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Statistical Clustering of Major Solutes: Use as a Tracer for Evaluating Interbasin Groundwater Flow into Indian Wells Valley, California

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ABSTRACT

Many previous studies have demonstrated use of specific solutes or isotopes as tracers of groundwater flow. We present a technique that uses standard hydrochemical information to create statistically based hydrochemical facies, which are then used as tracers of groundwater flow. This approach reduces potential subjective bias during interpretation of single tracer data in complex systems with multiple sources or conflicting multiple tracer data. Standard hydrochemical data from 1,368 water samples that spanned more than 80 years were analyzed using cluster analysis to decipher groundwater flow paths in Indian Wells Valley (IWV), California. The statistically derived hydrochemical facies form distinct spatial patterns in which all major-ion concentrations increase progressively from Sierra Nevada (recharge) to China Lake playa (discharge), consistent with the topographically driven flow of groundwater (the typical case for basin and range flow systems). However, once individual samples could be placed in the context of the normal hydrochemical evolution, anomalies are readily identifiable. The distribution of water chemistry in the southeastern part of the IWV does not conform to the regional trend. Groundwater from that part of the IWV is statistically more similar to waters from the Kern Plateau area (in the high Sierra Nevada outside the local watershed) than to waters from the local watershed. The groundwater is interpreted to originate from the fracture-directed interbasin flow from the Kern Plateau area that is directly recharging the alluvial aquifer in the subsurface. Inclusion of this flow could substantially alter current water budgets and water resources management approaches.

INTRODUCTION

Water resources play an increasingly critical role in our world as population continues to grow and the related development places even more stress on the hydrologic system. The demand for greater volumes of fresh water is further complicated as the disposal of hazardous waste affects the limited supply of potable water. This situation makes an improved understanding of groundwater circulation patterns especially important. In this study, evidence of interbasin flow through fractured metamorphic and igneous rocks that have been previously considered to be impermeable has significant implications regarding both water resources and the effects of fractures on the permeability of fractured igneous and metamorphic rocks.

During the past 20 years, many studies have used tracers to delineate oceanic circulation patterns (Smethie et al., 1986; Measures and Edmond, 1988; Krysell et al., 1994; and Moore et al., 1998), water movement in watersheds (Rose et al., 1996; Clow et al., 1997; Negrel et al., 1997; Leibundgut, 1998; and Gamlin et al., 2001), interactions between ground and surface water (Neumann and Dreiss, 1995; Li and Spalding, 1996; Katz et al., 1997; and Rodgers et al., 2004), anthropogenic contamination's movement, source, and attenuation (Hurst et al., 1991; Thierrin et al., 1992; Guzman and Jarvis, 1996; Komor, 1997; Gaebler and Bahr, 1999; Antich et al., 2000; Paridaens and van Marcke, 2001; Divine et al., 2003; and Hogan and Blum, 2003). A number of these applications have included the use of radioactive tracers for aquifer flow paths and environmental problems (Kuzmenko et al., 1992; Corbett et al., 1997; and Johnson et al., 2000). In most studies a single natural or artificial component, pair of components, or isotopic ratios are used as tracers. For instance, the isotopes of B, C, Cl, H, and O (Desaulniers et al., 1981; Fritz et al., 1990; James et al., 2000; and Kloppmann et al., 2001), rare earth elements (Johannesson et al., 1997), minor and trace elements (Farnham et al., 2000), and krypton-85, chlorofluorocarbons, and sulfur hexafluoride (Cook et al., 1996; Cook and Solomon, 1997; and Bauer et al., 2001) have been used to delineate flow paths in aquifers. The spatial variability observed in the composition of these tracers provides insight into aquifer heterogeneity and connectivity and can be used to estimate mean residence times of groundwater.

Typically, detection and direct measurement of water transfer across topographic divides (interbasin flow) are usually extremely difficult; however, tracer studies are a powerful tool for detection of this flow component. However, most of the environmental and anthropogenic tracers generally require elaborate sample collection, handling, and analysis techniques due to extremely low abundances in natural aqueous systems, together with good understanding of the hydrochemical background and the chemical behavior of the tracers (Sabatini and Austin, 1989; Krysell et al., 1994; Ball and Trudgill, 1997; Sutton et al., 2001; and Plummer et al., 2004). Often, performing such a tracer study on the regional scale is prohibitively expensive, considering the large number of samples that would be required to effectively determine the flow paths.

Although there have been prior applications of multiple components as tracers (Spall et al., 1992; Katz et al., 1997; Negrel et al., 1997; and Swarzenski et al., 2001), the approach of this study differs from the previous studies in that it uses multivariate statistical technique (cluster analysis) to define hydrochemical facies and applies those facies as tracers. In this context, the nonsystematic variations within the normal background pattern were examined to evaluate the hypothesis that there is substantial interbasin flow into the alluvial aquifer. The insight that is gained from the current study can be used to develop a realistic conceptual groundwater flow model for the basin. The technique is particularly useful because it does not require unusual analytical procedures and makes use of the standard hydrochemical data readily available for many locations.

The objectives of this paper are (1) to describe the major hydrochemical facies in the study area, (2) to use these hydrochemical facies as tracers to delineate groundwater flow paths in the aquifer system, and (3) to evaluate the existence of an interbasin flow component postulated by authors in recent studies.

BACKGROUND

In the western United States, where the water rights doctrine of "prior appropriation" is commonly recognized, the amount of water allocated in a given basin is usually determined from estimates of perennial recharge derived from the topographic drainage area of the basin. Although many watersheds and their aquifers can be delineated by topographic boundaries, in some cases groundwater may flow across topographic boundaries into adjacent watersheds. Such flow is referred to as interbasin flow. Obviously, existence of a substantial interbasin flow component may result in significant errors if a conventional application of the practice of assuming that watersheds are delineated solely by topographic boundaries is in doubt.

An interbasin flow component is usually recognized when water budget imbalances are calculated or characteristic chemical differences are observed that do not fit into the conceptual hydrochemical model for the system. For example, previous studies (Eakin and Moore, 1964; Eakin and Winograd, 1965; Winograd and Eakin, 1965; Eakin, 1966; and Mifflin and Hess, 1979) have used water budget calculations to identify and quantify interbasin flow in parts of Nevada that are adjacent to the current study area. These studies indicated the existence of systems that involve transfer of water over long distances through bedrock and across areas that form drainage divides on the land surface. Maxey (1968) and Naff and others (1974) used major-ion data to detect interbasin water transfer. Later, Johannesson and others (1997) used rare earth elements in a similar fashion. However, in these cases the interbasin flow is through fractured limestone bedrock, which has been recognized as capable of such flow due to karstic alteration along fractures.

The Indian Wells Valley (IWV) is located in southeastern California (Figure 1) and is characterized by extreme aridity, scarcity of surface waters, and steady population growth that places heavy demands on groundwater supplies. This makes an accurate model of groundwater circulation patterns especially important. This type of understanding can be gained from regional-scale tracer studies, which can then be used for the development and effective management of the critical groundwater resources.

A large amount of historic hydrochemical data (major ions) is available for many areas, allowing study of temporal and spatial distributions of these parameters. The chemical data used are compiled in the study by Güler (2002) and isotopic data can be found in the study by Thyne and others (1999). Güler and Thyne (2004) showed that the major-ion chemistry of the waters from the IWV area is explained by progressive water-rock interaction down the horizontal flow gradient. That work demonstrated that the observed variations in water chemistry define the normal background in which the water chemistry systematically changes with increasing water-rock interactions along topographically defined flow paths. This prior work provides the context for interpreting the spatial distribution of the hydrochemical facies as tracers for groundwater flow paths as a tool to test the hypothesis of interbasin flow. In addition, we have used the limited stable isotopic data (δD, $\delta^{18}O$) to provide an independent means to evaluate the interpretations from the statistically derived hydrochemical facies.

Controversy exists regarding the source of groundwater in the IWV. Lee (1912) was first to suggest that the

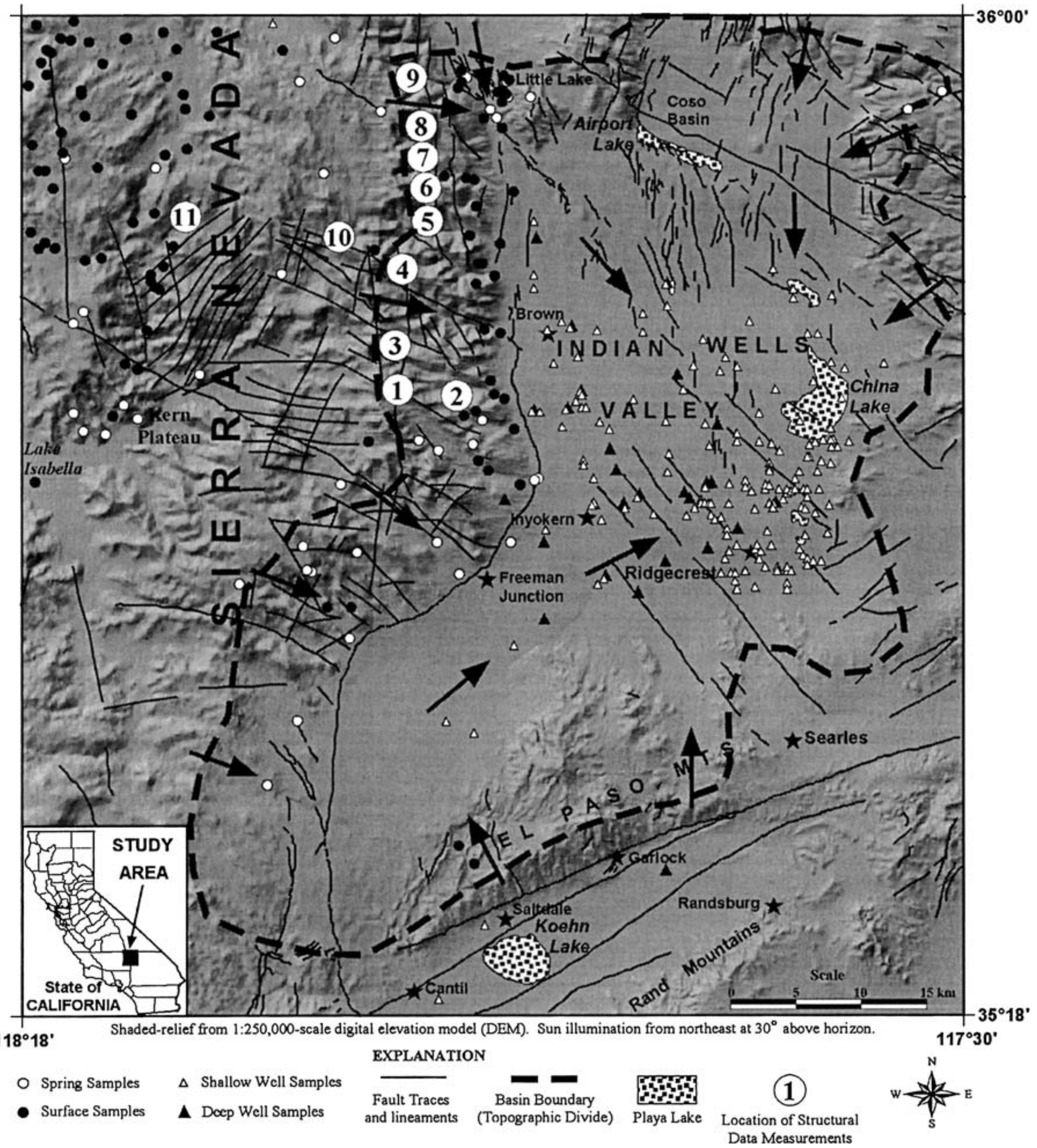

Figure 1. Map of Indian Wells Valley showing the locations of the water samples and major fault traces and lineaments. Lineaments digitized from Ostdick (1997). The heavy dashed line outlines the topographic drainage for the valley. Arrows indicate the directions of groundwater flow into the Indian Wells Valley groundwater basin.

valley is a closed basin. The closed-basin model assumes that recharge to the groundwater reservoir is derived from precipitation in the local topographic drainage basin only. Later researchers who worked in the area also adopted a closed-basin conceptual model in their studies (Buwalda, 1944; Bailey, 1946; Moyle, 1963; Kunkel and Chase, 1969; Bloyd and Robson, 1971; Dutcher and Moyle, 1973; Berenbrock, 1987; Berenbrock and Martin, 1991; and Berenbrock and Schroeder, 1994). As a result of these studies, additional recharge sources were recognized, including (1) infiltration from irrigation water, (2) leakage from the Los Angeles aqueduct system, and (3) infiltration from domestic and industrial wastewater. However, these components were considered to be small compared with regional recharge.

Recent studies, however, have suggested that the closed-basin assumption might not be valid (Austin and Moore, 1987; Erskine, 1989; Whelan, 1990; Howard et al., 1997; Ostdick, 1997; Thyne et al., 1999; and Williams, 2004). According to this alternative conceptual

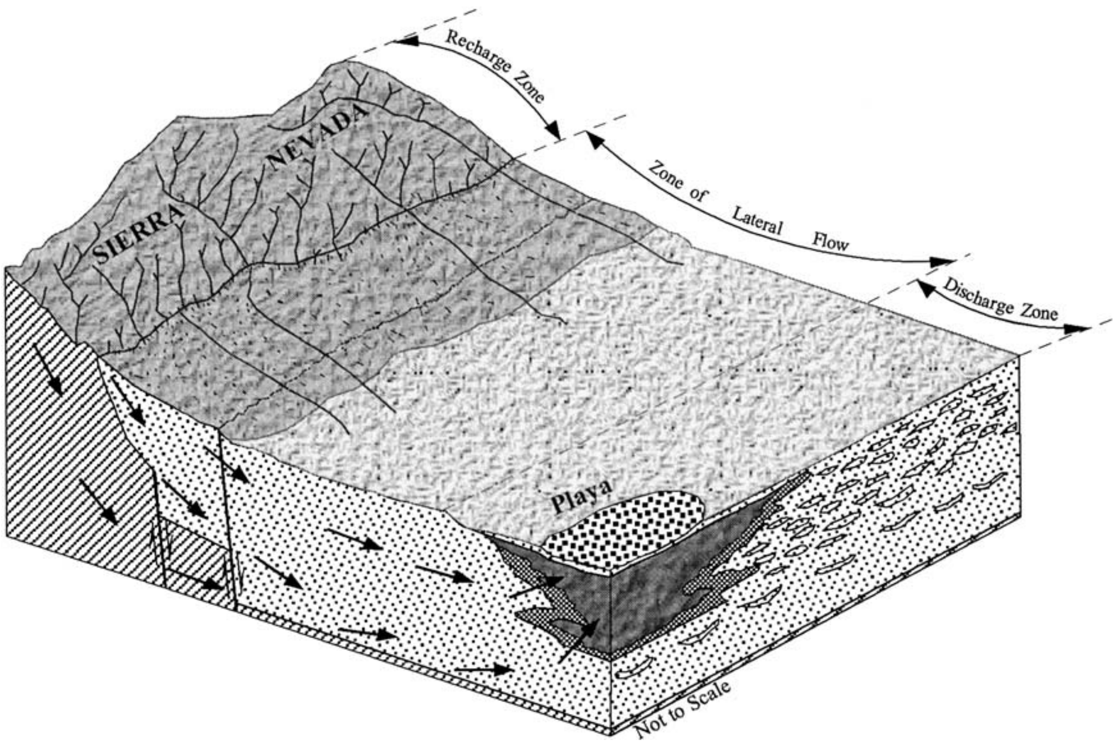

Figure 2. Schematic representation of an idealized groundwater flow system for the Indian Wells Valley area (after Hubbert [1940] and Tóth [1962, 1963]). Arrows indicate directions of groundwater flow.

model, significant amounts of subsurface (interbasinal) water flows into the groundwater basin across topographic divides via the fracture network in the igneous and metamorphic bedrock of the southeastern Sierra Nevada, discharging upward into the alluvial aquifer. In these studies, a variety of evidence of an interbasin flow component, including hydrochemistry, aquifer flux calculations, and the presence of structural discontinuities that may act as conduits for groundwater flow, was presented. For example, Thyne and others (1999) noted the existence of an apparent recharge surplus in the southwest section of the IWV, nearly an order of magnitude greater than the precipitation-based recharge available from the adjacent Sierran watershed. They also noted the distinctive chemical character of the groundwater from the southwest portion of the valley, which does not resemble waters from other parts of the aquifer system. The different chemical character of these waters has long been recognized, but the source of these waters remains unresolved. None of these previous studies used statistical techniques to reduce potential subjective bias during interpretation of hydrochemical data.

HYDROLOGIC FRAMEWORK

In a classic basin and range groundwater system (Maxey, 1968), water flows from high-elevation recharge areas in the mountains to topographically lower discharge areas. The IWV has a surface drainage area of approximately 2,641 km^2, where the topographic drainage is entirely internal (Figure 1). Most of the recharge to the valley aquifer originates from the adjacent Sierra Nevada mountain range and is largely derived from the infiltration of stream flow derived from snowmelt runoff. In this area, groundwater is found in two areas with different porosities: (1) fracture porosity found in the granitic mountain watersheds and (2) intergranular porosity found mostly in alluvial basin-fill aquifers. In the mountain watersheds, the water from precipitation (snow and rain) at high altitudes infiltrates into a network of interconnecting fractures and faults within the granitic rocks and under the influences of hydraulic pressure and gravity moves toward points of lower head. The water moves into the alluvial groundwater system after crossing the Sierra Nevada fault zone (Kunkel and Chase, 1955; Dutcher and Moyle, 1973). Eventually, this water evaporates from the surface of the China Lake playa or is transpired by plants, completing the local hydrologic cycle. In a general sense, groundwater flow system in the area is similar to that proposed by Hubbert (1940) and Tóth (1962, 1963). The idealized flow system for the area is shown in Figure 2. The system may be considered to consist of three integral parts: (1) a recharge area in which movement of water is downward, (2) an area of lateral flow, and (3) an area of discharge where movement of water is upward.

For this study, the aquifer is considered to consist of the unconsolidated sediments within the basin (Kunkel and Chase, 1969; Bloyd and Robson, 1971; Dutcher and Moyle, 1973; and Berenbrock and Martin, 1991). Previous hydrologic studies have divided the aquifer system into two hydrostratigraphic zones, the shallow and deep aquifers. The extent of the shallow aquifer is limited to the area from China Lake westward to the center of the valley and from the area south of Airport Lake southward to the community of Ridgecrest. The deep aquifer represents the total saturated thickness of the alluvium throughout the valley. These investigations inferred that the fine sediments underlying the playa confine, or partially confine, the deep aquifer in the eastern portion of the valley. The main reason for this division is the upward gradient between the hypothesized deep aquifer and shallow aquifer and the presence of some artesian wells in the vicinity of the playa, but this gradient is inherent due to this region being the area of discharge within the valley. Local confined zones are scattered throughout the valley, most notably in the outer, coalescing lobes of the alluvial fans, but there is no evidence from well logs or geophysical data that there is distinct layering of separate aquifers.

Both evapotranspiration and recharge are poorly quantified in the basin, making water budget calculations uncertain. Recent measurements of recharge have been made for portions of the drainage area (Thyne et al., 1999), but evapotranspiration has only been estimated based on measurements from analogous areas. However, several studies that made estimates of these properties generally agree on the amounts (see Thyne et al., 1999, for further discussion).

HYDROCHEMICAL FACIES DISTRIBUTION

Groundwater in the IWV aquifer can be divided into five hydrochemical facies based on hydrochemical similarities and differences, which were statistically defined using hierarchical cluster analysis (Güler, 2002; Güler and Thyne, 2004; and Thyne et al., 2004). Hierarchical cluster analysis is a multivariate statistical technique used to determine if samples can be grouped into statistically distinct groups. Comparisons based on multiple parameters from different samples are made and the samples grouped according to their ‘‘similarity’’ to each other. The classification of samples according to their parameters is termed Q-mode classification. Previous studies have used this technique to successfully classify water samples (Williams, 1982; Alberto et al., 2001). The hydrochemical facies used in this study are similar to classic hydrochemical facies in that they are an aggregate parameter that combines information from all the chemical data used but differ in that they are based on objective criteria rather than subjective means that are normally used (Güler et al., 2002).

The database used in this study is a compilation of the available data (spring, surface, and well water samples) in the Indian Wells-Owens Valley area. Database construction procedures are discussed in detail in the article by Güler et al. (2002), where the sources of the data are also presented. The database consists of chemical analyses for 152 spring, 153 surface, and 1,063 well samples, including temporal series (samples collected over a period at the same location). In the case of time series, the more recent and/or more complete sample data were included in the statistical analysis. Although the database had up to 39 hydrochemical variables, only the 11 most common variables (specific conductance, pH, Ca, Mg, Na, K, Cl, SO_4, HCO_3, SiO_2, and F) were used in the statistical analysis. The database treatment procedures and detailed explanation of the hierarchical cluster analysis technique used by this study can be found in the article by Güler et al. (2002).

The hydrochemical facies (statistical groups) are plotted on a site map using ArcView GIS software (ESRI, Redlands, CA) in Figure 3. The five facies exhibit spatial coherence, reflecting physiographic control and the similar water-rock interactions and flow paths for each group. Group 1 water samples are located in the high Sierra Nevada and plot above the 2,000-m elevation (Figure 3). Group 2 samples are mostly located below the 2,000-m elevation in the Sierra Nevada and other mountain ranges. Group 3 samples are usually located on the basin floor and spatially between group 2 and group 4 samples. Group 4 samples are found near the discharge areas of the China Lake playa and have the second highest total dissolved solids (TDS) values. Group 5 waters have the highest TDS values and coincide with the China Lake playa or nearby discharge areas (Figure 3).

In general, the spatial distribution of water groups in the study area conforms to the topographic flow path (group 1→group 2→group 3→group 4→group 5) as suggested by the basin and range groundwater system conceptual model (Maxey, 1968). The TDS value increases as the water moves from Sierran recharge areas to the playa discharge at China Lake (Figure 4). The recharge evolves from dilute Ca-Na-HCO_3 water (mean TDS value, 67 mg L^{-1}) to less dilute Na-Ca-HCO_3 water (mean TDS value, 356 mg L^{-1}) to a more concentrated Na-HCO_3-Cl water (mean TDS value, 1,018 mg L^{-1}) to a brackish Na-Cl water (mean TDS value, 5,133 mg L^{-1}), and finally to a Na-Cl brine (mean TDS value, 93,588 mg L^{-1}). Table 1 gives the mean values for the major ions in each group and the TDS. As part of a systematic and sequentially developed

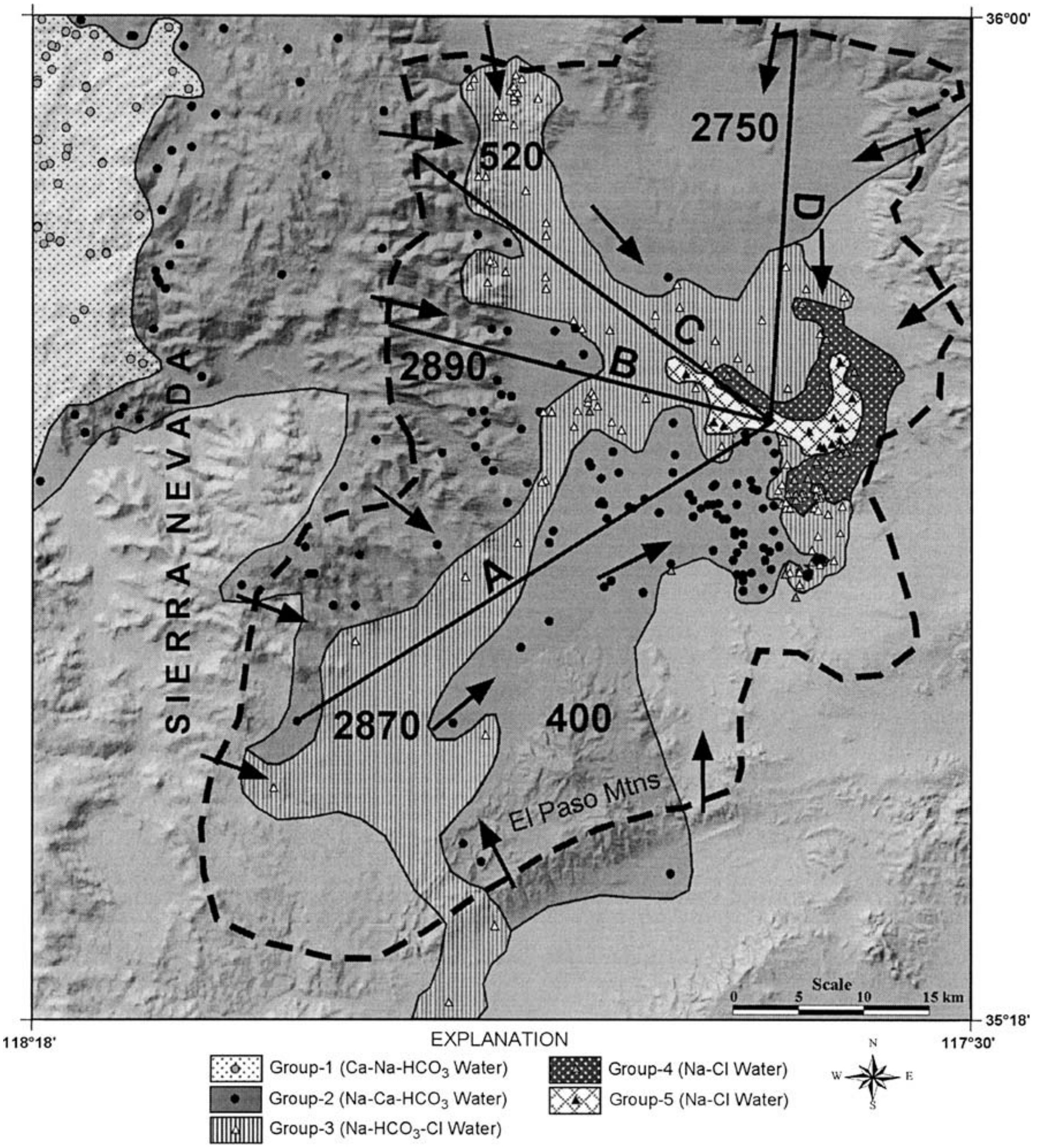

Figure 3. Spatial distribution of the statistically defined five hydrochemical facies in the Indian Wells Valley. Arrows indicate directions of groundwater flow. Water chemistry changes along profiles A, B, C, and D are depicted in Figure 4. Relative percentage of groundwater areal distribution by type is 59.76 percent for group 2, 33.81 percent for group 3, 4.32 percent for group 4, and 2.11 percent for group 5. Areas calculated from within-basin group boundaries, which were drawn by hand. Numbers indicate recharge estimates of Bloyd and Robson (1971) (values are in acre-ft/year) (1.0000 acre-ft = 1,233.5 m^3).

hydrochemical evolution model (Thyne et al., 2004), inverse geochemical models (PHREEQC, Parkhurst and Appelo, 1999) were constructed based on the water chemistry for each group and the mineralogy of the area. The PHREEQC mass balance models used mean water chemistry of each group as input and demonstrated that the systematic changes in water chemistry can be attributed solely to the expected water-rock interaction and defined the normal hydrochemical evolution for the study area.

The spatial distribution of hydrochemical facies in portions of the southwestern basin, however, does not conform to the well-defined regional trend. The groundwater (group 2 type) from that part of the valley has chemistry that is statistically similar to waters from the Kern Plateau area (in the high Sierra Nevada outside the local watershed) rather than water from the local watershed. This finding does not appear consistent with the present closed-basin models for the hydrologic system in the IWV. Assuming that the spatial extent of each water group (Figure 3) represents an approximate volume of groundwater, group 2 samples (59.76 percent) in the valley far exceed the amount of other water types, and this large volume cannot be reconciled with prior closed-basin models. The adjacent topographic drainage of the El Paso Mountains produce only 400 acre-ft/year (493,400 m^3/year) of recharge (Bloyd and Robson, 1971), which is insufficient to explain the large volume of group 2 water.

Figure 4 shows the change in groundwater chemistry along profiles A, B, C, and D. These profiles are generally parallel to the groundwater flow direction, and increasing TDS values along the profiles can be attributed to the hydrochemical evolution. Along profiles B, C, and D (Figure 4), the TDS value slowly increases until near the China Lake playa, where the TDS value jumps sharply with highly saline waters. However, the TDS values along profile A decrease midway along the profile, suggesting an influx of fresher water along the flow path. This decrease cannot be explained by the closed-basin conceptual model, since TDS values of the water along the flow path should increase owing to water-rock interaction processes. Furthermore, the sudden increase in the TDS value at the end of profile A appears to be a sharp mixing front between group 2 and 5 waters. This sudden jump from group 2 to 5 (lack of group 3 and 4 waters between them) appears to indicate an encroachment of a fresher groundwater tongue near the China Lake playa.

Figure 5 shows a more detailed distribution for the group 2 water subgroups across the two watersheds. Although there are some group 2 samples near the western edges of the basin, as would be expected since group 2 samples represent the slightly more evolved lower elevation samples, most group 2 well samples are found north of Ridgecrest near the eastern margin of the basin. This cluster of samples has chemistry similar to the higher elevation samples in the Kern River watershed (most of the SU 1 samples). The figure also shows that both the deep and shallow wells have this distinctive chemical signature, which supports the assumption that the spatial extent of group 2 samples can be used to estimate the volume.

To provide an independent tracer, the available hydrogen stable isotopic data were contoured (Figure 6) and the values plotted along the flow transects in Figure 4. The variation in isotopic values with the evolution in water chemistry is fairly small along these transects until the playa, except along transect A where δD shows more abrupt variation and has more negative values (dashed lines in Figure 4). In map view, the contours show an

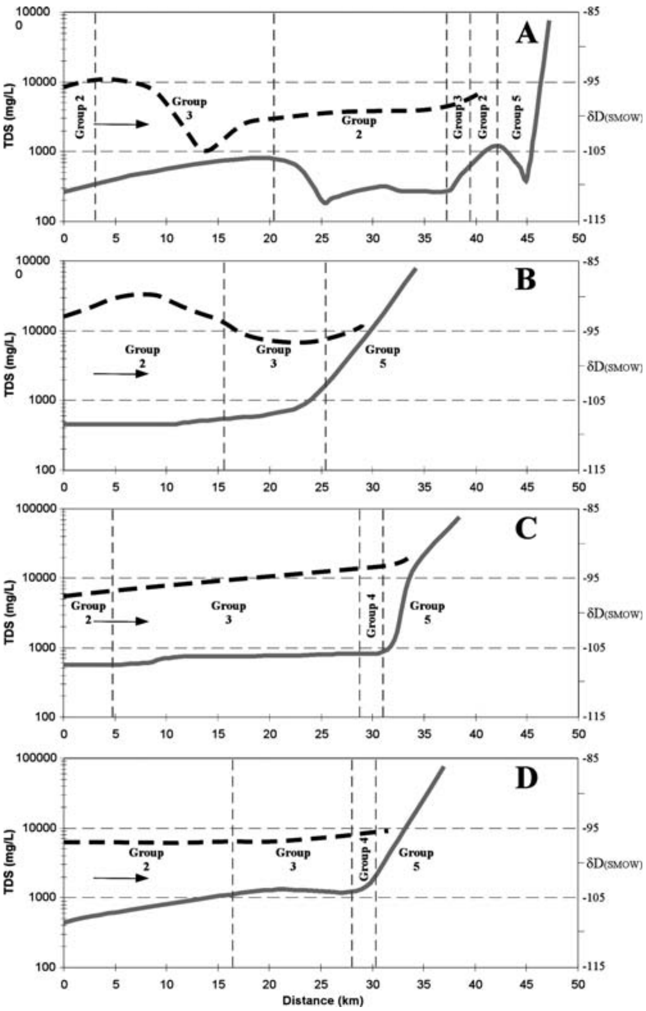

Figure 4. Water chemistry changes along profiles A, B, C, and D in the Indian Wells Valley. Dashed lines are hydrogen isotope values. See Figure 3 for the profile locations. Arrows indicate directions of groundwater flow.

anomalous distribution of depleted hydrogen isotopic values (<−100 per mil) that is generally coincident with the group 2 hydrochemical facies. No recharge sources within the topographic watershed have such negative values, but recharge in the Kern Plateau area has such values.

Prior studies have also found the same low TDS water in the southwestern portion of the basin (Berenbrock and Schroeder, 1994; Houghton, 1994; and Ostdick, 1997). Previous authors have proposed that the anomalous chemical and isotopic signature represents relict Pleistocene recharge (Berenbrock and Schroeder, 1994). This hypothesis implies some degree of hydraulic isolation in the southwesterly portion of the basin. Prior studies have suggested that some faults in alluvium between Inyokern and Freeman Junction may form barriers to groundwater flow, compartmentalizing the basin (Bloyd and Robson,

Table 1. *Mean parameter values for the five principal water groups determined by the hierarchical cluster analysis.**

Group	N†	pH	Ca	Mg	Na	K	Cl	SO_4	HCO_3	SiO_2	TDS
1	81	7.3	7.3	0.9	7.2	0.9	1.3	1.6	44.7	21.5	67.5
2	229	8.0	37.1	8.5	67.1	3.6	41.1	50.9	195	32.5	356
3	168	7.9	76.5	33.7	236	12.9	199	192	442	42.7	1,018
4	80	7.9	143	79.9	1,574	52.0	1,900	892	660	41.2	5,133
5	20	8.9	107	110	35,501	714	42,844	5,635	9,417	33.7	93,588

TDS = total dissolved solids.
*The pH values are given in standard units; other values are given in mg L^{-1}.
†Number of samples within respective water groups.

1971; Dutcher and Moyle, 1973), but no hydrologic model has been presented that supports this hypothesis (Bloyd and Robson, 1971; Berenbrock and Martin, 1991; and Clark, 1998). In fact, the distribution of hydrochemical facies in that area shows good hydrologic continuity, implying that movement of groundwater is not impeded by the existence of faults dissecting the basin-fill sediments (Zellmer, 1988).

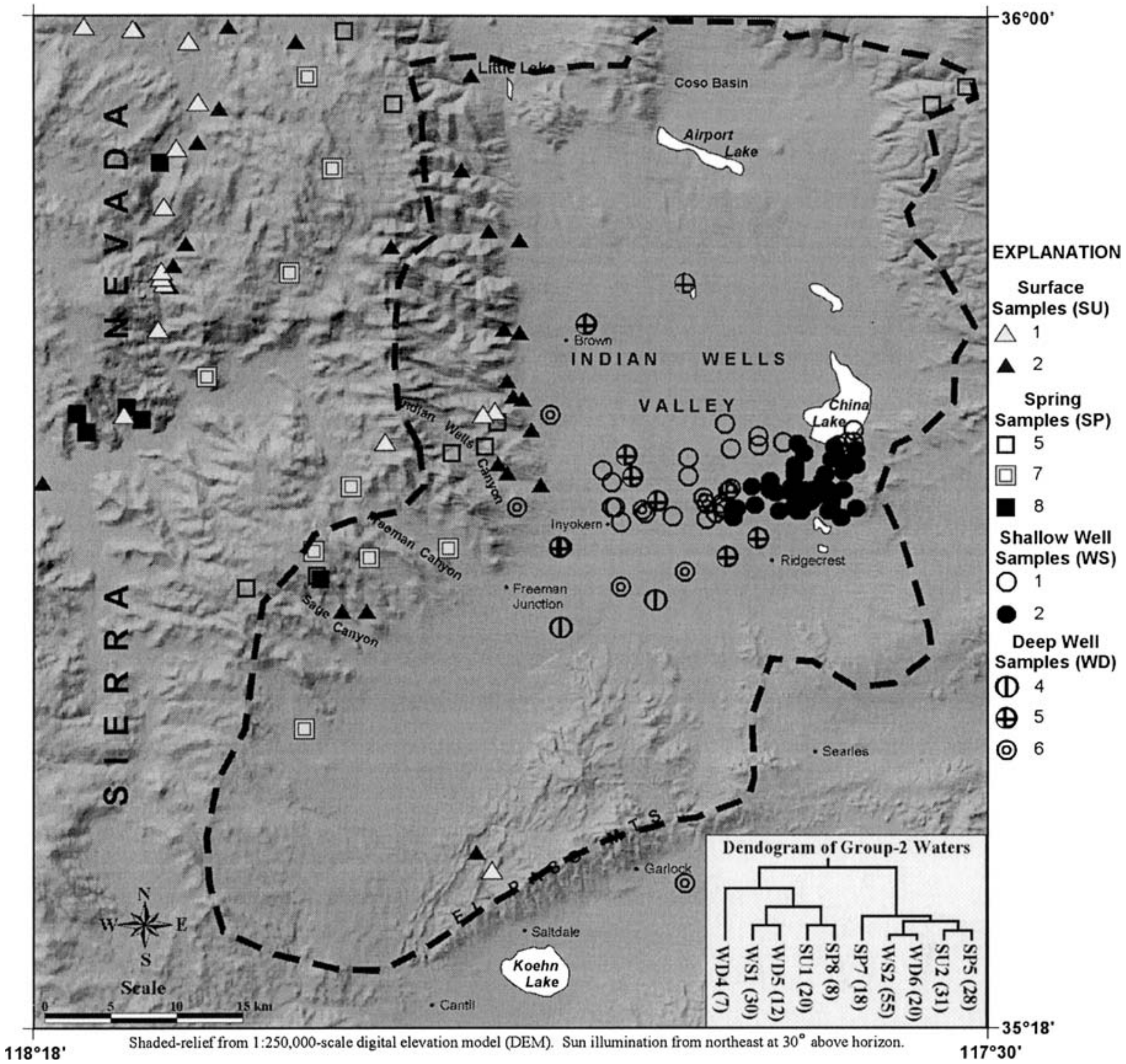

Figure 5. Sample locations for the group 2 samples in the Indian Wells Valley and Kern River watersheds. The legend at right refers to the statistically-defined subgroups within group 2 and the dendogram in the lower right corner shows the similarity between subgroups (number of samples in subgroup in parentheses).

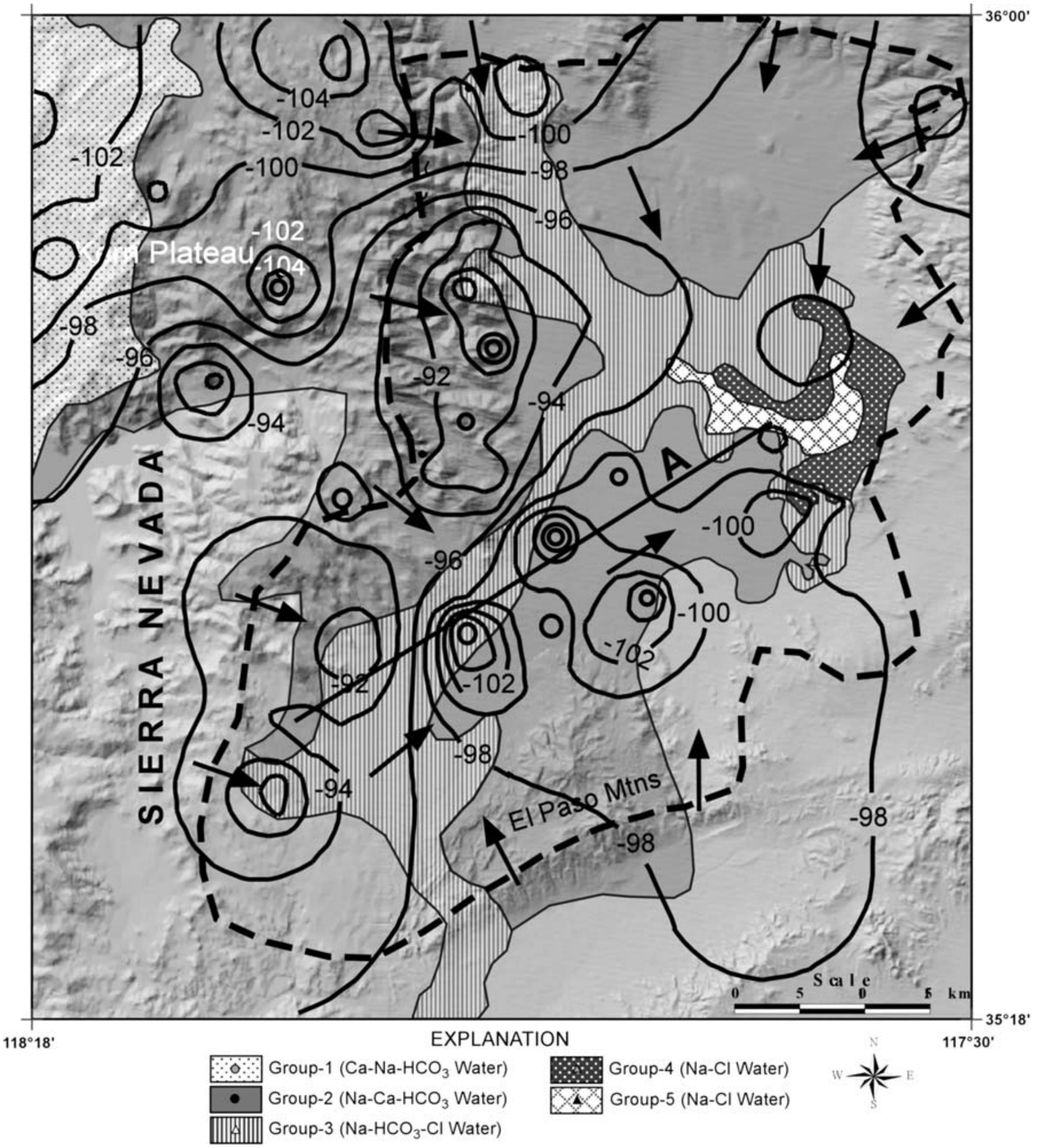

Figure 6. Map view of δD contours (Rockware least-distance method) based on 121 spring, stream, and well locations from the Indian Wells Valley area. Data from Thyne et al. (1999), Einloth (2000), and Friedman (2000). Contour interval is 2 per mil.

EVIDENCE FOR FRACTURE-DIRECTED INTERBASIN FLOW

Because no convincing evidence exists of hydrologic discontinuities, we assume piston flow through the southern portion of the alluvial basin. Using an aquifer storage volume of 2.2 million acre-ft. (2,700,000,000 m^3) (Dutcher and Moyle, 1973) and an annual topographic recharge of between 3,000 and 4,000 acre-ft (3,700,000 to 4,900,000 m^3) (Bloyd and Robson, 1971; Thyne et al., 1999), the aquifer volume is calculated to be replaced every 550 to 733 years. This residence time is not significantly longer than for other portions of the valley (Berenbrock and Martin, 1991) and should allow enough time for normal hydrochemical evolution, which is not what is observed.

For the groundwater in southeastern IWV to be derived from the Kern Plateau region, recharge would have to enter the valley through a system of faults and fractures in the Sierra Nevada and cross the phreatic divide between the watersheds. Numerous studies have demonstrated the potential importance of faults and

Table 2. *Statistical summaries of the structural (fracture) orientation data taken from Sierra Nevada canyons.**

Location	Vector Orientation, Mean ± 95 Percent Confidence Interval	No. of Measurements
Indian Wells Canyon (1)	287.32° ± 24.75°	14
Short Canyon (2)	270.74° ± 21.46°	29
Grapevine Canyon (3)	88.09° ± 48.44°	5
Sand Canyon (4)	80.20° ± 33.43°	8
Noname Canyon (5)	80.80° ± 36.65°	9
Ninemile Canyon (6)	85.87° ± 29.53°	16
Deadfoot Canyon (7)	279.58° ± 23.55°	26
Fivemile Canyon (8)	279.21° ± 18.64°	35
Little Lake Canyon (9)	275.43° ± 18.78°	29
Chimney Creek (10)	86.55° ± 24.14°	16
Kern Plateau (11)	277.57° ± 15.79°	41
All data	274.22° ± 7.17°	227

*Data are from California State University at Bakersfield (unpublished field studies by Malden Zic). Numbers in parentheses identify the locations shown in Figure 1.

fractures in controlling groundwater flow in crystalline rock environment (Meinzer, 1923; Caswell, 1979; and Folger et al., 1996). In these environments, fractures and faults may either provide conduits to groundwater flow (Pollard and Aydin, 1988) or act as barriers to it (Allen and Michel, 1998).

Ancient and recent tectonic events in the study area created an extensive system of faults and fractures in close proximity to several major active fault zones of California, including the Sierra Nevada frontal fault, Kern Canyon fault, and Garlock fault. Earthquakes are common in the area, and there are local areas of active deformation and elevated heat flow (Zellmer, 1988). Becker (1891) was probably the first to recognize that faults and fractures are common and pervasive in the granitic rocks of the Sierra Nevada. These fractures (faults?) are generally defined as features of regional extent (Mayo, 1947; Lockwood and Moore, 1979), and the exposed rock faces contain numerous fractures (Segall and Pollard, 1983; Tonnessen, 1991). Prior studies in the Sierra Nevada also have shown that the orientation and distribution of these weakness zones may provide preferential pathways for surface water and groundwater (Erskine, 1989; Howard et al., 1997, 1997b).

In the southeastern part of the Sierra Nevada, networks of intersecting fractures and faults exist (evidenced by the pattern of faults and lineaments in Figure 1) and could be capable of transmitting large amounts of groundwater. Groundwater movement in crystalline rocks of this region is postulated to occur primarily through intensely fractured regions that are connected in three dimensions. To help evaluate this potential flow path, fracture orientation measurements were taken in Sierra Nevada canyons (locations in Figure 1). The measurements indicate the presence of two major fracture sets with significant variations in orientation (Table 2), but no single fracture set is predominant, suggesting that there is a high potential for interconnection of fractures that can form regional-scale flow paths. The present stress regime in the adjacent Sierra Nevada is extensional to the north, which enhances the permeability of east-west trending fractures (Barton et al., 1995). A recent analysis of the effect of the regional stress field on fracture flow shows preferential flow would occur from the plateau toward the southwest, assuming sufficient permeability and interconnection of fractures (Williams, 2004).

The use of hydrochemical facies as a tracer in the study area shows a pattern consistent with systematic hydrochemical evolution along topographically driven flow paths. The exception is the observation of an abrupt transition from more saline to less saline water along the flow path from the Freeman Junction to Ridgecrest. This apparent reversal of normal hydrochemical evolution is coincident with significantly more negative stable isotopic values. The only area with similar isotopic and chemical composition is outside the topographic watershed. Our interpretation of these data as a set of tracers is that interbasin flow is entering the IWV and discharging upward from fractures in the bedrock between Inyokern and the China Lake playa.

SUMMARY AND CONCLUSIONS

This study used statistically derived hydrochemical facies as tracers to determine whether a region within the fractured metamorphic and igneous rocks of the Sierra Nevada is the source of interbasin, fracture-directed recharge to the southwestern portion of the IWV. The key hydrochemical data include the following:

1. Juxtaposition of less evolved (low TDS value), younger group 2 waters with more evolved (high TDS value), older group 5 waters near the China Lake playa.
2. Existence of large amounts of relatively fresh group 2 groundwater in the basin that cannot be accounted for by local recharge.
3. Virtually no evolution along profile A in Figure 3 (from the southwest corner to the center of the basin, where group 2 waters are located).
4. Abrupt transition from group 2 to group 5 waters along profile A without intermediate water types between them.
5. The spatial similarity of an independent stable isotopic tracer with the anomalous hydrochemical facies.

Anomalous hydrochemical data are considered to be classic indications of interbasin flow (Maxey, 1968; Naff et al., 1974), as are imbalances in water budgets.

However, the definition of anomalous can be subjective, and uncertainties in determining water budgets have made confirmation of the interbasin flow in IWV difficult. In this study, we used the anomalous distribution of objectively defined hydrochemical facies that are coincident with anomalous isotopic signatures to locate the area where interbasin flow discharges into an alluvial aquifer. Coupled with the existence of an extensive, well-connected fracture network, the data support a hypothesized open-basin model for IWV more than prior closed-basin models. Acceptance of closed- or open-basin models would have different effects on the groundwater management practices and could have an enormous impact on water rights and estimates of water supplies for this arid region. If existence of interbasin flow is accepted, groundwater recharge to the IWV could be considerably greater than the amount currently estimated and a new paradigm for the regional flow system may be required. This requires alteration of the traditional closed-basin models to accommodate interbasin flow and integration with alluvial basin-fill aquifer properties to successfully predict the available water quantity. A model that can integrate all these components will provide an effective and successful water resources management tool for the region.

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