have reacted during flow. Many investigators have shown that groundwaters commonly inherit chemical signatures from the rocks with which they react (e.g., Garrels and Mackenzie, 1967; White et al., 1980; Frape et al., 1984; Hem, 1985; Smedley, 1991). Here we investigate the chemical relationships between spring and well waters from southern Nevada using a suite of major cations (Ca, Mg, K, Na) and 27 trace elements. These data are reduced using the multivariate statistical technique principal component analysis (PCA) to investigate compositional similarities and/or differences between spring and well water samples as a function of their major cation and trace element signatures. The results of the statistical analyses are compared to information gained from previous studies including isotopic, potentiometric head, and water temperature data, and subsequently combined with groundwater rare earth element (REE) and pumping test data to examine and decipher relationships between the "deep" carbonate groundwaters and those groundwaters from the overlying Cenozoic volcanic rock aquifers/aquitards (e.g., Stetzenbach et al., 1999; Farnham et al., 2000).

2. Hydrogeologic setting

The study region contains more than 11 000 m of Precambrian through Paleozoic sedimentary rocks that are principally of marine origin. Additionally, there are roughly 4000 m of rhyolitic and quartz latitic Tertiary volcanic rocks that overlie these Paleozoic rocks, which are themselves overlain in places by Quaternary basin-fill, alluvial, and lacustrine sediments (Winograd and Thordarson, 1975; Plume and Carlton, 1988). The two principal aquifers in the region are the lower Paleozoic (i.e., Cambrian through Devonian) carbonate aquifer that is locally up to 4600 m thick, and the basin-fill aquifers (Winograd and Thordarson, 1975; Dudley and Larson, 1976; Winograd and Pearson, 1976; Claassen, 1985; Thomas et al., 1996). The Tertiary felsic volcanic rocks, which occupy much of the NTS and Yucca Mountain region, have also been identified as important groundwater-bearing units (Winograd and Thordarson, 1975; Peterman et al., 1992; Fridrich et al., 1994).

The Paleozoic carbonate-rock aquifers in southern Nevada are characterized by regional (i.e., interbasin) flow of groundwaters recharged as far north as the mountain ranges of central Nevada (Winograd and Thordarson, 1975; Dettinger et al., 1995; Davisson et al., 1999). Evidence exists that groundwaters of the lower carbonate aquifer of southern Nevada are commonly complex mixtures of groundwaters recharged in different regions and through different aquifer rocks. For example, the regional carbonate groundwaters that discharge from Ash Meadows are thought to be mixtures of groundwaters recharged in

Table 1
Major cation and trace element concentrations for groundwaters from southern Nevada. Major cations are in mM, Li and Sr are in μM, Ti through U are in nM, and the REEs, Re, and Th are in pM

	Big	Bradford	Cold	Crystal pool	Fairbanks	Jackrabbit	Kings Pool	Longstreet	Rogers
mM									
Ca	1.13	1.48	1.92	1.23	1.21	1.21	1.21	1.23	1.22
Mg	0.81	1.19	1.52	0.9	0.87	0.93	0.87	0.88	0.87
K	0.23	0.27	0.38	0.23	0.2	0.21	0.2	0.2	0.2
Na	4.34	4.6	8.29	3.42	3.15	3.66	2.99	3.15	3.1
μM									
Li	15	13.4	20.4	11.6	10.7	11.4	11.3	11	11.1
Sr	11.1	13.4	19.4	10.6	9.69	10.7	9.57	10	10.3
nM									
Ti	14.4	20.9	22.5	20.3	15.8	8.98	14.4	13.7	17.8
V	30.2	43.2	28.7	27	15.5	33.5	29.1	26.1	20
Cr	11.5	96.2	2	8.87	6.54	19.9	6.04	52.5	8.58
Cu	33.1	56.9	53.9	30.3	20.9	24.2	18.3	28	23.6
Zn	13.4	7.93	17.4	6.81	10.8	11.5	16.8	11.9	9.28
As	381	265	231	256	146	335	208	209	239
Rb	190	199	236	200	184	198	173	177	176
Mo	71.6	136	234	77	70.7	103	64.5	66.1	67.7
Sn	1.17	0.67	0.92	0.95	0.51	0.59	1.18	0.7	0.69
Ba	291	296	128	503	401	379	507	388	411
W	1.35	1.45	1.07	1.5	1.16	1.37	1.24	1.15	0.88
U	10	27	29.4	10.9	9.51	13.8	12.6	12	11.1
pM									
La	23.3	16.9	19.9	16.3	33.2	14.8	36	28.8	25.9
Ce	22.9	13.1	34.6	19.1	11.1	22.5	59.9	20	14.6
Nd	9.2	10	13.4	8.7	11.6	7.19	9.6	4.5	23.3
Sm	17.2	5.6	8.7	25.4	9.4	2.53	68.4	19.6	14.5
Gd	2.7	2.5	3.4	2.3	2.5	1.6	1.9	0.89	4.3
Tb	0.21	0.19	0.46	0.32	0.35	0.12	0.03	0.03	0.69
Dy	2.3	2.4	3.35	1.6	2.5	1.17	2	0.84	3.5
Ho	0.53	0.59	0.67	0.5	0.4	1.31	0.26	0.84	0.7
Er	1.92	1.8	2.27	0.94	1.4	0.84	1.2	0.58	2
Yb	1.2	1.8	1.95	0.9	1.1	1.52	1.5	0.96	1.3
Lu	0.08	0.13	0.19	0.15	0.13	0.15	0.03	0.03	0.11
Re	35.1	65	124	43.2	32.7	51	42.7	40	38.8
Th	1.85	2.21	5.15	1.43	4.43	2.21	1.03	1.29	2.54

	Northeast[a]	Northwest[b]	Crystal	Hiko	Ash	Cold Creek	Deer Creek	Grapevine	Willow Creek
mM									
Ca	1.25	1.25	1.13	1.16	1.18	1.97	1.3	1.43	1.8
Mg	0.89	0.89	0.89	0.9	0.61	0.62	0.47	1.56	0.53
K	0.19	0.2	0.12	0.17	0.18	0.01	0.01	0.05	0.01
Na	3.03	3.07	1.12	1.22	1.34	0.09	0.03	1.05	0.08
μM									
Li	10	10.7	3.18	4.69	6.12	0.19	0.07	1.62	0.18
Sr	8.93	9.81	2.82	3.82	5.37	2.89	0.54	8.3	3.65
nM									
Ti	11.6	14.3	11.7	17.6	11.9	4.38	4.37	4.36	6.42
V	27.5	31.2	19.2	40.3	30.7	13.5	4.81	4.21	14.2
Cr	6.45	3.48	2.91	3.66	4.4	11.7	8.17	3.83	9.41
Cu	20.5	15.9	5.35	2.68	6.4	4.43	4.53	6.53	4.09
Zn	8.67	8.79	6.53	5.8	5.67	21.5	6.97	20.8	17.9
As	186	193	167	201	444	5.53	2.44	6.01	4.93
Rb	135	146	97.8	148	206	3.44	1.68	12.3	3.43
Mo	63.3	63.1	54.9	56.7	44.7	9.18	4.32	7.34	7.73
Sn	1.34	0.45	0.1	0.1	0.1	0.11	0.03	0.1	0.05

Table 1 (*continued*)

	Northeast[a]	Northwest[b]	Crystal	Hiko	Ash	Cold Creek	Deer Creek	Grapevine	Willow Creek
Ba	479	547	607	806	1126	154	45.8	546	159
W	1.21	1.26	3.33	4.54	9.9	0.04	0.04	0.07	0.05
U	12.3	12.2	17.1	20.4	11.3	7.56	2.31	7.69	6.72
pM									
La	23.4	22	9.5	11.2	30.5	33.7	53.1	20.6	68.1
Ce	27.8	11.9	6.6	18	0.13	6.8	69.6	9.8	10
Nd	4.7	3.6	4.1	2.3	4.8	16.7	27.1	9.9	35.7
Sm	9.2	4.5	1.6	1.3	6	3.5	6.7	3.1	28.9
Gd	1.3	1	0.71	0.3	1.4	4.3	7.8	5.5	12
Tb	0.03	0.03	0.41	0.4	0.52	0.63	0.9	0.77	1.8
Dy	0.82	0.43	0.49	0.18	1.1	4.3	6.8	5.2	10.7
Ho	0.03	0.03	0.15	0.12	0.34	1.2	1.5	1.5	2.1
Er	0.65	0.15	0.3	0.09	0.87	3	5.3	4.6	8.7
Yb	0.84	0.29	0.44	0.14	0.97	3.4	3.4	4	7.2
Lu	0.03	0.03	0.1	0.06	0.16	0.53	0.63	0.45	0.85
Re	37.2	45.4	101	93.5	60.2	60.4	42.4	32.9	82.3
Th	1.71	2.91	1.09	1.02	1.76	1.09	0.85	1.12	1.32

	Willow	Tippipah	Cane	Topopah	ER-30	J-13	J-12	UE-10j1A	UE-10j2A
mM									
Ca	0.6	0.14	0.9	0.22	0.08	0.33	0.37		
Mg	0.28	0.01	0.39	0.07	0.03	0.08	0.09		
K	0.03	0.07	0.15	0.14	0.04	0.12	0.12		
Na	0.17	1.85	1.83	0.6	2.89	1.89	1.81		
μM									
Li	0.19	1.7	3.95	0.66	8.54	5.49	5.65		
Sr	1	0.07	1.23	0.08	0.11	0.45	0.51		
nM									
Ti	6.31	85.6	26.5	40.5	4.46	14.4	18		
V	7.28	27.5	187	26.3	130	180	106		
Cr	4.84	1.67	15.4	1.66	44.3	21.4	19.2		
Cu	5.79	10.2	5036	8.45	5.59	18	17.8		
Zn	2.19	17.6	151	112	2.28	9.06	10.2		
As	3.61	27.2	96.2	21.8	129	161	136		
Rb	20.1	82.7	113	117	48.4	114	160		
Mo	2.76	7.3	44.1	4.03	38.1	77.7	76.7		
Sn	0.14	0.03	0.16	0.03	0.04	0.08	0.03		
Ba	486	2.48	135	1.88	8.11	8.37	13.2		
W	0.03	0.06	1.52	0.13	4.27	5.33	2.68		
U	0.59	2.2	7.25	0.32	8.17	2.01	2.44		
pM									
La	434	2322	141	1008	26.3	17.8	20.9	9.7	14.6
Ce	184	5053	158	3213	36.3	18.2	17.1	6.7	8.8
Nd	328	1576	178	863	12.7	8	0.42	4.8	3.9
Sm	76.6	396	40.9	181	2.4	1.8	45	1.8	1.3
Gd	86.9	280	44.6	185	2.1	1.9	1.3	0.77	0.6
Tb	11.6	45	14.8	32	0.31	0.38	0.06	0.52	0.16
Dy	61	141	65	190	2.1	2.6	1.4	0.84	0.66
Ho	11.8	30	17	36	0.49	0.82	0.28	0.27	0.17
Er	32.6	84	46.4	138	1.4	2.4	0.65	0.75	0.58
Yb	25.1	81	52.2	125	1.4	2.8	0.12	0.85	0.54
Lu	4.1	13	7.4	21	0.19	0.64	0.06	0.18	0.1
Re	35.3	59.1	113	91.3	55	50.7	14		
Th	5.9	270	1.18	61.6	0.82	4.19	1.59		

[a] Point of Rocks, Northeast.
[b] Point of Rocks, Northwest.

the Spring Mountains, through-flow groundwaters of the regional carbonate aquifer characterized by groundwaters from the Pahranagat Valley (e.g., Hiko, Crystal, and Ash Springs), and a minor component from felsic volcanic rocks on the NTS (Winograd and Friedman, 1972; Winograd and Thordarson, 1975; Dudley and Larson, 1976; Winograd and Pearson, 1976; Cowart, 1979; Dettinger, 1989; Osmond and Cowart, 1982; Farmer, 1996; Thomas et al., 1996). For example, Winograd and Friedman (1972) argue, based on deuterium analyses, that the Ash Meadows groundwaters are mixtures of approximately 60–65% groundwaters recharged in the Spring Mountains and 30–35% through-flow groundwaters from the Pahranagat Valley. These same mixing proportions are supported by uranium-series isotope analyses (Cowart, 1979; Osmond and Cowart, 1982; Farmer, 1996) and more recently verified by Thomas et al. (1996) using stable oxygen and hydrogen isotopes. In addition to the Ash Meadows springs, the Spring Mountain springs except Willow Spring (Fig. 1, Table 1), and the Pahranagat Valley springs all represent groundwaters believed to be associated with the regional Paleozoic carbonate aquifer. The other spring waters and well waters examined in this study (i.e., Tippipah, Topopah and Cane Springs, and wells ER-30, J-12, and J-13) are thought to be associated with the felsic volcanic rocks of the NTS and Yucca Mountain regions. These non-carbonate groundwaters are, consequently, considered to have chemical signatures influenced primarily by chemical reactions involving the Tertiary rhyolites and quartz latites of the NTS/Yucca Mountain region (e.g., Winograd and Thordarson, 1975). Moreover, wells ER-30, J-12, and J-13 are all finished in these Tertiary tuffs.

Although the hydrogeology of the region is complex, structural and borehole geologic data indicate that Paleozoic carbonate rocks extend beneath much of the NTS and Yucca Mountain region (Winograd and Friedman, 1972; Winograd and Thordarson, 1975; Dudley and Larson, 1976; Winograd and Pearson, 1976; Fridrich et al., 1994; Dettinger et al., 1995; Thomas et al., 1996). Consequently, groundwaters of the regional carbonate aquifers must also extend beneath the volcanic rock aquifers/aquitards and alluvial deposits exposed on the NTS and at Yucca Mountain. In part, groundwaters from the Tertiary felsic volcanic rocks and basin-fill deposits percolate downward and eventually mix with the regional Paleozoic carbonate aquifer, although isotopic, water temperature data, and potientiometric head levels indicate that groundwaters from the underlying carbonate aquifer also flow upward into the Tertiary volcanic rocks in the vicinity of Yucca Mountain (Szymanski, 1989; Stuckless et al., 1991; Fridrich et al., 1994; Bredehoeft, 1997). The downward percolating waters could influence the chemistry of the regional carbonate groundwaters by contributing solutes acquired by reacting with the overlying alluvium and/or the volcanic rocks (e.g., Winograd and Thordarson, 1975; Thomas et al., 1996). On the other hand, the upwelling carbonate groundwaters near Yucca Mountain could also contribute chemical signatures inherited from reactions with the Paleozoic carbonate rocks to the groundwaters of the overlying volcanic rock aquifers/aquitards. Thus, characterizing the chemical compositions of groundwaters from these aquifers/aquitards more fully, including trace element concentrations, may provide an additional means of tracing groundwater mixing and groundwater–aquifer rock relationships in the region.

3. Methods

3.1. Sampling and analytical techniques

The methods used to sample groundwaters from the springs and wells have been thoroughly discussed in the literature (Stetzenbach et al., 1994, 1999; Hodge et al., 1996, 1998; Johannesson et al., 1997). In brief, groundwater samples were pumped from the springs using a peristaltic pump equipped with acid-washed Teflon® tubing, subsequently passed through an in-line Gelman Sciences filtering capsule (pore size 0.45 μm; polyether sulfone membrane), and collected in acid-washed, high-density polyethylene sample bottles (Nalgene). Samples from the wells were collected identically, except each well was pumped until constant pH measurements were obtained in order to ensure that the samples were representative of the local groundwater. Well J-13 is used for water supply and thus is pumped continuously. Most of the wells that were sampled were pumped for at least 24 h prior to sample collection. The pumping flow rate

varied depending on how much water the well produced. After the well and spring water samples were filtered, they were immediately acidified to pH < 2 with ultrapure nitric acid (SeaStar Chemicals). Filled sample bottles were subsequently double bagged in clean plastic bags, placed in a clean plastic chest, and transferred to the laboratory for analysis.

Major cations were determined by atomic absorption spectrometry (Perkin–Elmer Model AA-20). Trace element concentrations were measured by inductively coupled plasma-mass spectrometry (ICP-MS; Perkin–Elmer Elan 5000) with ultrasonic nebulization (Stetzenbach et al., 1994; Hodge et al., 1996, 1998). The ultrasonic nebulization (Cetac Technologies Model U-5000) increased the sensitivity of the instrument by roughly a factor of 30 over cross-flow nebulization and decreased the potential interferences from oxide formation in the plasma stream (Stetzenbach et al., 1994; Hodge et al., 1996, 1998). Moreover, nebulizer flow was adjusted to 0.517 l/min, at which point oxide formation in the plasma stream was never more than 1% (Guo, 1996). The ICP-MS was also equipped with an active film multiplier ion detector (ETP Scientific) that, along with the ultrasonic nebulizer, further increased the sensitivity of the instrument by roughly 100 times (Stetzenbach et al., 1994).

The ICP-MS was calibrated with multielement solutions with concentrations ranging from 0.025 μg/kg to 10 μg/kg, prepared from multielement standards purchased from Perkin–Elmer. Calibration check standards were prepared, by 10-fold dilution, from the NIST Standard Reference Material (SRM) "Trace Elements in Water" No. 1643b, which contained many of the elements of interest (Hodge et al., 1998). In addition, calibration check standards for elements not in the NIST SRM were prepared from NIST traceable standards purchased from High Purity Standards (Charleston, SC).

Many of the trace elements were present in the groundwaters at concentrations greater than 10 μg/kg (e.g., Li, Ti, As, Rb, Sr, Ba) and consequently, for these elements, the water samples required dilution prior to analysis. The remaining trace elements, except the REEs which required preconcentration, could be quantified directly, and the methods were previously described in detail (Stetzenbach et al., 1994, 1999; Hodge et al., 1996, 1998). The REEs were preconcentrated 50-fold by cation exchange and quantified by ICP-MS using the following REE isotopes: ^{139}La, ^{140}Ce, ^{141}Pr, ^{146}Nd, ^{149}Sm, ^{151}Eu and ^{153}Eu (mean value), ^{157}Gd, ^{159}Tb, ^{163}Dy, ^{165}Ho, ^{166}Er, ^{169}Tm, ^{172}Yb, and ^{175}Lu (Stetzenbach et al., 1994). Because oxides of Ba formed in the plasma stream can interfere with Eu analysis (e.g., Jarvis et al., 1989), Ba was removed from the solution using a modification of the method of Cerrai and Ghersini (1966), where an aliquot of each sample was passed through a cation-exchange column packed with Bio-Beads SM-2 adsorbent coated with di-(2-ethylhexyl) orthophosphoric acid (Hodge et al., 1998). In this extraction process, Eu as well as the other REEs are adsorbed, whereas Ba is not. The technique typically removes more than 90% of the Ba and subsequent recoveries of Eu in spiked aliquots using this technique have been reported to be 97% on average (Johannesson et al., 1997; Hodge et al., 1998). A series of five REE reference standards of known concentrations (10, 50, 100, 500, and 1000 ng/kg) were used in sample analysis to confirm the measurements and calibrate the ICP-MS (Stetzenbach et al., 1994; Johannesson et al., 1997). An internal standard (i.e., Pt for the REEs, Tb for all other trace elements) was added to each sample to monitor for matrix effects, differences in sample viscosity, solute build-up on the sampler and skimmer cones, and instrument drift during the analyses (Guo, 1996).

3.2. Principal component analysis

PCA is a multivariate statistical technique used for data reduction and for deciphering patterns within large sets of data (Hull, 1984; Wold et al., 1987; Joliffe, 1986; Stetzenbach et al., 1999). Because PCA is based solely upon eigenanalysis of the correlation or covariance matrix, the data are not required to be normally distributed (Meglin, 1991). In using PCA, a large data matrix can be reduced to two smaller matrices, one consisting of principal component (PC) scores and the other containing the loadings (Stetzenbach et al., 1999). The PC scores (s) are linear combinations of the standardized data (x) with the loadings (l) as the coefficients:

$$s_{n,c} = \sum x_{n,e} \times l_{e,c}$$

where n identifies the sampled spring or well water, e

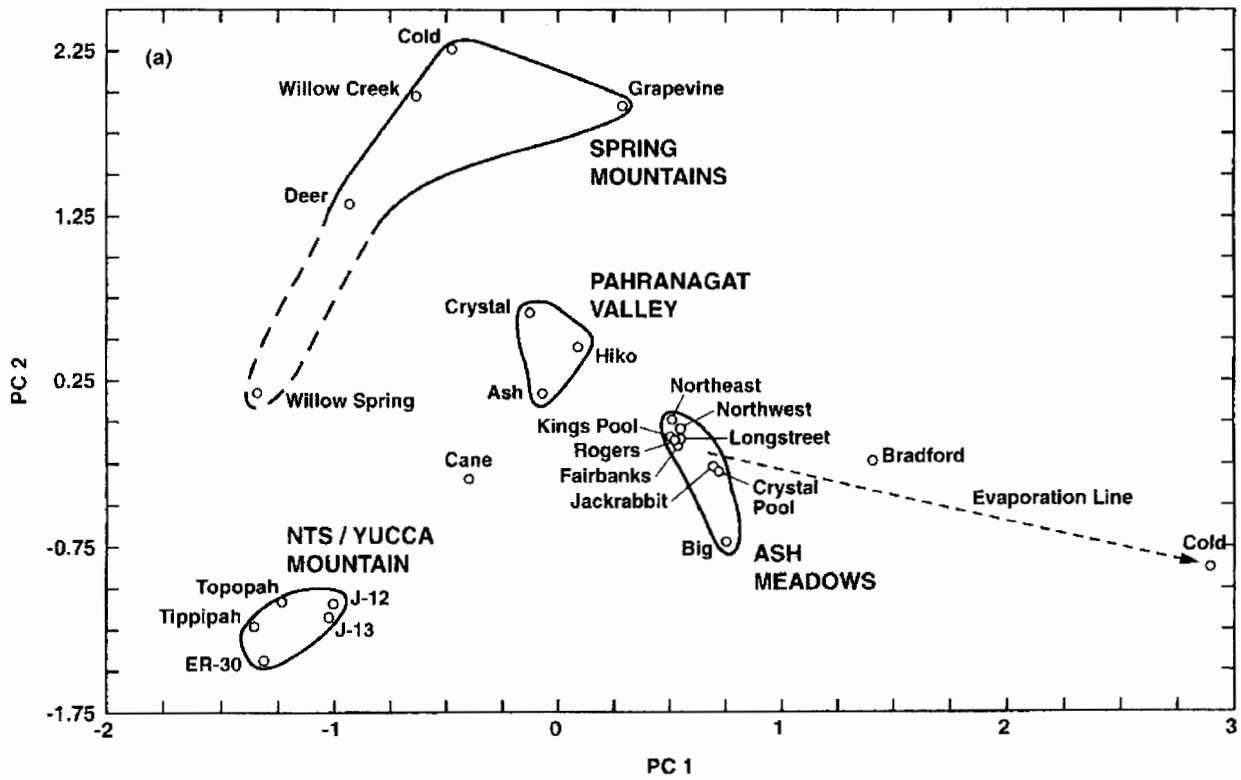

Fig. 2. Plot of principal component 1 (PC1) versus principal component 2 (PC2) for (a) major cations and (b) 27 different trace elements (see Table 1). Springs and wells from the different geographic location studied (i.e. Ash Meadows, Spring Mountains, Nevada Test Site/Yucca Mountain, and Pahranagat Valley) are identified. See text for more discussion.

is the chemical measurement (e.g., different trace elements), and c identifies the principal component (Stetzenbach et al., 1999; Farnham et al., 2000). The maximum amount of variance is explained in the first PC, with decreasing variance explained in each subsequent component. All PCs are uncorrelated (i.e. orthogonal) to one another.

In this study, PCA was applied to the correlation matrix to ensure the same weight of each of the elements on the analysis. The statistical software package Statistica, Release 5.1 (StatSoft, 1997) was used for all PCA. We present the results of only the first two principal components for each analysis because they account for the majority of the variance in the original data. The PC scores for each water sample are plotted, and the plots are visually inspected for clustering/similarities. Springs and/or well waters that are compositionally similar are manifested in the PC score plots as clusters.

4. Results

The chemical data used in this study are listed in Table 1, and the sampling sites are shown in Fig. 1. The four major cations, Ca, Mg, Na, and K, along with 27 different trace elements quantified in each groundwater sample, were used in the multivariate analysis. Fig. 2a is a plot of the PCA results using the major cations (Ca, Mg, Na, K) for groundwaters of the carbonate aquifer from Ash Meadows, the Spring Mountains, and the Pahranagat Valley, as well as groundwaters from the felsic volcanic rock aquifers/aquitards of the NTS and Yucca Mountain region (Tippipah, Topopah, and Cane Springs, and wells ER-30, J-12, and J-13). In Fig. 2a, principal component 1 (x-axis) accounts for approximately 66% of the variance inherent in the major cation data for these springs and well waters, whereas principal component 2 (y-axis) explains 27% of the variance. The total

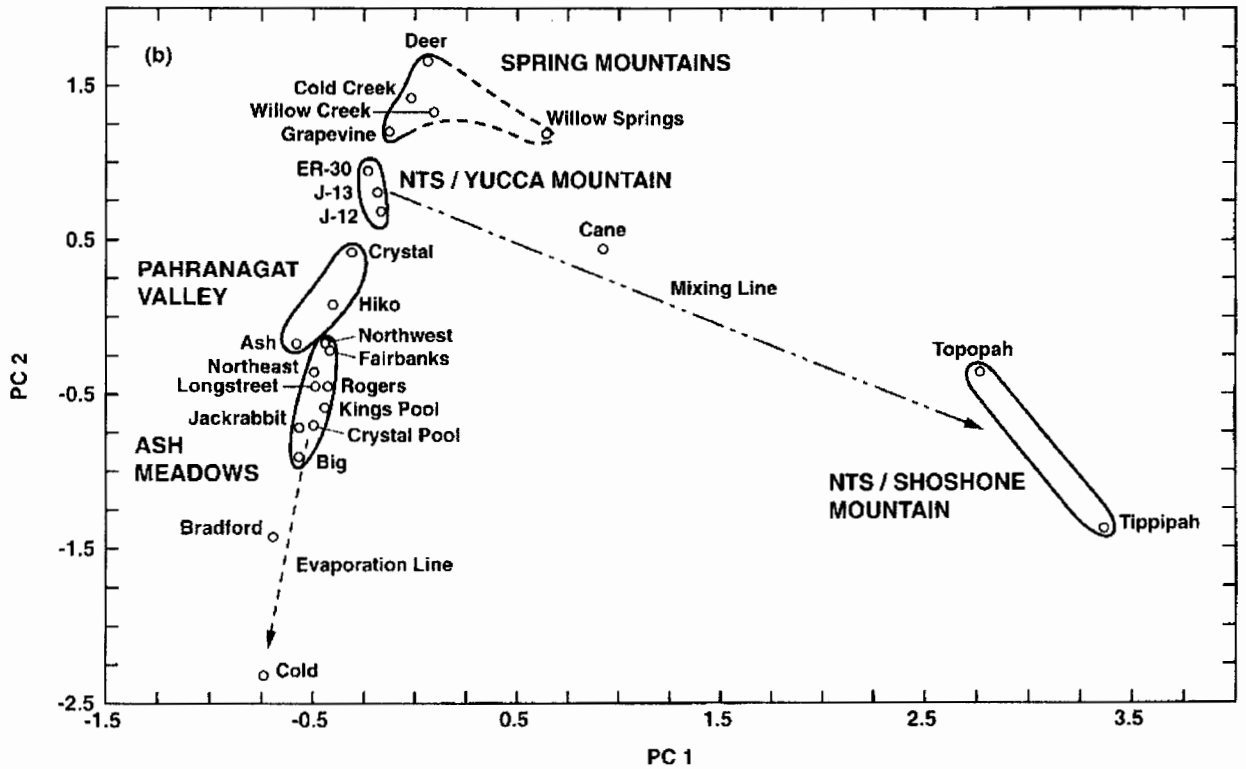

Fig. 2. (*continued*)

variance of the data set expressed by principal components 1 and 2 is thus 93%.

Fig. 2a indicates that, except for Cane Spring, those groundwaters collected from wells or springs associated with the volcanic rock aquifers/aquitards plot within a tight cluster in the lower left corner. Except for the Willow Spring sample, groundwaters from the Spring Mountains also plot in a cluster (i.e., upper left of Fig. 2a). Willow Springs groundwater issues from Mesozoic sandstone and not Paleozoic carbonate rocks as do the other Spring Mountain groundwaters. The Ash Meadows groundwaters also form a tight cluster in the center of Fig. 2a with the exception of Cold and Bradford Springs. We will show later that Cold Spring, Bradford Spring, and perhaps Big Spring may be excluded from the Ash Meadows cluster because they have experienced post-discharge modification by evaporative concentration and/or evapotranspiration (Hodge et al., 1996; Stetzenbach et al., 1999). Finally, the carbonate groundwaters of the Pahranagat Valley plot as a cluster that falls between the Spring Mountain and Ash Meadows clusters, albeit closer to the Ash Meadows groundwaters (Fig. 2a).

The results of the PCA for the 27 trace elements (Table 1) are shown in Fig. 2b. In this case, PC 1 represents 50% of the variance of the trace element data set for these groundwater samples, and PC 2 accounts for 16% of the total variance. Together they explain 66% of the variance in the trace element data set. The strong clustering of the groundwaters from each sampling location that was observed for the PCA of the major cations (Fig. 2a) is not observed for trace element PCA results. Instead, except for Topopah, Tippipah, Cane, and Willow Springs, the springs and wells plot along the left side of Fig. 2b.

5. Discussion

5.1. Statistical analysis of major cation compositions

The carbonate aquifer groundwaters from the

Spring Mountains, Pahranagat Valley, and Ash Meadows all plot in Fig. 2a in distinct and separate groups. Moreover, these carbonate groundwaters plot away from the felsic volcanic aquifer/aquitard groundwaters collected from the NTS/Yucca Mountain region (Fig. 2a). The distinct clustering in Fig. 2a of all the groundwaters collected and analyzed in this study reflects the different total and relative major solute concentrations of these waters (Table 1). For example, the tight clustering of the volcanic aquifer/aquitard groundwaters and their separation from the carbonate groundwaters in Fig. 2a are expected based on the relatively higher Na and K concentrations of the volcanic groundwaters compared to the carbonate groundwaters, which are instead typified by higher Ca and Mg concentrations (Table 1). For the carbonate groundwaters, those from the Spring Mountains are more dilute than Pahranagat Valley groundwaters, which are similar although slightly more dilute in terms of Na than the Ash Meadows spring waters (Winograd and Thordarson, 1975; see Table 1). These relationships are reflected in the clustering patterns of the carbonate groundwaters in Fig. 2a, with Pahranagat Valley groundwater plotting between the Spring Mountain and Ash Meadows clusters, albeit closer to the Ash Meadows groundwaters. The compositional differences between Spring Mountain and Pahranagat Valley groundwaters may reflect recharge of some Spring Mountain groundwaters through younger carbonate rocks (i.e., Mississippian to Permian) than the older (Cambrian through Devonian) carbonate rocks of the regional carbonate aquifer (Winograd and Thordarson, 1975; Thomas et al., 1996). Alternatively, the lower Na concentrations of Spring Mountain groundwaters compared to those of Pahranagat Valley may be due to the close proximity of the Spring Mountain springs to their recharge zone (i.e., the Spring Mountains).

Within the cluster of Ash Meadows springs, the separation along the "evaporation line" in Fig. 2a between Big, Bradford, and especially Cold Spring and the other Ash Meadows springs likely reflects the influence of evaporative concentration and/or evapotranspiration on waters from these three springs (e.g., Hodge et al., 1996; Stetzenbach et al., 1999). Hodge et al. (1996) demonstrated that the Ash Meadows spring waters fall along an evaporative concentration line (i.e., slope of unity) on a plot of Na versus Cl concentrations, with Cold Spring being the most concentrated spring and those springs that discharge directly from dolostones of the Bonanza King Formation (i.e. the Point of Rocks springs) being the most dilute. Moreover, although the Na and Cl concentrations in Cold Spring water are a factor of about two to three greater than the eight other Ash Meadows springs examined, excluding Big and Bradford, Springs, the Na/Cl ratios of all of the Ash Meadows groundwaters are similar (Table 2; Stetzenbach et al., 1999). These Na/Cl ratios strongly support that Big, Bradford, and Cold Springs are related to each other, and the other Ash Meadows springs, by evaporative concentration/evapotranspiration (e.g., Eugster and Hardie, 1978). Therefore, the current model for Cold Spring is that it represents groundwater initially discharged along the Ash Meadows spring-line that subsequently reinfiltrated into the alluvial basin-fill deposits west of the spring-line and was concentrated, by evaporation or evapotranspiration in the shallow zone, before finally discharging again at Cold Spring (Hodge et al., 1996; Stetzenbach et al., 1999).

Table 2
Mole ratios of Na and Cl for the Ash Meadows Springs (from Hodge et al., 1996)

Ash Meadows Springs	Na:Cl
Big	6.45
Bradford	4.8
Cold	5.73
Crystal Pool	5.45
Fairbanks	5.57
Jackrabbit	5.51
Kings Pool	5.34
Longstreet	5.79
Point of Rocks, Northeast	5.42
Point of Rocks, Northwest	5.46
Rogers	5.7
Scruggs	5.71

In terms of PC 2 (Fig. 2a), the Ash Meadows spring waters exhibit closer associations with the volcanic groundwaters of the western NTS and Yucca Mountain regions and the carbonate groundwaters from Pahranagat Valley than the carbonate groundwaters from the Spring Mountains. This clustering pattern is explained by the higher Na concentrations of Ash Meadows groundwaters compared to Spring

Mountain groundwater (Table 1). Groundwaters from the volcanic rocks of the NTS and Yucca Mountain regions are known to typically be rich in Na (e.g., Winograd and Thordarson, 1975). Consequently, the relatively higher Na concentrations of Ash Meadows groundwaters compared to others from the carbonate aquifers of southern Nevada suggest that groundwaters from the NTS/Yucca Mountain region may contribute to the discharge at Ash Meadows. Indeed, Winograd and Thordarson (1975) estimated that up to 5% of the Ash Meadows groundwater originated from the volcanic rock aquifers/aquitards of the NTS.

Willow Spring from the Spring Mountains and Cane Spring from the NTS plot outside of their expected clusters in Fig. 2a. As mentioned above, Willow Spring discharges from Mesozoic sandstone within the Red Rock Canyon region on the eastern side of the Spring Mountains (Sandstone Bluffs of Thomas et al., 1996). Moreover, the elevation at which Willow Springs discharges is substantially lower, on average, than the point of discharge of the other springs from the Spring Mountains examined in this study (see Thomas et al., 1996). As a result of being the only spring discharging from sandstone, Willow Creek does not show any close statistical association based on chemical composition with any of the other spring or well waters examined in this study. Cane Spring, however, is more of an enigma. In terms of major cation composition, Cane Spring plots relatively close to the Pahranagat Valley groundwater (Fig. 2a) despite discharging from volcanic rocks. It is possible that Cane Spring, which also plots between the volcanic groundwaters and the carbonate groundwaters of the Pahranagat Valley (Fig. 2a), represents a mixture of carbonate and volcanic groundwaters (see below). Another possible explanation is that Cane Spring groundwater has acquired a carbonate mineral signature by dissolution of pedogenic carbonates or carbonate dust from the region (R. L. Jacobson, 1997, pers. comm.).

5.2. *Statistical analyses of trace element composition of groundwaters*

The results of the PCA of the trace element data for the groundwaters from the springs and wells studied reveal two remarkable features. First, in Fig. 2b, Tippipah and Topopah Springs plot at a substantial distance from the other groundwater samples and, consequently, these two springs are vastly different in terms of their trace element composition than all of the other groundwaters examined in the study. Secondly, the PCA results of the trace element data indicate that the groundwaters collected from wells ER-30, J-12, and J-13 more closely resemble the trace element composition of the carbonate groundwaters from Ash Meadows, the Spring Mountains, and Pahranagat Valley than either Tippipah or Topopah Springs, which discharge directly from felsic volcanic rocks (Fig. 2b). The similarity in trace element composition of well waters from ER-30, J-12, and J-13 and the carbonate groundwaters is extraordinary because these wells are finished in felsic volcanic rocks and are thought to be representative of waters from the volcanic aquifers/aquitards (Nitsche et al., 1992; Efurd et al., 1998) and thus have only chemically reacted with these volcanic rocks.

Groundwaters issuing from Tippipah and Topopah Springs represent perched waters that are recharged through Tertiary tuffs of Shoshone Mountain on the NTS (Winograd and Thordarson, 1975). These Tertiary felsic volcanic rocks belong to the Timber Mountain Caldera Complex (Frizzell and Shulters, 1990). Waters recharged on Shoshone Mountain subsequently percolate downward and eventually discharge from Tippipah and Topopah Springs and consequently, they are thought to have interacted only with felsic volcanic rocks. As a result, they have inherited chemical signatures that reflect chemical reactions with the felsic volcanic rocks. This hypothesis is supported, for example, by the shale-normalized REE patterns of Tippipah and Topopah Spring waters which match, in shape, the shale-normalized REE patterns of felsic volcanic rocks from the NTS and Yucca Mountain regions (Fig. 3; Johannesson et al., 1997, 2000). On the other hand, groundwaters from the carbonate aquifer have distinct REE signatures that more closely resemble REE signatures of carbonate rocks from southern Nevada (Johannesson et al., 1997, 2000). Because of the similar REE signatures of Tippipah and Topopah Spring waters to those of the local felsic volcanic rocks, and because the groundwaters issuing from these springs are perched, they can be thought of as volcanic end-member groundwaters that have not been "contaminated" by

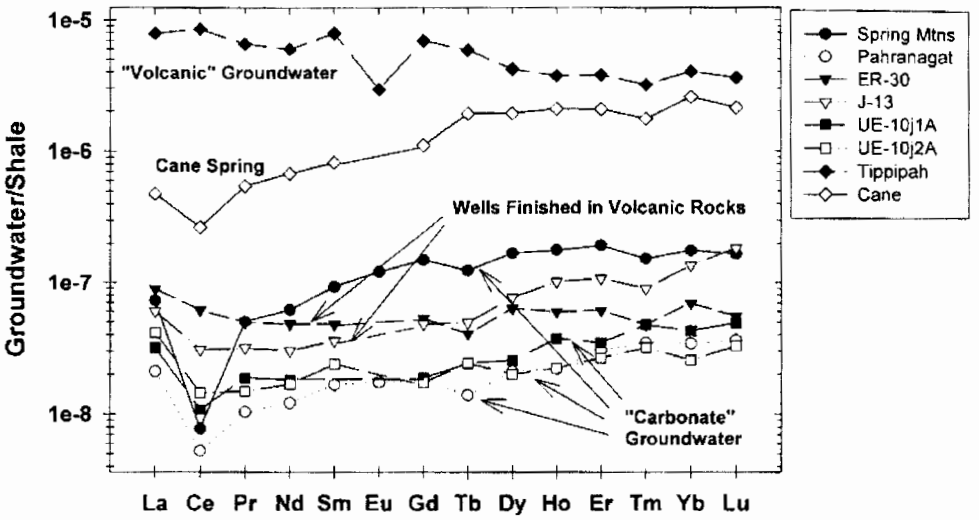

Fig. 3. Shale-normalized REE concentrations for groundwaters from southern Nevada. Groundwater samples collected from wells finished in the volcanic rocks of the NTS (i.e. ER-30, J-13) have REE concentrations and shale-normalized signature that closely resemble the groundwaters from the regional carbonate aquifer (Spring Mountains, Pahranagat Valley, well UE-10j). Groundwaters collected from Cane Spring have REE concentrations and shale-normalized signature that are intermediate between the carbonate groundwaters and the end-member volcanic groundwaters (i.e. Tippipah Spring).

groundwaters from the regional carbonate aquifer. Interestingly, the major solute composition of waters from Tippipah and Topopah Springs are similar, although slightly less alkaline, to other perched waters from the NTS/Yucca Mountain region (e.g., Yang et al., 1996; Rousseau et al., 1999; Zhou et al., 2000). Unfortunately, these previous studies do not report trace element data other than some values for Al, Br, and Sr for perched waters from the study region, thus, direct comparison is difficult.

In terms of the carbonate groundwaters sampled in this study, the PCA results for the trace element data exhibit a similar pattern to that determined for the major cations (compare Fig. 2a and b). More specifically, the Ash Meadows and Spring Mountain groundwaters plot separately in Fig. 2b, whereas the Pahranagat Valley groundwaters plot in between the Ash Meadows and Spring Mountain cluster but closer to the Ash Meadows groundwaters. Again, Cold Spring and Bradford Spring plot away from the main cluster of the Ash Meadows groundwaters in Fig. 2b, reflecting the effects of evaporative concentration/evapotranspiration on more conservative trace elements (e.g., Re, Mo, W, V, Cr, U; Hodge et al., 1996). Because the regional carbonate groundwaters are oxygenated (e.g., Winograd and Robertson, 1982), negatively charged trace metal/metalloid oxyanions or complexes can remain in solution and exhibit conservative behavior (e.g., Starik and Kolyadin, 1957; Ku et al., 1977; Hodge et al., 1996).

Again, a case can be made that Willow Spring and Cane Spring do not cluster with their respective groups in Fig. 2b (i.e., Spring Mountain and NTS/Yucca Mountain groundwaters or Tippipah/Topopah Spring waters, respectively). The difference in the trace element chemical signature of Willow Spring is likely related to interactions of this groundwater with the Mesozoic sandstone from which it discharges. On the other hand, Cane Spring presents more interesting possibilities. In Fig. 2b, Cane Spring plots on a straight line connecting Tippipah and Topopah Springs at one end with NTS/Yucca Mountain wells ER-30, J-12, and J-13 at the other end. Furthermore, Cane Spring plots closer to ER-30, J-12, and J-13 than to either Tippipah or Topopah Springs (Fig. 2b). One way to interpret the line between Tippipah/Topopah and wells ER-30, J-12, and J-13 is as a mixing line (e.g., Christophersen and Hooper, 1992). In this case, because Cane Spring has a trace element signature more similar to the well waters from ER-30, J-12, and J-13 than to either

Tippipah or Topopah Springs, Cane Spring waters would be a mixture of predominantly regional carbonate groundwaters (e.g., Spring Mountain groundwaters) and a lesser amount of groundwaters characteristic of those that have only chemically reacted with felsic volcanic rocks (i.e., Tippipah and Topopah Springs). Earlier investigations of the REEs in spring waters from the NTS/Yucca Mountain region also demonstrated that Cane Spring water is compositionally different from Tippipah and Topopah Spring waters (Esser et al., 1994).

More striking, however, is that the PCA indicates that ER-30, J-12, and J-13 have trace element signatures that are statistically more similar to the regional carbonate groundwaters discharging from Ash Meadows, the Pahranagat Valley, and the Spring Mountains than to the strictly volcanic rock groundwaters characterized by Tippipah and Topopah Springs (Fig. 2b). Again, these results can be interpreted as indicating that groundwaters from these wells are mixtures of regional carbonate groundwaters and local volcanic groundwaters. Although the major cation analyses suggest that these well waters represent volcanic end-member groundwaters (Fig. 2a), the trace element data clearly indicate that groundwaters from wells ER-30, J-12, and J-13 are also compositionally similar to groundwaters from the underlying carbonate aquifer (Fig. 2b). In addition to these PCA results, REE concentrations for groundwaters from wells ER-30, J-12 and J-13 have shale-normalized signatures that more closely resemble the REE signatures of groundwaters from the regional carbonate aquifer than the volcanic end-member groundwaters represented by Tippipah and Topopah Springs (Fig. 3). In addition, these well waters (ER-30, J-12, J-13) have REE patterns similar to groundwaters collected from well UE-10j in northern Yucca Flat (Fig. 1), which is finished in the Paleozoic carbonate aquifer (i.e., UE-10j1A and UE-10j2A, Fig. 3; USDOE, 1995). The fact that groundwaters from the carbonate aquifer directly beneath northern Yucca Flat have REE patterns that closely resemble other southern Nevada carbonate groundwaters, as well as REE patterns of groundwaters from wells finished in the overlying volcanic rocks in the vicinity of Yucca Mountain, supports upwelling of regional carbonate groundwaters into the overlying volcanic rock aquifers/aquitards of the NTS/Yucca Mountain region.

The results of the major cation PCA (Fig. 2a) may reflect the domination of one or two of the major cations in these groundwaters. As an example, for those groundwaters that interact with the volcanic rocks, large amounts of highly soluble Na may be dissolved that would in effect mask a carbonate groundwater signature that would be dominated by Ca and Mg. It is important to point out that all of the carbonate groundwaters are either saturated, oversaturated, or close to saturation with respect to calcite (e.g., Thomas et al., 1996), whereas the groundwaters from the volcanic rocks are all undersaturated with respect to calcite. Furthermore, groundwaters in the regional carbonate aquifer for all the regions investigated in this study, as well as beneath the NTS, are substantially undersaturated with respect to albite (Thomas et al., 1996). Consequently, it is likely that carbonate groundwater could readily dissolve significant quantities of Na from the felsic volcanic rocks. Because glass is common in these volcanic rocks, and due to the fact that glass is especially unstable and relatively easy to weather (White et al., 1980), we expect that carbonate groundwaters interacting with the felsic volcanic rocks could liberate considerable amounts of Na from these rocks which, in turn, could significantly modify the major cation concentrations of the groundwater towards higher Na concentrations.

5.3. Supporting data

Geochemical and hydrogeologic data supporting upwelling of groundwaters from the Paleozoic carbonate aquifer into the overlying Tertiary volcanic rocks of the NTS/Yucca Mountain region have been presented and discussed previously by numerous investigators. Fridrich et al. (1994), for example, emphasized three features that indicate upward flow of groundwater occurs along fault zones, from the carbonate aquifer into the volcanic rocks, in the vicinity of Yucca Mountain. These factors are: (1) linear thermal highs along the north-trending fault zones near Yucca Mountain that penetrate the volcanic rocks; (2) the carbon isotope data of Stuckless et al. (1991) that suggest mixing of the carbonate groundwaters with those from the volcanic rock systems; and (3) the higher hydraulic head in the carbonate aquifer compared to that in the overlying volcanic aquifers/aquitards in the vicinity of Yucca Mountain. In

particular, the hydraulic head in well UE-25p1 (Fig. 1), which is completed in the carbonate aquifer, was reported to be 20 m higher than in the overlying volcanic rock aquifers/aquitards (e.g., Bredehoeft, 1997). Furthermore, Bredehoeft (1997) estimated that the upward flow of groundwater along faults near Yucca Mountain, including Paintbrush and Bow Ridge Faults to the east in Midway Valley and the Solitario Canyon Fault to the west, could be as much as 1000 m^3/day.

Data from a recent pump test near Yucca Mountain also strongly supports the possibility that carbonate groundwater is upwelling beneath some parts of the region or at least is a significant component of the groundwater in the felsic volcanic rock aquifers/aquitards. Over a period of 18 months, groundwater well UE-25c #3 (part of the C-hole complex) at Yucca Mountain (Fig. 1), and on the NTS, was pumped at a rate of ~570 l/min, during which approximately 254-million l of groundwater was removed. Well UE-25c #3 is finished in the Crater Flat Tuff at a depth of 914.4 m below ground surface and roughly 513 m below the water table (Geldon, 1993). Within 1 min of initiation of the pumping, the static water level in the well dropped 3.7 m. After approximately 100 min, steady-state conditions were attained with the water level 4.9 m lower than before commencement of the pumping. Remarkably, within 5 min of cessation of pumping, the static water level in the well had returned to within 0.15 m of the original level from a total drawdown of slightly over 4.9 m (A. Gelden, USGS, 1997, pers. comm.). These water level–pumping relationships, especially the behavior during the well recovery, are not generally supportive of the bulk of the groundwater being derived from the felsic volcanic rocks of the region. Instead, the observations reported for UE-25c #3 are more similar to the behavior of wells penetrating the carbonate aquifer (e.g., Winograd and Thordarson, 1975). Therefore, these data support the likely contributions of water from the regional carbonate aquifer to the overlying tuffaceous rocks (Geldon, 1993).

5.4. Conceptual model

In Fig. 4, we present a highly schematic, hydrogeologic cross-section of the NTS/Yucca Mountain region showing the principal water-bearing units: the regional Paleozoic carbonate aquifer, Quaternary basin-fill deposits, and the Tertiary tuffs. In general, regional groundwater flows in the Paleozoic carbonate rocks, at depth, from north to south and beneath, for example, parts of the NTS and Yucca Mountain region (Winograd and Thordarson, 1975; Dettinger, 1989; Fridrich et al., 1994; Thomas et al., 1996). A component of groundwater is likely recharged to the regional carbonate aquifer via precipitation at higher elevations on the NTS, such as Shoshone Mountain, Pahute Mesa, and/or Rainier Mesa. Another component of groundwater may be recharged further north within central Nevada (Davisson et al., 1999). Recharge water from higher elevation regions of the NTS would subsequently percolate downward through the Tertiary volcanic rocks, possibly contributing to the regional groundwater flow (Winograd and Friedman, 1972; Winograd and Thordarson, 1975; Dettinger, 1989; Fridrich et al., 1994; Thomas et al., 1996). However, isotopic, water temperature, potentiometric head, and now our trace element data and PCA investigation indicate that important quantities of groundwater from the regional carbonate aquifer may also "upwell" from the regional system into the overlying tuffaceous rocks (Stuckless et al., 1991; Fridrich et al., 1994; Bredehoeft, 1997; Fig. 4). In the vicinity of Yucca Mountain, such upward flow would be hydrogeologically expected to occur along fractures or faults that penetrate the Paleozoic carbonates and overlying Tertiary volcanics due to higher potentiometric head in the regional carbonate aquifer in this region than in the overlying tuffs and alluvial deposits (Geldon, 1993; Fridrich et al., 1994; Bredehoeft, 1997). Moreover, the strong similarities in the trace element signatures for the groundwaters from wells finished in the Tertiary volcanic rocks (i.e., J-12, J-13, ER-30) and the regional carbonate aquifer groundwaters (including those from well UE-10j; Fig. 3) argues against inheritance of a trace element signature representative of fracture flow only in the overlying volcanic rocks for these NTS/Yucca Mountain groundwaters. Instead, upward flow of regional carbonate aquifer groundwater into the overlying volcanic pile near Yucca Mountain best explains the similar trace element signatures, including REEs, higher water temperatures along certain faults (Fridrich et al., 1994), isotopic data (Stuckless et al., 1991), the higher hydrologic heads in the regional

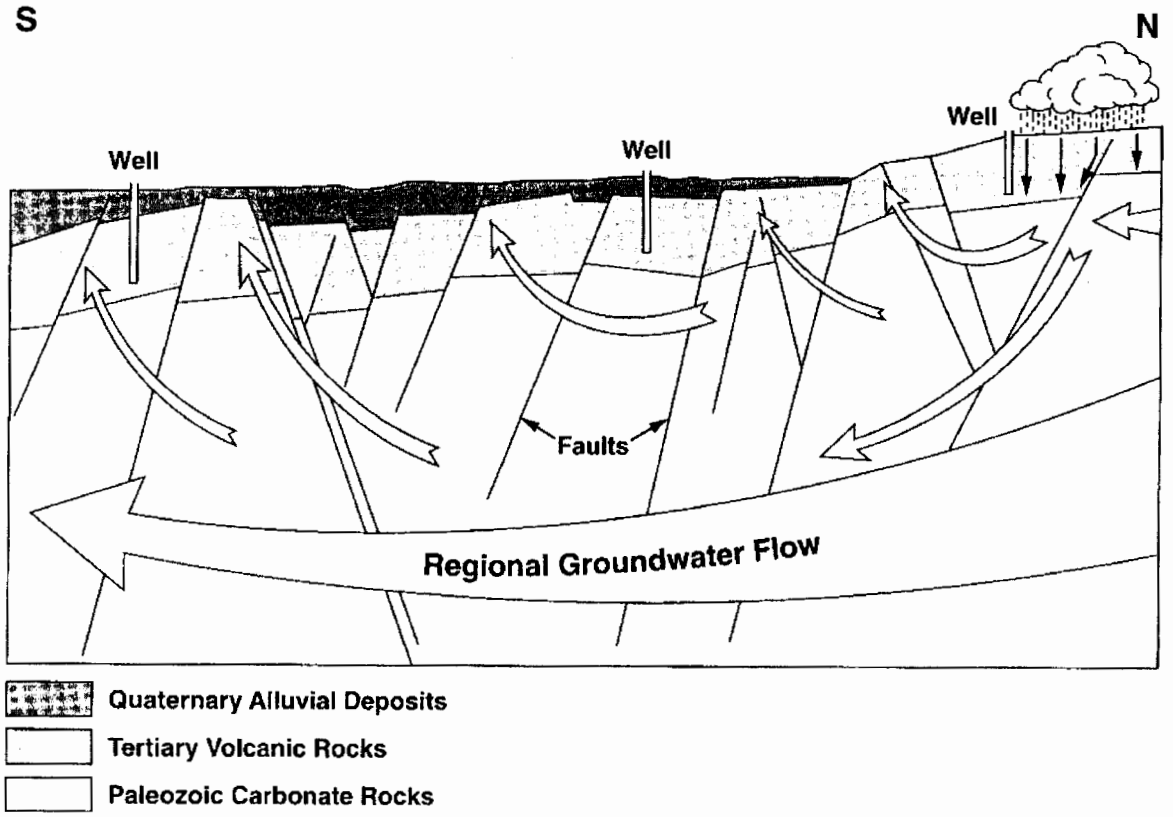

Fig. 4. Highly schematic hydrogeologic cross-section through an hypothetical part of the NTS illustrating possible contributions of groundwater from the regional carbonate aquifer to the overlying Tertiary volcanic rocks. Approximate dimensions of this cartoon cross-section are 60 km long by 4 km deep.

carbonate aquifer than in the overlying volcanic rocks (Fridrich et al., 1994; Bredehoeft, 1997), and even the behavior of groundwater in well UE-25c #3 near Yucca Mountain during a recent pump test.

6. Conclusions

Major cations and trace element concentrations from groundwaters collected from springs and wells in southern Nevada, including groundwaters from the NTS and Yucca Mountain region, were measured. The multivariate statistical method PCA was used to reduce the major cation and trace element data of the sampled groundwaters in order that chemical similarities and differences could be readily recognized. For the groundwater system studied, there have been a multitude of previous investigations that have provided a model of the general hydrogeology and groundwater flow regime. Based on the knowledge gained from these studies, we demonstrated that the statistical associations and non-associations depicted on the PCA plots for the major cations can be explained in terms that fit the current understanding of the groundwater flow regime. Of course, we cannot conclude from the apparent match of the PCA results and the suspected groundwater flow that the flow model is, in fact, correct. However, the agreement does lend support to the current understanding of groundwater flow in southern Nevada, as well as the use of PCA as another technique of investigating complex hydrogeologic systems. Finally, the PCA of the trace elements suggests that groundwaters from felsic volcanic rocks in the vicinity of Yucca Mountain, previously thought to have interacted only with the volcanic rocks, have a significant component that is

characteristic of the underlying carbonate aquifer. These trace element chemical signatures, along with published carbon isotopic values, water temperate data, and hydraulic head levels, suggest that groundwaters from the underlying carbonate aquifer may be in intimate contact with groundwaters of the volcanic rocks and that "upwelling" of groundwater from the carbonate rocks into the overlying volcanic rocks is a real possibility. However, a closer examination of the hydrogeology and hydrochemistry of the study area is warranted to verify or refute our interpretation of the statistical association between the "deep" carbonate groundwaters and those from the overlying volcanic rock aquifers/aquitards.

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