

**The Hydrogeology of Southwest Indian Wells Valley, Kern County, California:  
Evidence For Extrabasinal, Fracture-Directed Groundwater Recharge  
From the Adjacent Sierra Nevada Mountains**

**James R. Ostdick**

**Submitted for fulfillment of the thesis requirements for the degree of:**

**Master of Science in Hydrogeology  
California State University, Bakersfield**

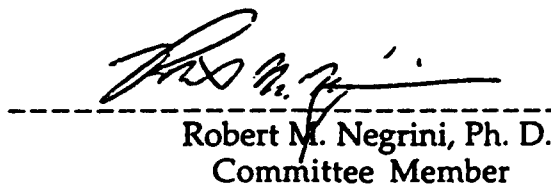
**March 17, 1997**

APPROVED

For the Department of Physics and Geology:

  
-----  
Janice M. Gillespie, Ph. D.  
Committee Chair

  
-----  
Geoffrey D. Thyne, Ph. D.  
Committee Co-Chair

  
-----  
Robert M. Negrini, Ph. D.  
Committee Member

## **DEDICATION**

**I offer this work to honor the love of my parents, Lee and Marie Ostdick.**

## ABSTRACT

Analysis of the surface hydrology, regional lineaments, groundwater flow and aqueous geochemistry of the southwest Indian Wells Valley and the adjacent Sierra Nevada Mountains in southeastern California suggests an extrabasinal source of recharge for the desert valley's deep alluvial aquifer.

Orographic precipitation data from within the conventional surface drainage area indicate that 4,125 acre-feet of precipitation were available for groundwater recharge to the valley in 1994-95, one of the wettest years on record. The chemistry of the mountain front surface samples showed a Ca-Na-HCO<sub>3</sub>-SO<sub>4</sub> water type with an average total dissolved solids (TDS) concentration of more than 500 mg/l and a mean deuterium signature of -91‰. In contrast, groundwater samples from deep southwest monitoring wells in the adjacent valley were a Na-HCO<sub>3</sub> type with mean values of 250 mg/l TDS and -103‰ deuterium. These data, plus comparisons with high Sierran isotope samples, suggest that surface runoff from the canyons adjacent to Indian Wells Valley is not the source of the majority of the southwest groundwater, but rather that the recharge is coming from higher elevations of 7,000 to 9,000 feet. The stable isotope values and ionic concentrations of the southwest groundwater are similar to those of samples high on the Kern Plateau, which lies to the west of the conventional surface drainage divide for Indian Wells Valley.

To test the hypothesis that additional recharge may be entering the basin from beyond the divide, the amount of groundwater flow through the southwest aquifer was calculated using Darcy's Law and compared to the precipitation recharge figure. The calculated flux of 33,750 acre-feet per year greatly exceeded the 4,125 acre-feet of recharge available in 1994-95 from the conventional drainage area.

Because the topographic boundaries of the region preclude surface flow from the Kern Plateau, the most likely conduit for extrabasinal recharge to southwest Indian Wells Valley is fractured Sierran crystalline rock. Aerial photographs and satellite images from the Sierra Nevada Mountains reveal northwest and northeast trending lineaments throughout the study area from the South Fork of the Kern River to Bird Spring Canyon. Field work in the canyons of the conventional drainage areas confirmed northwest-northeast conjugate joint sets at the surface and perennial spring water coming from both horizontal and vertical fractures. These observations further support the hypothesis that subsurface flow from higher elevations beyond the surface drainage boundaries is the primary source of the fresh, abundant, isotopically light groundwater in the southwest basin.

Water conservation should be the credo of any desert community. The data and interpretations presented in this thesis should be carefully reviewed and tested by the Indian Wells Valley Water Management Steering Committee before any development based on this potential resource is considered. If the recommended testing procedures are completed and a consensus is reached among water scientists that a significant flux of extrabasinal recharge to the southwest has been proven, the committee has a responsibility to preserve and protect the aquifer as the valley's drinking water supply for the future. Further studies may show that other alluvial basin aquifers in the arid southwestern United States may also benefit from similar unconventional sources of groundwater recharge.

## ACKNOWLEDGMENTS

This project is part of a comprehensive hydrogeological and hydrogeochemical study of Indian Wells Valley and the southern Sierra Nevada Mountains by the Department of Physics and Geology at California State University, Bakersfield. It has been funded by grants from the Geothermal Program Office of the Naval Air Weapons Station at China Lake, California; the National Science Foundation; the Geological Society of America and the National Ground Water Association. Technical assistance was provided by the Geothermal Program Office at China Lake and the North American Chemical Company of Trona, California. Representatives of the Indian Wells Valley Water District and the Kern County Water Agency contributed valuable time for background consultation and constructive criticism.

Special thanks go to John and Louise Knecht of Inyokern; Frank Monastero, Al Katzenstein and Steve Bjornstad at China Lake; Gail Moulton, Dipti Barrari, Brian Allen and Ray Trujillo at North American; Roy Tucker and Mike Hokanson at the water district and Ken Turner at KCWA.

Invaluable assistance was contributed by many field partners: Charlie and Luke Bauer; Cheryl Blume; Michelle Casterline; Heather Cressall; Robert Fratello; Tom and Carolyn Ganner; Joy Gillick; Dawn Hanson; Patrick Howard; Kayo; Janet, Jessica and Allison McAlee; Erik Oehlschlager; Chuck and Candace Pierce; Andy Sherman; Dan Steward; Jason Thompson; Alan White; Mladen Zic and the legendary Sparky the Dog.

I owe most of what I have learned about geology and part of what I know about character, determination and hard work to Jan Gillespie, Geoff Thyne and Rob Negrini. Pressure makes diamonds.

## TABLE OF CONTENTS

|                                                         | <u>Page</u> |
|---------------------------------------------------------|-------------|
| Dedication                                              |             |
| Abstract                                                | ii          |
| Acknowledgements                                        | iv          |
| Table of Contents                                       | v           |
| List of Figures                                         | vii         |
| List of Plates                                          | viii        |
| List of Tables                                          | viii        |
| List of Appendices                                      | ix          |
| <b>1. INTRODUCTION</b>                                  |             |
| 1.1 Statement of the Problem                            | 1           |
| 1.2 Purpose of This Study                               | 2           |
| 1.3 Location of the Study Area                          | 2           |
| 1.4 Structural Setting                                  | 4           |
| 1.5 Geological Setting                                  | 6           |
| 1.6 Hydrogeological Setting                             | 6           |
| 1.7 Summary of Previous Work in Indian Wells Valley     | 12          |
| <b>2. METHODS AND MATERIALS</b>                         |             |
| 2.1 Southern Sierra Nevada Surface Hydrology            |             |
| a. Conventional Surface Drainage Area Boundaries        | 18          |
| b. Precipitation Gage Locations and Recharge Estimation | 18          |
| c. Surface Flow Measurements                            | 21          |
| d. Surface Water Chemistry Sampling Sites and Protocol  | 21          |
| 2.2 Southwest Indian Wells Valley Groundwater Recharge  |             |
| a. Monitoring Well Locations                            | 23          |
| b. Stratigraphic Cross-Section Locations                | 25          |
| c. Groundwater Chemistry Sampling Sites and Protocol    | 25          |
| d. Gravity Survey Line Locations                        | 26          |
| e. Groundwater Flow Calculation Parameters              | 28          |
| 2.3 Southern Sierra Nevada Lineament Data Collection    | 29          |
| <b>3. RESULTS</b>                                       |             |
| 3.1 Southern Sierra Nevada Recharge                     |             |
| a. Conventional Surface Drainage Area Measurements      | 30          |
| b. Precipitation Measurements and Recharge Estimates    | 30          |

|                                                              |             |
|--------------------------------------------------------------|-------------|
|                                                              | <b>Page</b> |
| c. Surface Flow Estimates                                    | 36          |
| d. Surface Water Chemistry Data                              | 37          |
| 3.2 Southwest Indian Wells Valley Groundwater Recharge       |             |
| a. Depth to Water Measurements                               | 44          |
| b. Description of Stratigraphic Cross-Sections               | 52          |
| c. Groundwater Chemistry Data                                | 53          |
| d. Gravity Profiles                                          | 57          |
| e. Groundwater Flow Calculations                             | 61          |
| 3.3 Sierran Lineament Map and Rosette Diagrams               | 63          |
| 4. DISCUSSION                                                |             |
| 4.1 Southern Sierra Nevada Recharge                          |             |
| a. Quantity of Surface Recharge                              | 67          |
| b. Sources and Flowpaths of Sierra Nevada Recharge           | 68          |
| c. Age Dates of Surface Samples                              | 72          |
| 4.2 Southwest Indian Wells Valley Groundwater                |             |
| a. Quantity of Southwest Groundwater Flow                    | 75          |
| b. Sources and Flowpaths of Groundwater                      | 78          |
| c. Age Dates of Southwest Indian Wells Valley<br>Groundwater | 82          |
| d. Anomalous Groundwater Samples                             | 84          |
| 4.3 Sources and Flowpaths of Group I Sierran Recharge        |             |
| a. Sources of Group I Water                                  | 85          |
| b. Flowpaths of Group I Water                                | 86          |
| 5. CONCLUSIONS                                               | 95          |
| 6. RECOMMENDATIONS                                           | 96          |
| REFERENCES                                                   | 98          |
| APPENDICES                                                   | 104         |

## LIST OF FIGURES

| <u>Figure</u>                                                                        | <u>Page</u> |
|--------------------------------------------------------------------------------------|-------------|
| 1. Location map                                                                      | 3           |
| 2. Regional fault map                                                                | 5           |
| 3. Regional geographical features                                                    | 7           |
| 4. Lithology of the study area                                                       | 8           |
| 5. Pleistocene lake drainage in eastern California                                   | 10          |
| 6. 1996 potentiometric surface map of Southwest Indian Wells Valley                  | 11          |
| 7. Surface drainage map with sampling sites and precipitation gage locations         | 19          |
| 8. Monitoring well location map with stratigraphic cross-section lines A-A' and B-B' | 24          |
| 9. Gravity survey lines and isopach map of the alluvial fill southwest of Inyokern   | 27          |
| 10. 1994-95 Freeman Canyon precipitation                                             | 32          |
| 11. 1995-96 Freeman Canyon precipitation                                             | 33          |
| 12. Spring 1995 surface water fingerprint                                            | 40          |
| 13. Spring 1995 P <sub>CO2</sub> map                                                 | 41          |
| 14. Fall - Winter 1995-96 surface water fingerprint                                  | 42          |
| 15. Fall - Winter 1995-96 P <sub>CO2</sub> map                                       | 43          |
| 16. Spring - Summer 1996 surface water fingerprint                                   | 45          |
| 17. Spring 1996 P <sub>CO2</sub> map                                                 | 46          |
| 18. BR-1 hydrograph                                                                  | 48          |
| 19. BR-2 hydrograph                                                                  | 49          |
| 20. BR-3 hydrograph                                                                  | 50          |
| 21. MW-32 hydrograph                                                                 | 51          |
| 22. Spring 1995 groundwater fingerprint                                              | 54          |
| 23. Winter 1996 groundwater fingerprint                                              | 55          |
| 24. Gravity profile: highway 14 to Bowman Road                                       | 58          |
| 25. Gravity profile: BR-1 to Brown Road                                              | 59          |
| 26. Gravity profile: BR-1 to highway 178                                             | 60          |
| 27. Cross-section of alluvial fill: Freeman Junction to the Black Hills              | 62          |
| 28. Lineament map of the adjacent Sierra Nevada Mountains                            | 64          |
| 29. Rosette diagram of Indian Wells Canyon fracture data                             | 66          |
| 30. Stable isotope data plotted on the meteoric water line                           | 70          |

|                                                                          | <u>Page</u> |
|--------------------------------------------------------------------------|-------------|
| 31. Tritium decay curve                                                  | 73          |
| 32. Unconventional recharge area surface sample location map             | 74          |
| 33. Krieger-Stewart drawdown curve for Test Well 1                       | 77          |
| 34. Cation exchange effects on recharge                                  | 80          |
| 35. Elevation range of southwest Indian Wells Valley groundwater samples | 83          |
| 36. High Sierran samples fingerprint                                     | 87          |
| 37. Comparison of high Sierran, Group I and groundwater fingerprints     | 88          |
| 38. Cross-section of potential regional groundwater flowpaths            | 90          |
| 39. Regional flow system diagram                                         | 91          |
| 40. Stages of fault zone permeability                                    | 92          |

#### LIST OF PLATES

|                                                            |        |
|------------------------------------------------------------|--------|
| 1. Southwest to northeast stratigraphic cross-section A-A' | Pocket |
| 2. West to east stratigraphic cross-section B-B'           | Pocket |

#### LIST OF TABLES

|                                                                    |    |
|--------------------------------------------------------------------|----|
| 1. Maxey - Eakin recharge coefficients                             | 20 |
| 2. Conventional surface drainage area                              | 31 |
| 3. Comparison of precipitation gage data                           | 34 |
| 4. Surface recharge by elevation and canyon                        | 35 |
| 5. Surface flow measurements                                       | 38 |
| 6. Surface sample tritium data                                     | 44 |
| 7. Surface sample chemistry data comparisons                       | 56 |
| 8. Groundwater sample tritium data                                 | 56 |
| 9. Comparison of Kern Plateau, Group I and Group II chemistry data | 79 |
| 10. Groundwater age dating summary                                 | 84 |
| 11. Saturation indices at BR-2 shallow                             | 85 |

**LIST OF APPENDICES**

|                                           |     |
|-------------------------------------------|-----|
| 1. Gravity data                           | 104 |
| 2. Water sampling data                    | 108 |
| 3. Hydrographs                            | 112 |
| 4. Fracture data                          | 119 |
| 5. TW-1 drawdown data from 1989 pump test | 126 |

## **1. INTRODUCTION**

This report is organized into six sections, as indicated in the Table of Contents on page v. The reader is introduced to the subject matter in the first section and to the methods of investigation in the second. Section three presents the study's results without interpretation, followed in section four by a discussion of the data and a presentation of a hypothetical recharge model. The final two sections list the author's conclusions drawn from the data collected for this project and his recommendations for further inquiry. Appendices at the back of the thesis contain supplemental tables and figures mentioned in the text.

### **1.1 Statement of the Problem**

Accurate modeling of Indian Wells Valley groundwater is critical for effective water resource management in the communities of Inyokern, Ridgecrest and the Naval Air Weapons Station at China Lake. Because the agricultural, municipal and industrial water needs of the valley are met by pumping local wells, the quality of life and the economic stability of this California desert region are dependent upon the prudent development of its fresh water supply. Existing groundwater models (Bloyd and Robson, 1971; Berenbrock and Martin, 1991 and Berenbrock and Schroeder, 1994) concluded that Indian Wells Valley is a closed hydrological basin and that the deep valley groundwater is late Pleistocene in age. Modern recharge to the southwest alluvial aquifer was attributed only to ephemeral surface runoff from precipitation in the adjacent Sierra Nevada and, to a lesser degree, the El Paso Mountains. The presence of perennial springs ranging in elevation from 3,300 to 6,500 feet in the adjacent Sierras and fresh (less than 300 mg/l TDS) water at depths of up to 2,000 feet in the southwestern part of the valley suggest that the

region may be receiving recharge from sources other than ephemeral stream drainage. The potential for subsurface flow into the deep southwest aquifer along joints in the crystalline bedrock has not been addressed.

### **1.2 Purpose of this Study**

The purpose of this study is to investigate the quantity and sources of recharge, the groundwater flowpaths and the age of groundwater in the deep-basin alluvial sediments of the southwest corner of Indian Wells Valley. The high-quality, low-TDS water in the deep alluvial aquifer may be the result of recharge from higher elevations outside the basin's watershed to the north and west of the valley along fracture systems in the crystalline bedrock of the southern Sierra. If this is the case, the age of the groundwater in this part of the valley may be younger and the quantity of recharge may be greater than postulated by previous workers because a portion of the recharge may come from outside the conventional watershed areas.

### **1.3 Location of the Study Area**

Indian Wells Valley is located at longitude 117° 45' W, latitude 35° 45' N in southeastern California, approximately 125 miles north of Los Angeles and 110 miles east of Bakersfield, where the southwest corner of the Basin and Range physiographic province meets the Sierra Nevada province. The southwest Indian Wells Valley study area (Fig. 1) lies entirely within Kern County, extending from Owens Peak at the head of Indian Wells Canyon south to Wylie's Knob at the head of Bird Spring Canyon and from the crest of the Sierra Nevada east to Highway 395. It comprises portions of the following U.S. Geological Survey (USGS) 7.5' quadrangles: Walker Pass, Horse Canyon, Dove Springs, Onyx, Cane Canyon, Pinyon Mountain, Owens Peak, Freeman Canyon, Saltdale NW, Inyokern, Inyokern SE and Garlock. Additional 7.5' quadrangles used in the preparation of the Sierra Nevada lineament map were Sirretta Peak,

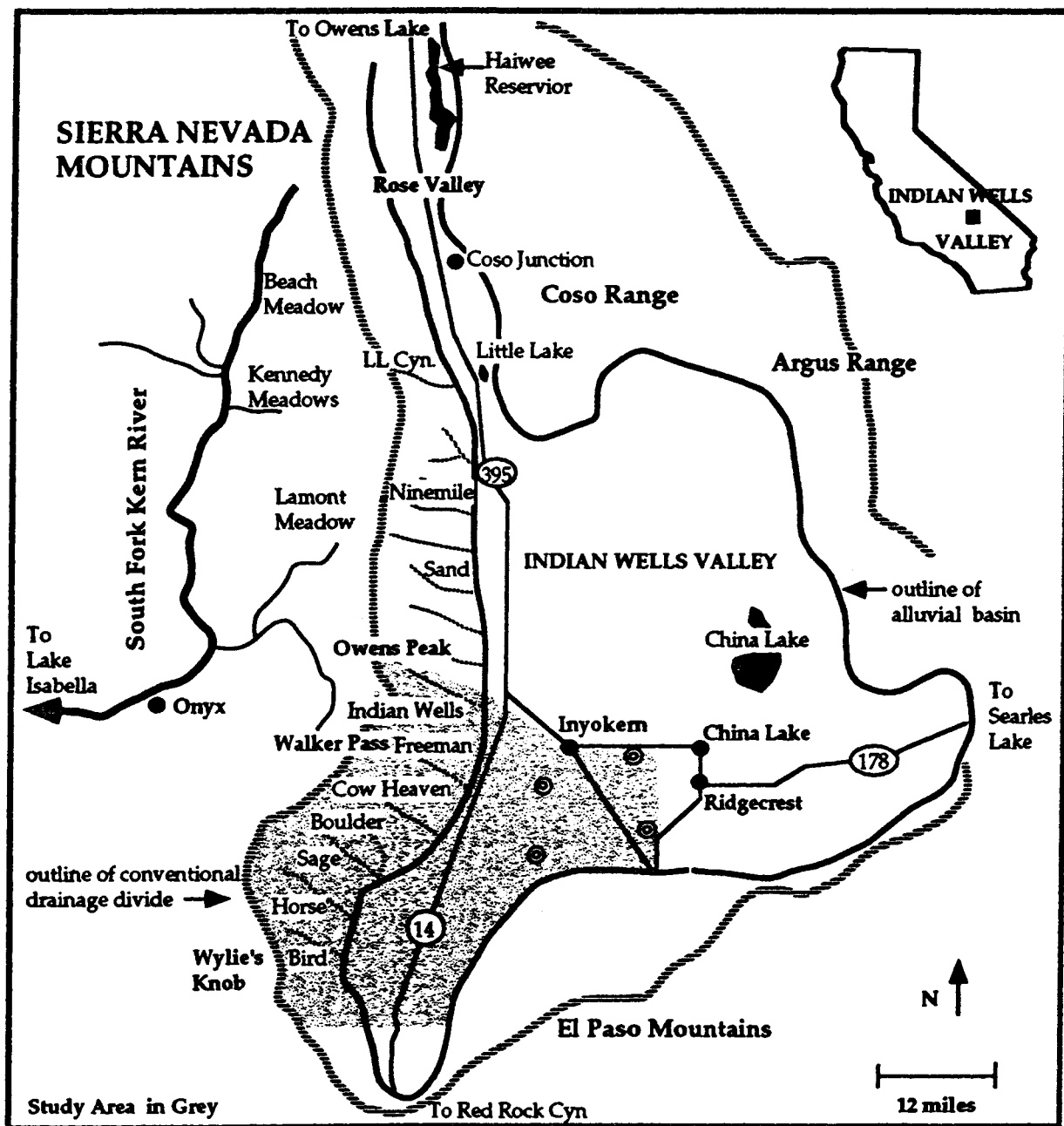


Figure 1. Location map for Indian Wells Valley. The southwest study area is colored in grey. It includes four USBR wells (concentric circles to the east) and seven Sierran canyons (highlighted labels to the west).

Rockhouse Basin, Sacatar Canyon, Cannell Peak, White Dome, Lamont Peak and Weldon.

#### 1.4 Structural Setting

Indian Wells Valley is a complex structural and topographic depression covering approximately 480 square miles, bordered by the southern Sierra Nevada Mountains to the west, the Coso and the Argus ranges to the north and east and the El Paso Mountains to the south (Fig. 1). The southwest study area lies in close proximity to three of the major fault zones of California: the Sierra Nevada Frontal Fault (at the eastern base of the Sierra Nevada Mountains), the Garlock Fault (10 miles to the south) and the San Andreas Fault (60 miles to the south). Figure 2 shows other faults that dissect the surrounding region, including the Little Lake Fault, the Wilson Canyon Fault, the Airport Lake Fault, the El Paso Fault, the Kern Canyon Fault, the Durrwood Fault, the Pinyon Peak Fault and an unnamed fault mapped through Bird Spring Pass. West-northwest trending en echelon faults may have controlled the formation of the major Sierran canyons in the region, such as Nine Mile, Indian Wells and Freeman Canyons (Diggles *et al.*, 1985).

In the early to mid-Tertiary period, the southern Sierras rotated clockwise approximately 45°, drastically altering their geomorphology and structure (Kanter and McWilliams, 1982). Evidence of this rotation can be seen in the drainage patterns and joint sets in the canyons examined for this project. Uplift along the Sierra Nevada Frontal Fault began in the late Miocene epoch and continued into the middle Pleistocene, resulting in several thousand feet of local relief (Chase and Wallace, 1986). Crustal extension in the southwest Basin and Range commenced in the last four million years and may serve as a mechanism for the delivery of geothermal fluids to Indian Wells Valley deep beneath the alluvial fill (Monastero and Katzenstein, 1995).

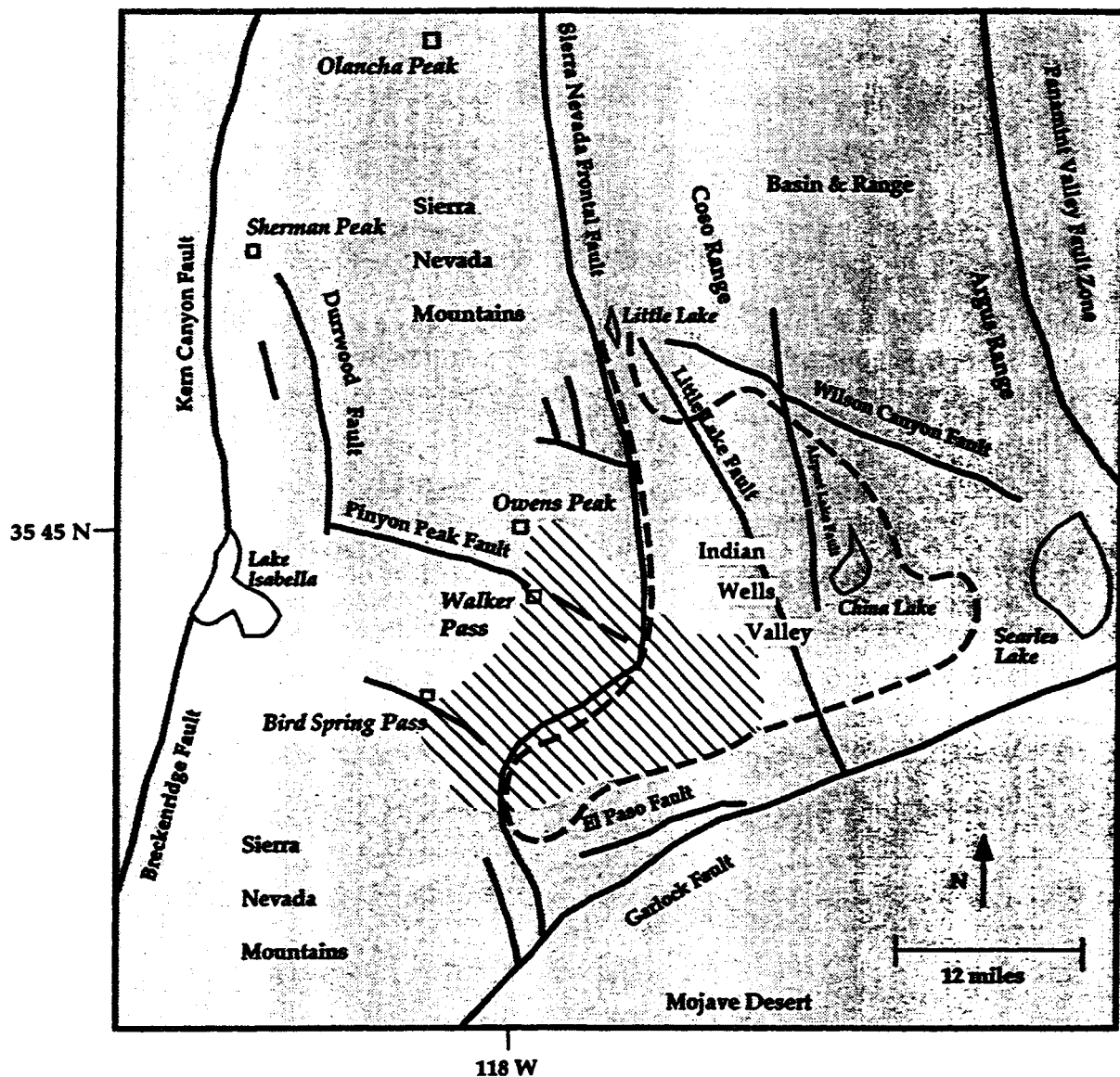


Figure 2. Regional fault map (after Monastero and Katzenstein, 1995). The Indian Wells Valley alluvial basin is marked with dashed lines and the study area is striped for reference.

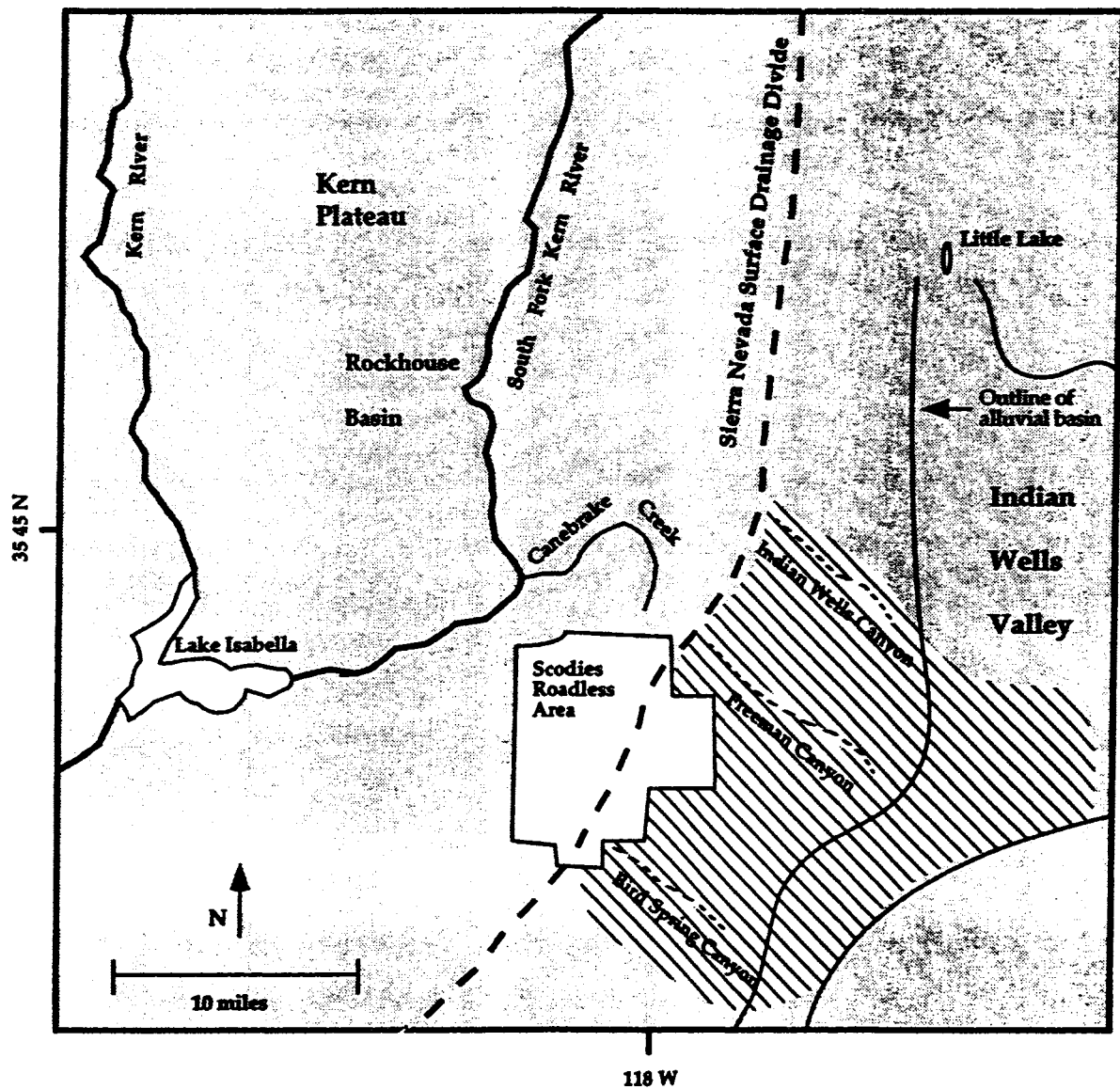
### 1.5 Geological Setting

The rocks of the Sierran portion of the study area consist of the pre-Cretaceous Isabella granodiorite, Sacatar quartz diorite, Summit gabbro and Kernville meta-sedimentary series described by Miller (1931). Harner *et al.* (1983) mapped the Scodies Roadless Area (Fig. 3) and further described the rock units and their variations. Diggles *et al.* (1985) mapped the roof pendants and foliated igneous rocks extending from Canebrake Creek (Fig. 3) across the Sierran crest and atop the southern ridge of Indian Wells Canyon.

The bedrock of Indian Wells Valley is presumed to be of the same granitic and metamorphic composition as the Sierra Nevada. It is overlain by Paleocene continental deposits of the Goler Formation, and the Miocene Ricardo Formation and Black Mountain basalt (Dibblee and Gay, 1952), which are exposed in Redrock Canyon to the south (Fig. 1). For the purposes of this report, the Goler and Ricardo formations will be referred to as consolidated sediments, in contrast to the unconsolidated older alluvium, younger alluvium and fan deposits which form the main water-bearing strata (Berenbrock and Martin, 1991). Poorly sorted debris flow deposits are conspicuous in the landscape close to the mountains northeast of Freeman Gulch (Fig. 4). Figure 4 summarizes the lithology and stratigraphy of the southwest Indian Wells Valley study area.

### 1.6 Hydrogeological Setting

The elevation of Indian Wells Valley ranges from about 2,150 feet in the vicinity of the China Lake playa to about 3,400 feet in the far southwest. Modern annual precipitation on the valley floor averages slightly over four inches, falling mainly in the winter months (Berenbrock and Martin, 1991). The watersheds adjacent to the study area, the El Paso Mountains and the southern Sierra Nevada Mountains, receive less than 6 inches and 15 inches of rain per year respectively (Rantz, 1967) and appear too arid to account for a large flux of



**Figure 3. Index map showing location of regional geographic features mentioned in text (after Diggles et al. 1985). The southwest Indian Wells Valley study area is highlighted for reference.**

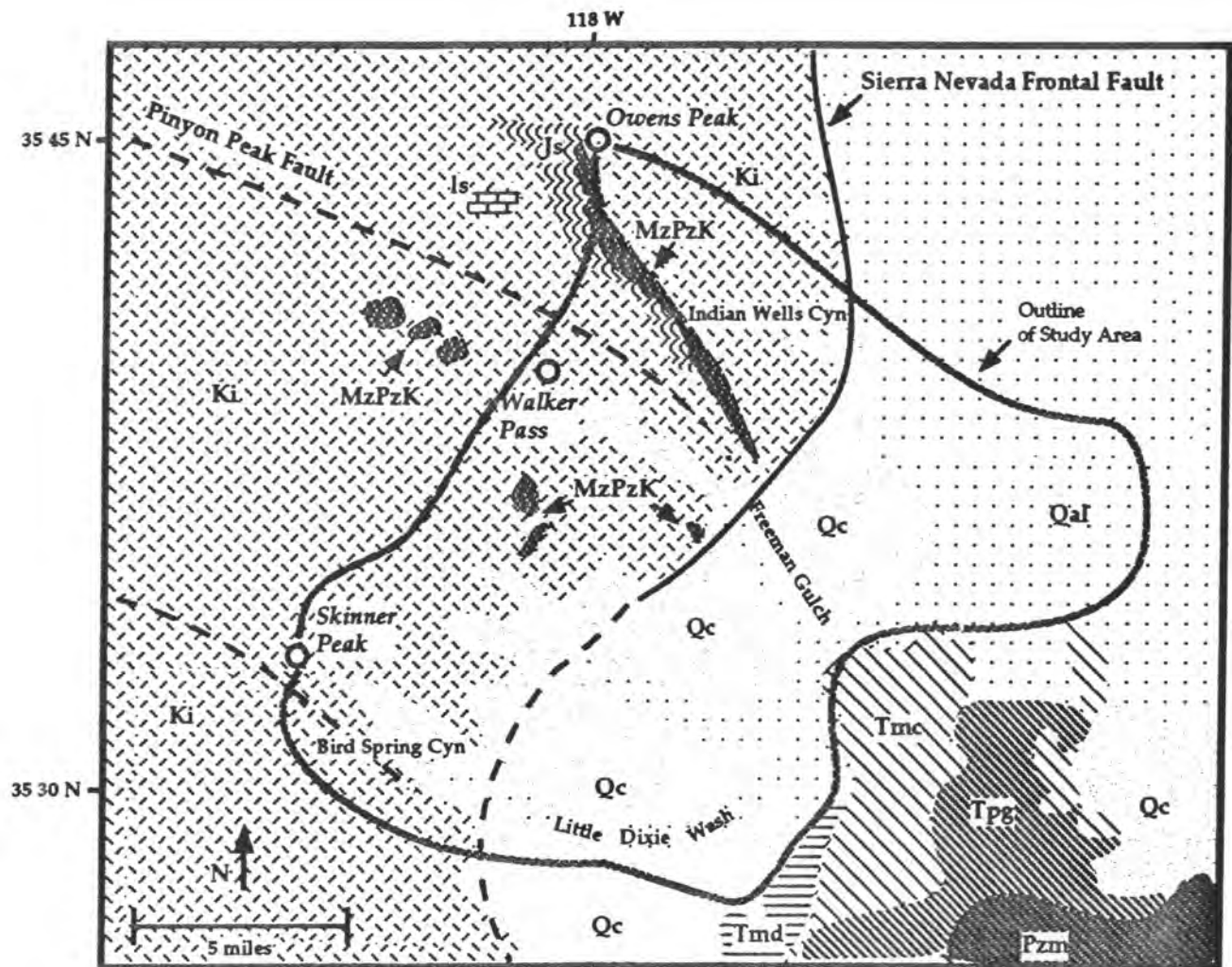


Figure 4. Geologic map of the study area and surrounding vicinity after Harner et al. (1983), Diggles et al. (1985), and Loomis and Burbank (1988).

Key:

|  |     |                         |  |       |                                  |
|--|-----|-------------------------|--|-------|----------------------------------|
|  | Qal | Recent alluvium         |  | Ki    | Cretaceous Isabella granodiorite |
|  | Qc  | Pleistocene non-marine  |  | Js    | Jurassic Sacatar quartz diorite  |
|  | Tmd | Tertiary Dove Spring Fm |  | MzPzK | Meso-Paleozoic metasediments     |
|  | Tmc | Tertiary Cudahy Camp Fm |  | ls    | Paleozoic limestone              |
|  | Tpg | Tertiary Goler Fm       |  | Pzm   | Paleozoic metamorphics           |

fresh water to the basin. Bloyd and Robson (1971), using the total surface area above 4,500 feet east of the Sierran topographic divide, estimated a value of 2,870 acre-feet per year for recharge from southwest ephemeral streams.

Due to the modern arid climate, there are no perennial surface lakes or streams on the valley floor. In the Pleistocene epoch, however, lower temperatures, increased precipitation and decreased evaporation combined to create a chain of lakes stretching from Mono Lake to Lake Manley in Death Valley (Fig. 5). The shores of the former Lake China may have reached highstand elevations in Indian Wells Valley of up to 2,500 feet (Saint-Amand, 1986) and have since retreated to form the present-day China Lake playa on the east side of the basin.

A portion of modern Indian Wells Valley groundwater recharge may still follow the path of the Pleistocene drainage, entering from Rose Valley through Little Lake gap, moving through the aquifer toward the playa and leaving the eastern side of the basin as subsurface flow bound for Searles Lake (Fig. 5). Although pumping of local wells has altered the natural flowpath in the area between Ridgecrest and Inyokern, the overall movement of groundwater in the study area southwest of Inyokern is still in a northeast direction toward the playa (Fig. 6). Muir and Birman (1986) conducted a ground temperature survey to determine shallow groundwater flow directions in the southwestern extension of the valley close to the Sierras. Their results showed that shallow groundwater from Sage Canyon (Fig. 1) flowed northeast toward the playa, but data from canyons south of Sage Canyon were less conclusive.

Multiple-completion monitoring wells drilled in 1991 by the U.S. Bureau of Reclamation (USBR) in southwest Indian Wells Valley yielded water with total dissolved solids (TDS) concentrations of less than 300 mg/l from nearly 2,000 feet below ground level (USBR, 1993). Transmissivities estimated from slug

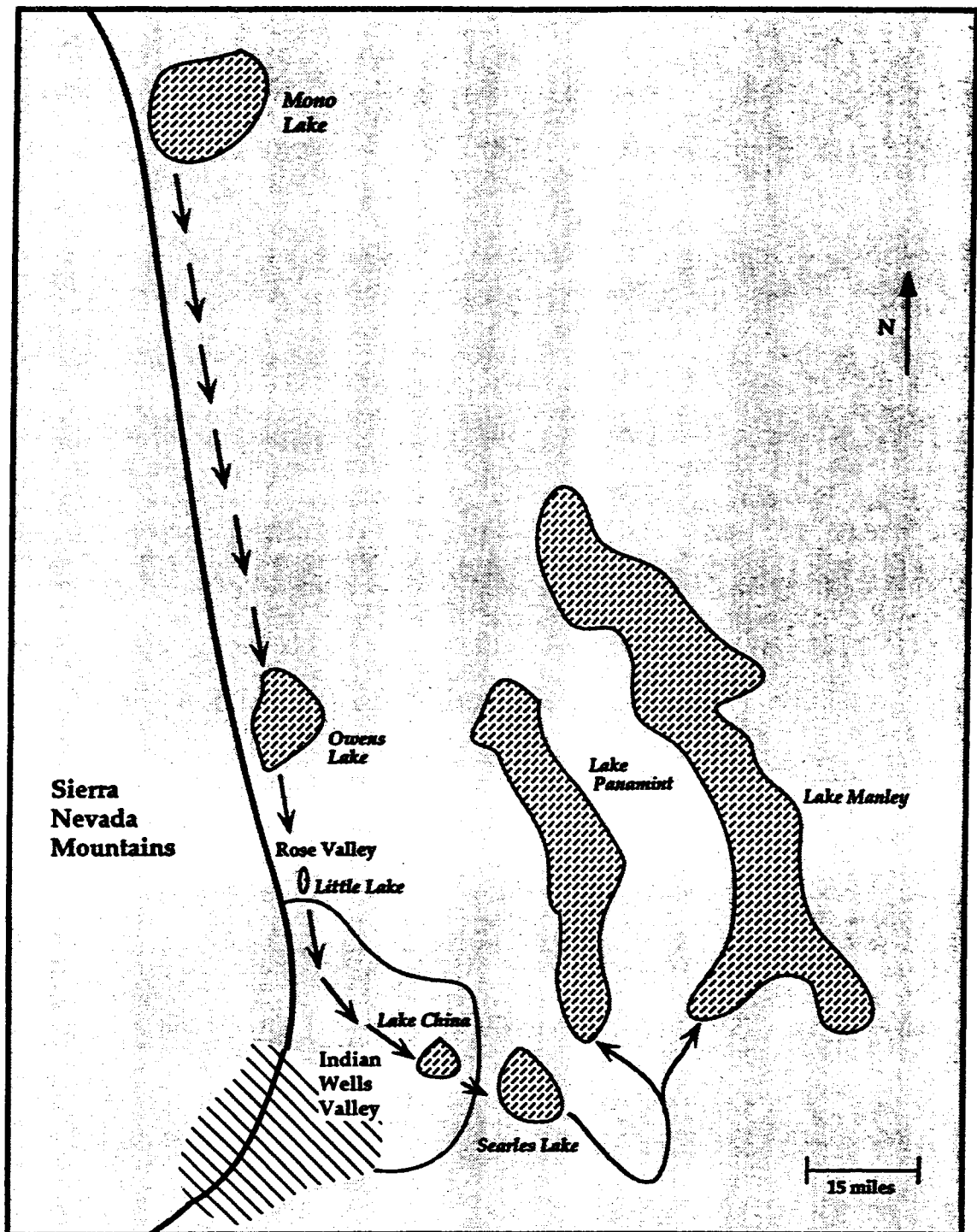


Figure 5. Path of Pleistocene lake drainage from Mono Lake through study area to Lake Manley (present-day Death Valley). Lake China highstands did not reach striped study area (Berenbrock and Schroeder, 1994).

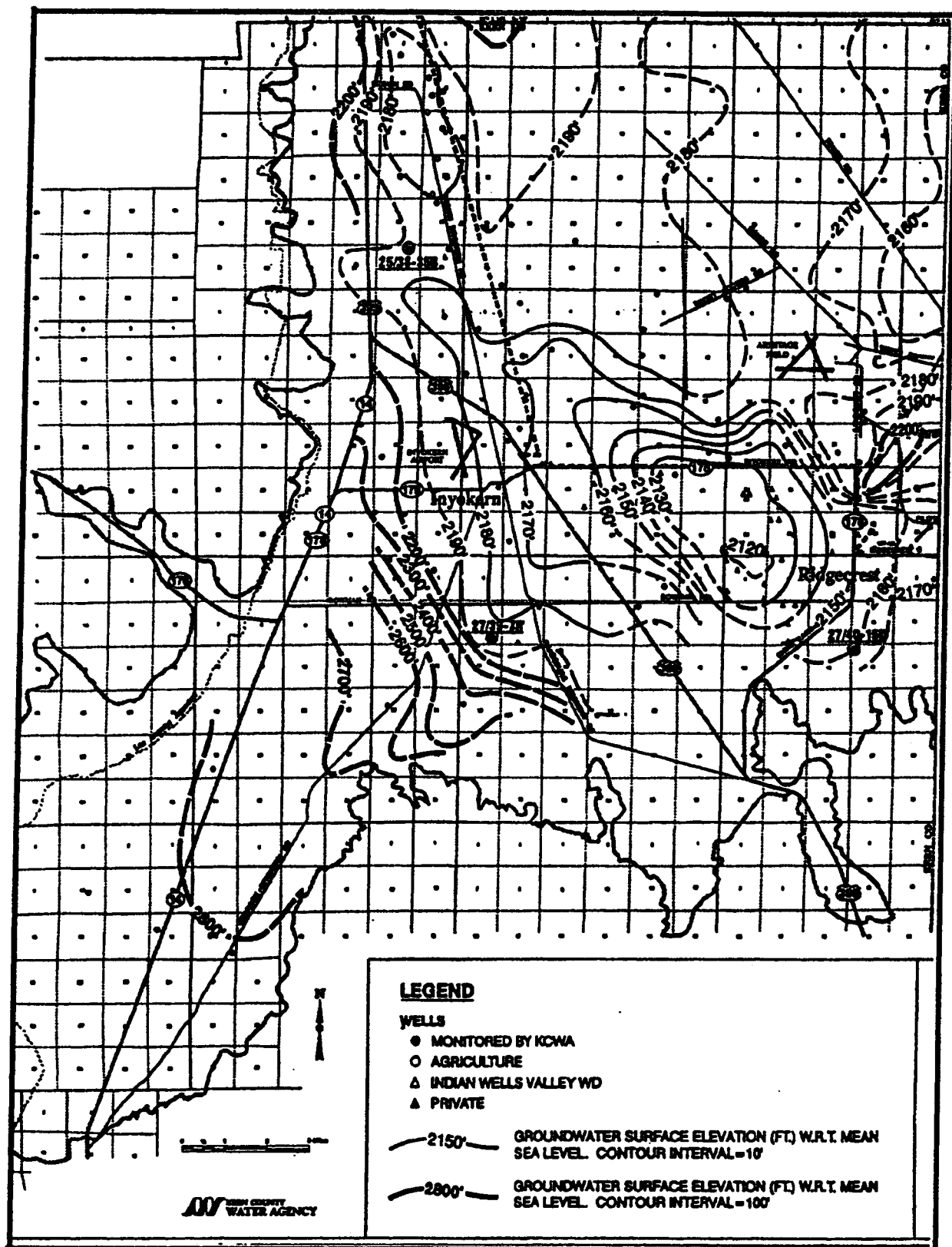


Figure 6. Spring 1996 potentiometric surface map of Indian Wells Valley from Kern County Water Agency.

tests were as high as 0.24 feet<sup>2</sup> per minute and head measurements indicated gradients as steep as 130-140 feet per mile (USBR, 1993). A barrier to groundwater flow, perhaps a low permeability fault zone, was proposed to lie southwest of the Inyo Well (well 27/39-7R in Fig. 6) based upon the observed steep gradients (Moyle, 1963) and geophysical field work (Zbur, 1963). Zbur (1963) characterized the proposed groundwater barrier as a "scissors" fault trending northwest across the valley in the vicinity of the Inyo Well. He inferred an element of strike slip motion along a northwest-trending fault, which may have resulted in a local zone of finely ground fault gouge with low permeability. The exact nature and extent of the proposed barrier is unknown, but it may account for the steep groundwater gradients observed in the southwest part of the basin.

#### **1.7 Summary of Previous Work in Indian Wells Valley**

Indian Wells Valley and the southern Sierra Nevada have been studied by geologists since the early 1900's, including Baker (1912), Lee (1913) and Thompson (1929). Baker described the relatively youthful geomorphology of the eastern Sierran front north of Indian Wells Canyon (Fig. 1) compared to the more mature drainage patterns and erosional features farther to the south along the mountain front. He suggested that the northern front may have undergone more recent uplift than the south.

Published geophysical and structural studies of Indian Wells Valley and its surrounding mountains are few. Mayo (1947) mapped four predominant regional joint patterns in the southern Sierras adjacent to the study area. He emphasized north-northeast fractures west of the Sierra Nevada Frontal Fault, extending well into the Kern Plateau region west of the Sierran topographic divide. A gravimetry survey of Indian Wells Valley by von Huene (1960) was followed by Zbur's (1963) seismic refraction, gravity and aeromagnetics investigation. Their work indicated the valley is not a simple down-dropped

block, but rather a highly complex, faulted, folded and warped tectonic trough. Zbur (1963) described three main structural configurations in the study area: a) a relic northwest and northeast oriented regional element, b) a north-south trend associated with Basin and Range extension and c) a northwest-northeast conjugate shear pattern related to the Garlock and San Andreas fault zones. Nilsen and Chapman (1971) interpreted a trend in the gravity contours southeast of Indian Wells Canyon (Fig. 1) as evidence of a small basement ridge jutting southeast into the valley below the alluvium. The same gravity study also proposed that sediments in the far southwest valley may be as thick as 6,000 feet. Wright (1976) categorized faults and stress fields in the Basin and Range and the Sierra Nevada, including conjugate-extensional shears in the Indian Wells Valley area. He suggested a direction of maximum principal stress for the region of approximately N 45° E.

Lee (1913) estimated the orographic effect on precipitation with increasing elevation to be 0.41 inches per 100 feet, based on rainfall records from Mojave and vegetation changes in the mountains west of Indian Wells Valley. He used these values to calculate runoff into the valley to be 27,000 acre-feet per year. Thompson (1929) included Rose Valley and the Coso Range (Fig. 1) as sources of runoff affecting Indian Wells Valley, increasing the runoff figure to nearly 50,000 acre-feet per year. Lee (1913) also attempted to identify which portions of the valley floor were covered by salt grass, pickleweed, sparse plants, dune sand and bare clay. He estimated an annual evapotranspiration rate of 31,630 acre-feet from the area covered by salt grass vegetation. Because the basin was assumed to be closed, the amount of evapotranspiration was thought to equal the amount of recharge under natural conditions.

Fetter (1994) defined safe yield as "the amount of naturally occurring ground water that can be withdrawn from an aquifer on a sustained basis,

economically and legally, without impairing the native ground-water quality or creating an undesirable effect such as environmental damage." The estimated safe yield from valley aquifers for both the Lee and the Thompson studies was 11,000 acre-feet per year.

The USGS published a series of investigations on the groundwater conditions of the valley, including open file reports by Kunkel and Chase (1969) and Bloyd and Robson (1971), and a water supply paper by Dutcher and Moyle (1973). Kunkel and Chase (1969) revised Lee's estimates of plant cover using the methods of Blaney (1952) and derived a value of 11,325 acre-feet for discharge of groundwater by evapotranspiration for the year 1912. This estimate of playa evapotranspiration was nearly 20,000 acre-feet/year less than Lee's (1913) figure and the estimated amount of recharge to the basin was lowered accordingly.

Kunkel and Chase (1969) calculated midvalley underflow to be 15,000 acre-feet per year and estimated perennial yield to be between 10,000 and 14,000 acre-feet per year. Saint-Amand (1986) concurred with these interpretations and buttressed many of the USGS findings with his own calculations. He estimated the annual recharge for the entire valley to be 11,000 acre-feet based on evaporative discharge from the playa. All of these studies assumed that Indian Wells Valley is a closed hydrological basin which receives recharge from precipitation runoff primarily from the adjacent Sierra Nevada and to a lesser extent, the Argus, Coso and El Paso Ranges and discharges by means of evaporation on the playa floor.

Bean (1989) interpreted the USGS data with a regional recharge concept in mind. He presented no new evidence for an open basin, but reworked the recharge calculations to include inflow from the Coso Range, the Argus Range, Rose Valley, municipal water treatment and irrigation, leakage from the Los Angeles Aqueduct and recharge from Sierran granites. Bean estimated total

recharge to Indian Wells Valley as 15,100 acre-feet per year, of which he attributed 2,500 acre-feet to fracture-directed flow from the Sierra Nevada. Bean did not explain the method he used to estimate the fracture-directed flow, nor did he measure precipitation or streamflow. Erskine (1989) presented arguments for an open basin based on hydrogeochemical and geophysical investigations (Whelan *et al.*, 1989 and Zbur, 1963) and proposed a deep-well drilling program to test for underflow from Rose Valley (Fig. 1). Erskine also presented a cross-section from Lamont Meadow in the Sierras through Sand Canyon (Fig. 1) in northwest Indian Wells Valley which suggested that the South Fork of the Kern River may contribute to the valley's groundwater.

Two computer models of the valley were constructed: a two-dimensional numerical model (Bloyd and Robson, 1971) and a three-dimensional model using MODFLOW (Berenbrock and Martin, 1991). Bloyd and Robson (1971) approximated recharge from precipitation in the Sierra Nevada Mountains by distributing their estimated figure of 9,850 acre-feet per year to stream drainage areas above 4,500 feet in the Indian Wells Valley watershed. Their model was calibrated by adjusting transmissivity values until head levels in the model matched field data from well measurements. Bloyd and Robson (1971) excluded the southwest aquifer from their basin model, even though they estimated that two-thirds of the Sierran recharge was derived from southwest streams. Berenbrock and Martin (1991) did not acknowledge faults or groundwater barriers in the valley and chose to model the southwestern part of the basin as a distant boundary.

Geochemical studies by Whelan *et al.* (1989), Smith *et al.* (1992) and Houghton (1994) analyzed stable isotope ratios, classified water types on the basis of their cation / anion constituents and plotted the water types across the valley to ascertain possible flow and mixing patterns. Whelan *et al.* (1989) described

eight water types valley-wide and proposed geothermal leakage into the Little Dixie Wash (Fig. 4) based upon temperature gradients in the groundwater. They did not recognize this area as part of Indian Wells Valley, however, referring to it as a separate "deep circular sub-basin." Smith *et al.* (1992) studied samples from five springs, four streams and seven wells in the Indian Wells Valley area. They concluded that the deep valley groundwater is Pleistocene in age by comparing the stable isotope ratios of well water with those of modern precipitation collected at Walker Pass (Fig. 1). Because the well water samples were isotopically lighter than the precipitation samples (indicating a dissimilar source), Smith *et al.* (1992) reasoned that the wells had been recharged when the climate in the conventional drainage area was colder and wetter. However, these samples were not radiometrically dated.

Houghton's (1994) research illustrated the complexity of the valley's flow systems and aquifer structure. Groundwater was classified into three groups based on predominant major ions. Group A water, sampled from the shallow aquifer in the southwest, was characterized by low dissolved solids (less than 400 mg/l) and a sodium bicarbonate composition. Group B water in the west and northwest showed a higher TDS concentration (up to 960 mg/l) of predominantly sodium bicarbonate ions. Group C samples near the playa consisted of highly saline (up to 7,780 mg/l TDS) sodium chloride/sodium sulfate waters. A sample from the South Fork of the Kern River, outside the valley's watershed near Kennedy Meadows (Fig. 1), yielded a low-TDS sodium bicarbonate water with a deuterium value of -107‰. Chemical analyses of well, stream and spring samples included two USBR wells and two streams in the study area. Houghton's investigation concluded that the best quality water is found in the southwestern corner of Indian Wells Valley.

Berenbrock and Schroeder (1994) combined a hydrogeochemical study of the valley with a simulation of advective transport using the particle-tracking code MODPATH. Calculated travel times from Little Dixie Wash to the Ridgecrest area ranged from 1,000 to 3,000 years at velocities of 15 to 39 feet per year. Their advective transport simulations were based on 1988 groundwater elevations, which did not include the USBR wells. Berenbrock and Schroeder used stable isotope ratios in the manner of Smith *et al.* (1992) to hypothesize a Pleistocene age for the deep groundwater, but did not attempt to age date the water with radioactive isotopes. None of the wells southwest of the hypothesized groundwater barrier were sampled for this study.

In 1993, the USBR, in cooperation with the Indian Wells Valley Water District, North American Chemical Company and the China Lake Naval Air Weapons Station (NAWS), published a technical report evaluating new information gained from a joint drilling project. Ten wells were drilled as deep as 2,024 feet in Indian Wells Valley, including four sets of nested piezometers in the study area. The USBR report included chemical analyses, electric logs, slug test and sounding data for each well. It recommended further development of the new piezometers and repeated sampling to establish confidence in the initial chemical analyses. The report concluded that the deep groundwater in the southwest was fresher and more abundant than previous research had indicated.

## 2. METHODS AND MATERIALS

The objectives of this investigation were accomplished by the procedures outlined in the section below, divided into the following categories: southern Sierra Nevada surface hydrology, southwest Indian Wells Valley groundwater recharge and southern Sierra Nevada lineament data collection. Data resulting

from these procedures are presented in section three and interpreted in section four.

## **2.1 Southern Sierra Nevada Surface Hydrology**

### **a. Conventional Surface Drainage Area Boundaries**

An attempt was made to quantify the amount of annual recharge made available to the southwest Indian Wells Valley aquifer from precipitation in the conventional surface drainage area. The boundaries of the conventional surface drainage area were defined as the Sierra Nevada Mountains topographic divide on the west, the 4,000-foot elevation contour on the east, the northern rim of Indian Wells Canyon on the north and the southern topographic divide of Bird Spring Canyon on the south (Fig. 7). The drainage area of each canyon was divided into subareas based on 500-foot elevation increments and measured with a Lasico planimeter on the USGS 7.5' quadrangles listed in section 1.3.

### **b. Precipitation Gage Locations and Recharge Estimation Methods**

Precipitation was measured for two years in rain gages placed at 500-foot elevation increments beginning at 4,000 feet in Freeman Canyon (Fig. 7) and continuing along the Pacific Crest Trail north of Walker Pass. Changes in vegetation with elevation in each canyon of the study area were noted in the course of field work. Consistent agreement of the occurrence of plant species at similar elevations in the various canyons would support the use of one canyon for precipitation measurements. Significant differences would add to the margin of error of this method. The gages were mounted on 4" x 4" posts three feet above the ground. In the 1994-95 season, the snow line was approximately 5,800 feet. Because the rain gages were not equipped to measure snow, precipitation above 5,500 feet was estimated by extrapolating the increase in precipitation with

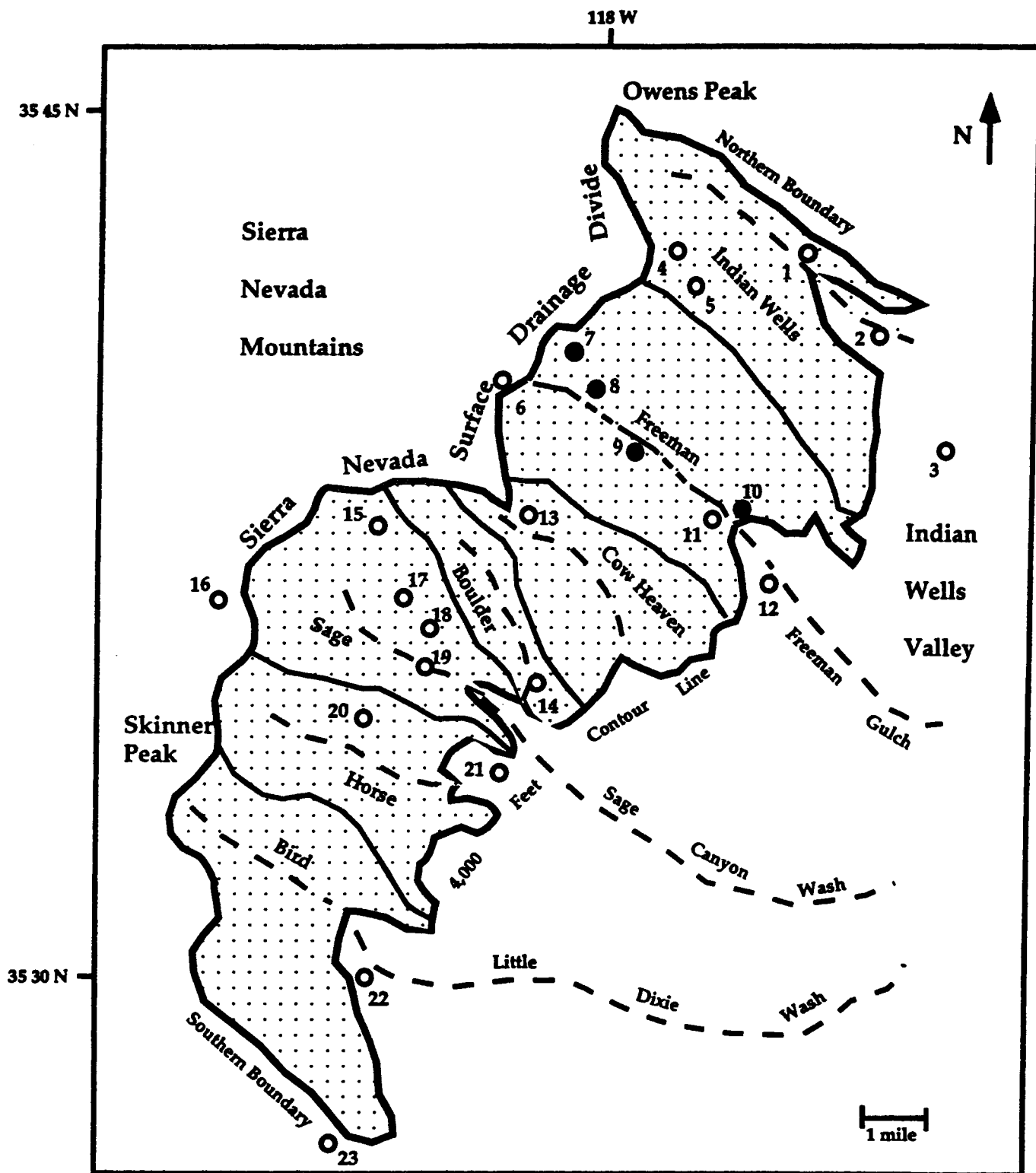


Figure 7. Map of conventional surface drainage recharge area above 4,000 feet. Open circles are surface sampling sites. Closed circles are precipitation gage sites. See Appendix 2 for location key.

elevation observed at the lower elevations. An increase of 1.9 inches per 500 feet of elevation was derived from the slope of the line of measured values from 4,000 to 5,500 feet. The same method was used to approximate precipitation at the upper elevations for the 1995-96 season.

Winter (1981) summarized uncertainties associated with rain gage measurements, noting that gages placed at ground level caught 5-15% more rain than those with openings a few feet above ground. This theory was tested in the 1995-96 season by placing a set of two gages, one at three feet and one at ground level, at the 4,000, the 5,000 and the 5,500 foot stations. Precipitation was measured at each gage and a percent difference was calculated.

Maxey-Eakin recharge coefficients (Table 1) were applied to the precipitation values determined for each increment of 500 feet in elevation in order to estimate the amount of precipitation available to recharge the southwest aquifer after losses by evapotranspiration.

**Table 1. Recharge coefficients applied to southwest Indian Wells Valley surface drainage data, after Eakin, Maxey *et al.* (1951).**

Drainage Area x Precipitation x Coefficient = Approximate Recharge

| <u>Precipitation Zone</u> | <u>Coefficient</u> |
|---------------------------|--------------------|
| > 20 inches               | 25 %               |
| 15-20 inches              | 15 %               |
| 12-15 inches              | 7 %                |
| 8-12 inches               | 3 %                |
| < 8 inches*               | 0                  |

\* No significant groundwater recharge is believed to occur in areas receiving less than 8 inches of annual precipitation (Eakin, Maxey *et al.* 1951).

### **c. Surface Flow Measurements**

During the winter and spring rainy seasons, stream flow (in cubic feet per second) was gaged with a Price AA Pygmy current meter when sufficient stream depth (greater than three inches deep) was present. However, stream depth was usually less than three inches deep. Therefore, the method more commonly used was to float an object in the current and time its passage along a measured path chosen for its cross-sectional uniformity and lack of debris. When possible, the same location was used each time the stream or spring was measured in order to compare flows over time. Longitude and latitude of the locations were measured with a Magellan NAV 1000 Plus global positioning system and recorded with the flow measurements.

### **d. Surface Water Chemistry Sampling Sites and Protocol**

Because of the importance of the hydrogeochemical data and the expense of laboratory analysis, great care was taken in choosing sites and setting protocol for collecting water samples. Longitude and latitude of spring and stream locations were identified with a Magellan NAV 1000 Plus global positioning system (Appendix 2). This insured that the sites were consistent and that sampling could be repeated by other workers. Figure 7 shows surface sampling sites as well as precipitation gage locations. Precipitation gages were sampled for stable isotope analysis only.

All samples were analyzed for cations, anions and metals by BC Laboratories of Bakersfield or the NAWS Environmental Analysis Facility at China Lake, accredited laboratories under contract with the NAWS Geothermal Program Office. All samples were analyzed for stable isotopes oxygen-18 and deuterium by Global Geochemistry Corporation of Canoga Park, California.

Tritium analysis of selected samples was performed by the University of Miami Tritium Laboratory in Miami, Florida.

Surface sites were sampled for this study in three rounds: March - May, 1995; November, 1995 - January, 1996; and April - June, 1996. Additional samples were collected in August, 1996. All surface samples were collected by the author, his thesis advisors or by CSUB hydrogeology undergraduate students under the author's supervision. Each sample was clearly labeled with time, date, location and name of sampler in waterproof permanent black ink. Any odor or color was noted, as were any unusual environmental conditions. Temperature, electrical conductivity and TDS were measured in the field with a Hach conductivity / TDS meter and pH was measured with an Orion pH meter. Both instruments were regularly calibrated for accuracy and both electrodes were thoroughly rinsed with deionized water before and after use. Alkalinity titrations were performed in the field using 1.6 M sulfuric acid, a magnetic stirring motor and a Hach digital titrator. Each sample (unless otherwise noted) was filtered in the field through a 0.45 micron filter with a Masterflex pump and stored in two one-liter plastic bottles, one for general chemical analysis and one for metals. Metals samples were acidified to a pH of about 2 with 8 M trace metal grade nitric acid. The bottles were pre-rinsed with sample water and were filled completely so as to leave no space between the sample and the lid. The 50-milliliter glass bottles for stable isotope samples were also pre-rinsed, filled to the top and their lids were secured with tape. Samples were packed in ice and delivered cold to the laboratories.

Charge imbalances were calculated for each sample by MINTEQA2 (Brown and Allison, 1987), a geochemical speciation model for environmental settings. Only the analyses with charge imbalances of  $\pm 10\%$  were used for data evaluation. Methods of evaluation included visual representations of the data in

the form of fingerprint plots and stiff diagrams after Mazor (1991). Saturation indices and CO<sub>2</sub> pressure were also calculated by MINTEQA2, using field pH, temperatures and alkalinities.

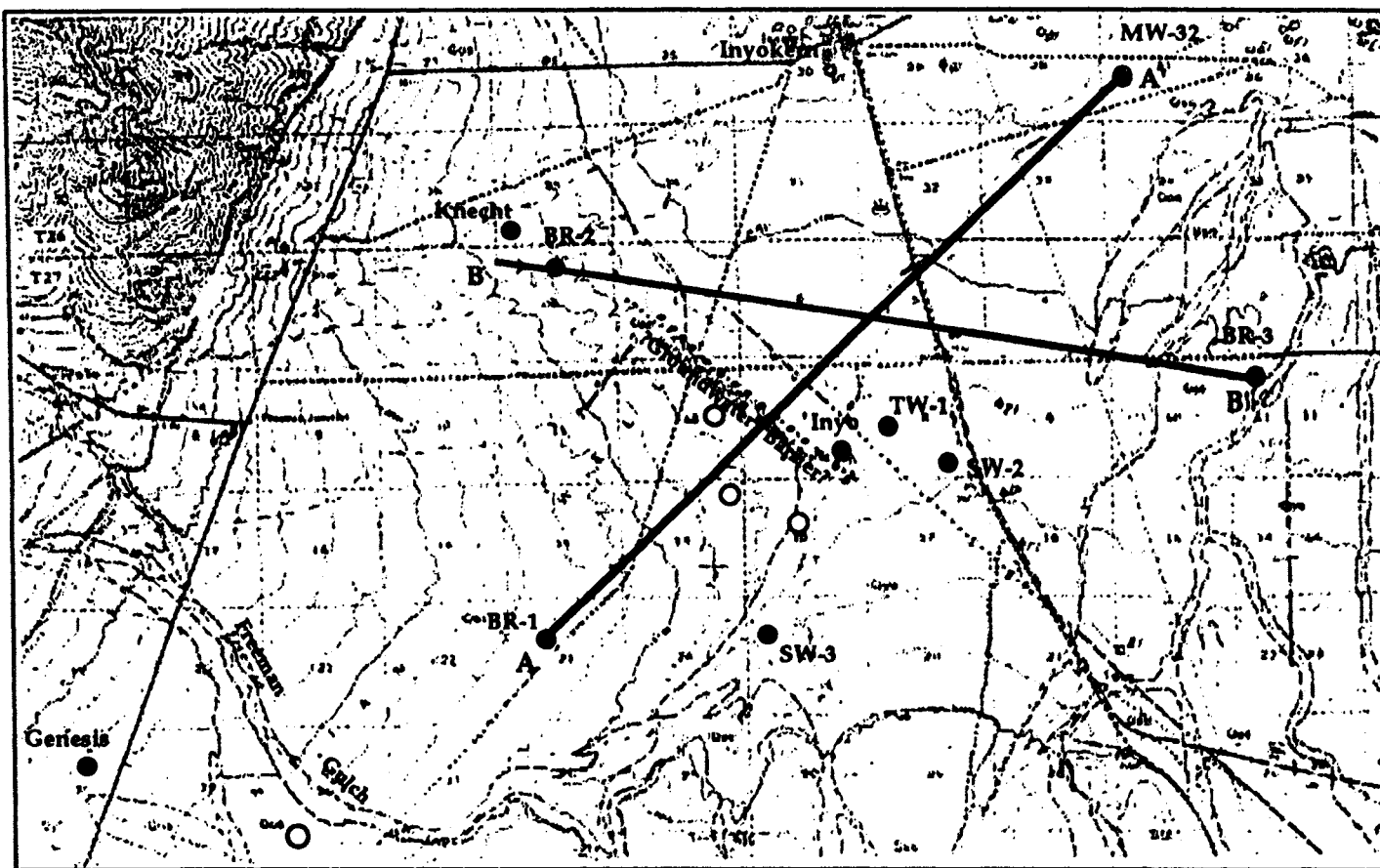
Seven surface samples were analyzed for the radioactive isotope tritium by the University of Miami Tritium Laboratory. These samples were collected in pre-rinsed one-liter plastic bottles in June, 1996, and August, 1996, from the South Fork of the Kern River near Onyx, Government Spring at South Kennedy Meadows, Indian Wells Canyon Mine Spring, Big Spring, Walker Pass Spring, McIvers Spring, and Bird Spring.

## **2.2 Southwest Indian Wells Valley Groundwater Recharge**

### **a. Monitoring Well Locations**

Southwest Indian Wells Valley is sparsely populated. Consequently, relatively few wells have been drilled there in comparison to other parts of the valley. Only wells for which driller's or electric logs, completion intervals and total depths are available were included in this study.

The groundwater surface elevation of southwest Indian Wells Valley was monitored monthly in the wells indicated in Figure 8. Pumping in the areas immediately surrounding these wells is minimal, with the exception of MW-32. Therefore, soundings should accurately reflect natural changes in the water table, not human activities. Wells were sounded with a 500-foot Solinst electric sounder. Hydrographs for each well were prepared from the data to provide a visual means of comparing seasonal changes in groundwater elevation. They were also used to assess the presence of multiple aquifers and the location of possible recharge and discharge areas.



**Figure 8. Monitoring well location map with stratigraphic cross-section lines A-A' and B-B'.**

## **b. Stratigraphic Cross-Section Locations**

Two cross-sections of the southwest basin were constructed from electric logs and driller's logs obtained from the USBR report, the Indian Wells Valley Water District and private landowners. Lines were chosen so as to include the greatest number of wells. Line A-A' runs southwest to northeast and line B-B' extends from west to east across the valley (Fig. 8). Correlations of the strata in these cross-sections, along with the hydrographs, were considered to investigate the size and extent of any confining layers within the alluvium. The cross-sections were also used to look for the presence of faults, volcanic material or other possible barriers to groundwater flow in the alluvium. Water chemistry data from known completion intervals were utilized to interpret the aquifer architecture from well to well.

## **c. Groundwater Chemistry Sampling Sites and Protocol**

The locations of well sample sites are indicated in Figure 8. Sampling techniques used for surface water were again employed for well samples, with the following additions. The USBR samples were collected by technicians employed by the North American Chemical Company (NACC) of Trona, California in the spring of 1995 and the winter of 1995-96. Before sampling, the USBR 2" piezometers were purged into a 55-gallon barrel by the NACC crew with compressed air from their 250-horsepower compressor until at least 1-2 well volumes were removed. Temperature, electrical conductivity and pH of the water were monitored and recorded at regular intervals during the process to confirm that each parameter had stabilized. These procedures insured that the samples were representative of the formation water. The Knecht well (Fig. 8) was sampled on three occasions by the author at the well head with the pump running. There was no chlorinator or filtering device at this well. The samples were filtered in the field and processed as outlined in the previous section. The

Genesis #1 and SW-3 wells were bailed by hand in June, 1996 using a 350-milliliter Norwell teflon bailer which was rinsed with deionized water before and after use. The bailed samples were collected after the temperature, conductivity and pH had stabilized. They were not filtered in the field.

Tritium samples were collected from the BR-1 shallow, BR-1 shallow-medium, BR-1 deep-medium, BR-2 medium and BR-2 deep piezometers in June, 1996 by a NACC technician and Drs. Thyne and Gillespie using NACC's down hole sampler. These samples were filtered in the field and transferred into 50-milliliter glass bottles for analysis. One-liter tritium samples were taken by the author in June, 1996 at Genesis #1 and SW-3 from the teflon bailer. These samples were not filtered in the field.

Results of the well analyses were evaluated by the same means as the surface samples. Stable isotope data from both surface and well samples were plotted along with data from unconventional sources. Maps were generated of the  $P_{CO_2}$  values calculated by MINTEQA2 for all the samples. Hydrogeochemical information was added to the stratigraphic cross-sections as a graphic means of interpreting sources and flow patterns of groundwater in southwest Indian Wells Valley.

#### **d. Gravity Survey Line Locations**

A groundwater flow barrier has been inferred in the study area based upon well-sounding data that show a steep increase in the groundwater gradient across a northwest-trending line (Moyle, 1963) in sections 1 and 12 of T27 R38 and section 7 of T27 R39 (Fig. 8). A gravity survey was designed to investigate the possibility of a continuous subsurface basement lineament or structure which might impede flow. A corollary purpose of the survey was to constrain the cross-sectional area of the basin for groundwater flow calculations. Three lines were surveyed (Fig. 9), using a Scintrex CG-3 gravimeter and a Trimble 4000 SSE global



positioning system operated by a crew from the NAWS Geothermal Program Office. A station was located every 500 feet along each line. Terrain, free air and Bouguer corrections were made by NAWS geophysics personnel. Data for each survey line were modeled by the author using GRAV2D™, a two-dimensional gravity modeling program for Macintosh, to create subsurface profiles. Densities of 2.35 g/cc and 2.67 g/cc were assigned to the unconsolidated sediments and the undifferentiated basement rocks, respectively, based on Basin and Range density parameters given in Mabey (1966). The profiles were then evaluated with respect to the flow barrier hypothesis. Profile data modeled with GRAV2D™ is listed in Appendix 1.

#### **e. Groundwater Flow Calculation Parameters**

Lipinsky and Knochenmus (1981), in their aquifer system study plan for Indian Wells Valley, recommended the use of Darcy's Law to approximate the recharge volume in the Freeman Gulch area (Fig. 8). Data in the USBR (1993) report, combined with this study's gravity survey, offered the opportunity to follow their recommendation. From the depth to basement data constrained by the gravity profiles and from the surveyed elevation data, a value was assigned to each station for the thickness of the alluvial fill at that particular point. The points were then contoured to form an isopach map of the alluvium in the surveyed area, using a contour interval of 100 feet (Fig. 9). On this map, a cross-section was drawn perpendicular to flow from Freeman Junction through BR-1 to the Black Hills basalt outcrop on the southeast side of the basin (Fig. 9) and the dimensions of the cross-sectional area of the alluvial aquifer were calculated. The amount of groundwater flowing through the aquifer between BR-1 and MW-32 was estimated using Darcy's Law. Values for the variables in the Darcy equation were derived from the isopach cross-section, 1996 water level measurements and slug test data from the USBR report (USBR, 1993). The estimated flow through

the aquifer was compared with the amount of recharge made available from precipitation in the conventional surface drainage area.

### **2.3 Southern Sierra Nevada Lineament Data Collection**

To examine the possible flowpaths of fracture-directed recharge into the deep-basin aquifer, a map of the dominant fracture patterns in both the conventional and the unconventional recharge areas was generated using methods outlined by Mabee *et al.* (1994). In this procedure, multiple observers (the author and CSUB hydrogeology students) independently mapped lineaments visible on aerial photographs and satellite images. The mapped lineaments were compared and common observations were saved. The orientations of surface fractures were measured at outcrops in each canyon of the study area to field-check for correlation between the lineament maps and near-vertical surface joint sets. Areas where lineaments and joints overlapped were considered likely to be underlain by fractures of the same orientation.

Strike and dip measurements from each of the canyons were converted to rosette diagrams using Rosy™, a two-dimensional orientation analysis program for the Macintosh, and compared to the lineament map as another way of graphically presenting the information. Based on the structural data, possible avenues of subsurface recharge were examined and a hypothesis for recharge was developed in conjunction with the hydrogeochemical data.

## **3. RESULTS**

### **3.1 Southern Sierra Nevada Recharge**

#### **a. Conventional Surface Drainage Area Measurements**

Planimeter measurements of the surface drainage area for southwest Indian Wells Valley were separated by canyon and by 500-foot elevation increments (Table 2). Of the 56,745 total acres of drainage area, 51% are between 4,000 and 5,000 feet, but only 7% of the total acreage is 6,500 feet or higher. This 7% figure is significant in the context of the stable isotope data which follows. Most (1,479 acres) of this total comprises the relatively flat table land above the head of Sage Canyon. Owens Peak, at the head of Indian Wells Canyon, is the only region above 8,000 feet in the study area, and it has an area of just 23 acres. There is no acreage above 7,500 feet in the surface drainage area south of Indian Wells Canyon.

#### **b. Precipitation Measurements and Recharge Estimates**

Precipitation gage data for the Freeman Canyon drainage area in the 1994-95 and 1995-96 water years are shown graphically in Figures 10 and 11. In 1994-1995, the average of the nine data stations was 16.9 inches of precipitation (using an increase of 1.9 inches per 500 feet of elevation for stations above the snowline as described in section 2.1b.). The 1995-96 water year was considerably drier in the study area than the previous year, averaging 10.9 inches of precipitation, using an increase of 1.6 inches per 500 feet at stations above the snowline. Both years were wetter than normal, based on regional Sierra Nevada snowpack records dating back to 1930. The April 1, 1995 water content of Sierran snow samples at Round Meadow (elevation 9,000 feet) and Beach Meadow (elevation 7,650 feet) on the Kern River Plateau was 178% and 162% of normal, respectively (California Department of Water Resources, 1996). The 1995-96 statistics showed 124% and 110% more water content than average at the above stations.

Table 3 compares the amount of rain collected in gages fixed at ground level versus the gages placed three feet above the ground. The ground level gages

**Table 2. Recharge areas in acres by canyon and by elevation.**

|                     | <b>4000 ft</b> | <b>4500 ft</b> | <b>5000 ft</b> | <b>5500 ft</b> | <b>6000 ft</b> | <b>6500 ft</b> | <b>7000 ft</b> | <b>7500 ft</b> | <b>8000 ft</b> | <b>Total</b> | <b>%</b> |
|---------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|--------------|----------|
|                     | (acres)        | (acres)        | (acres)        | (acres)        | (acres)        | (acres)        | (acres)        | (acres)        | (acres)        | (acres)      |          |
| <b>Indian Wells</b> | 2250           | 1960           | 1474           | 1158           | 742            | 423            | 285            | 151            | 23             | 8466         | 14.92    |
| <b>Freeman</b>      | 2827           | 3904           | 3878           | 1649           | 977            | 257            | 25             | 0              | 0              | 13517        | 23.82    |
| <b>Cow Heaven</b>   | 2278           | 2643           | 1438           | 507            | 432            | 378            | 124            | 0              | 0              | 7800         | 13.75    |
| <b>Boulder</b>      | 482            | 588            | 438            | 435            | 401            | 589            | 55             | 0              | 0              | 2988         | 5.27     |
| <b>Sage</b>         | 874            | 922            | 874            | 940            | 1225           | 1438           | 41             | 0              | 0              | 6314         | 11.13    |
| <b>Horse</b>        | 2422           | 1771           | 1398           | 1119           | 464            | 220            | 28             | 0              | 0              | 7422         | 13.08    |
| <b>Bird Spring</b>  | 4120           | 2518           | 2155           | 1087           | 200            | 117            | 41             | 0              | 0              | 10238        | 18.04    |
| <b>Total Acres</b>  | 15253          | 14306          | 11655          | 6895           | 4441           | 3422           | 599            | 151            | 23             | <b>56745</b> |          |
| <b>%</b>            | 26.88          | 25.21          | 20.54          | 12.15          | 7.83           | 6.03           | 1.06           | 0.27           | 0.04           | 100.00       | 100.00   |

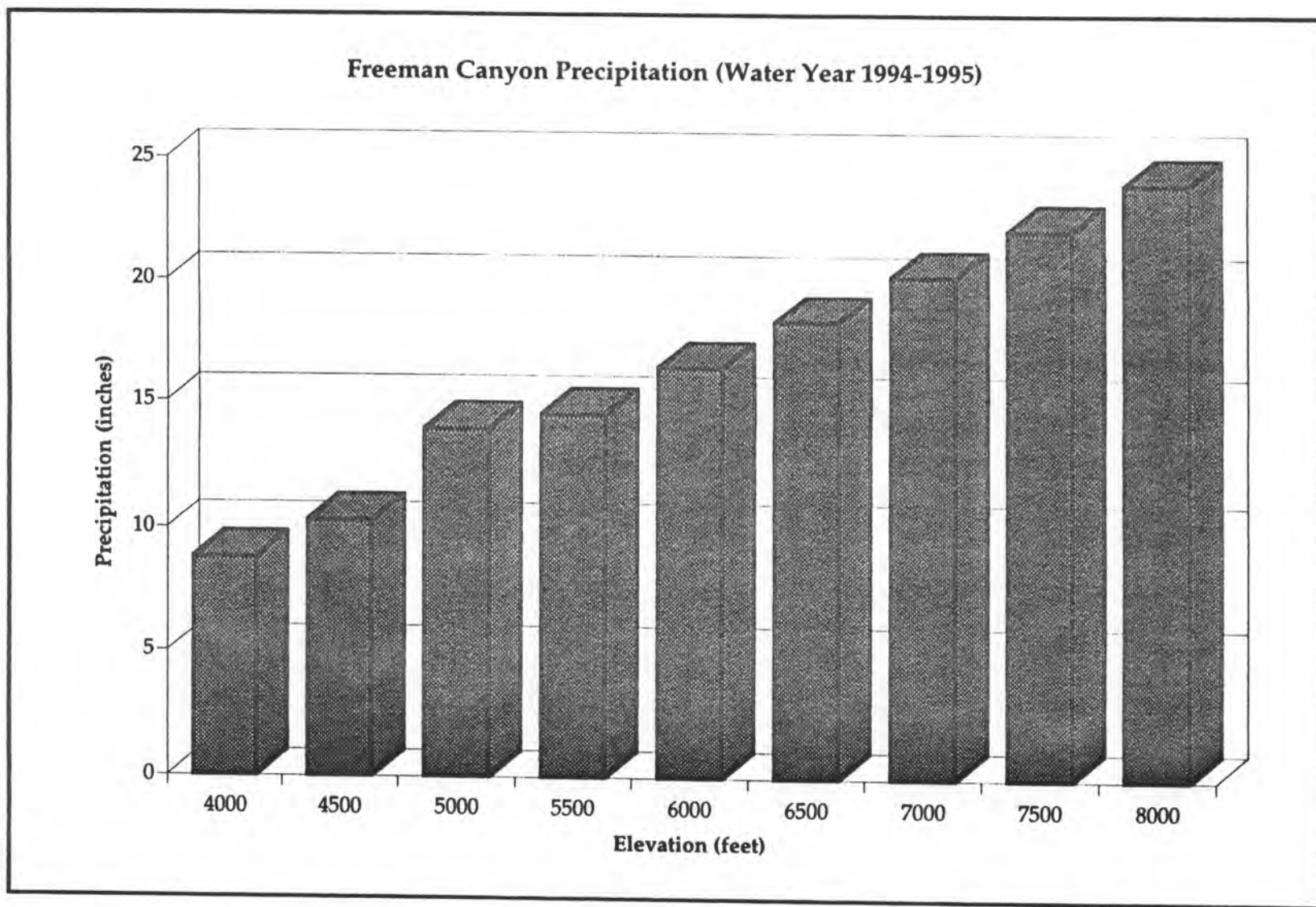
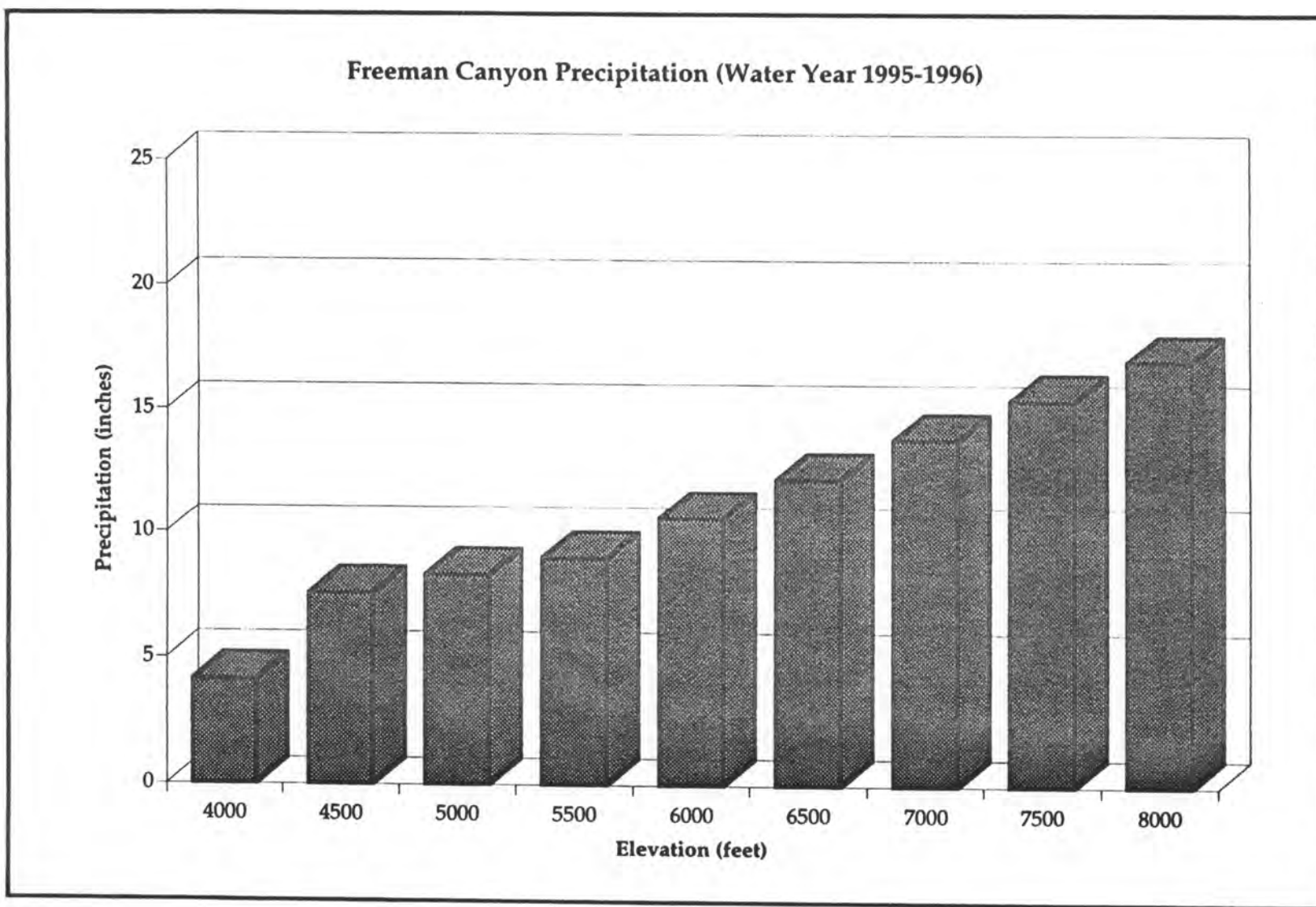


Figure 10. Orographic precipitation measured in Freeman Canyon during the water year 1994-1995.



**Figure 11. Orographic precipitation measured in Freeman Canyon during the water year 1995-1996.**

caught an average of 9.3% more rain, presumably due to less wind interference around the openings of the gages. This difference agrees with the observations of Winter (1981). The data for 1995-96 precipitation incorporate the ground level measurements. No adjustment was made to the 1994-95 data.

**Table 3. Comparison of precipitation gage data collected at ground level and three feet above ground at three elevations in Freeman Canyon.**

| <u>1995-96 Precipitation</u> | <u>4000 ft</u> | <u>5000 ft</u> | <u>5500 ft</u> |
|------------------------------|----------------|----------------|----------------|
| Ground Level                 | 4.13 in        | 8.91 in        | 9.72 in        |
| 3 Feet Above Ground          | 3.61 in        | 8.06 in        | 9.16 in        |
| Difference                   | 0.52 in        | 0.85 in        | 0.56 in        |
| Percent Difference           | 12.59 %        | 9.54 %         | 5.76%          |

Average Difference: 9.3%

The amount of recharge made available to the southwest Indian Wells Valley aquifer from precipitation in the Sierra Nevada surface drainage area (Fig. 7) was estimated using Maxey-Eakin recharge coefficients. Table 4 shows the number of acre-feet of recharge for each elevation increment in every canyon and the totals in acre-feet per year both by elevation and by canyon for each of the water years studied. A total of 4,125 acre-feet of water was available to infiltrate the southwest alluvium in 1994-95, over four times as much as the recharge figure for 1995-96 (924 acre-feet). The average of these two numbers, 2,525 acre-feet, compares favorably with the published estimates of 2,870 acre-feet from Bloyd and Robson (1971).

Table 4. Recharge data by canyon and by elevation for water years 1994-95 and 1995-96.

|              | 4000 ft     | 4500 ft     | 5000 ft     | 5500 ft     | 6000 ft     | 6500 ft     | 7000 ft     | 7500 ft     | 8000 ft     | Total       |
|--------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| 1994-95      | (acre-feet) | (acre-feet) | (acre-feet) | (acre-feet) | (acre-feet) | (acre-feet) | (acre-feet) | (acre-feet) | (acre-feet) | (acre-feet) |
| Indian Wells | 49.50       | 50.47       | 119.52      | 97.95       | 152.11      | 96.76       | 71.96       | 41.71       | 6.90        | 686.88      |
| Freeman      | 62.19       | 100.53      | 314.44      | 139.48      | 200.29      | 58.79       | 6.31        | 0.00        | 0.00        | 882.03      |
| Cow Heaven   | 50.12       | 68.06       | 116.60      | 42.88       | 88.56       | 86.47       | 31.31       | 0.00        | 0.00        | 483.99      |
| Boulder      | 10.60       | 15.14       | 35.51       | 36.79       | 82.21       | 134.73      | 13.89       | 0.00        | 0.00        | 328.88      |
| Sage         | 19.23       | 23.74       | 70.87       | 79.51       | 251.13      | 328.94      | 10.35       | 0.00        | 0.00        | 783.76      |
| Horse        | 53.28       | 45.60       | 113.35      | 94.65       | 95.12       | 50.33       | 7.07        | 0.00        | 0.00        | 459.41      |
| Bird Spring  | 90.64       | 64.84       | 174.73      | 91.94       | 41.00       | 26.76       | 10.35       | 0.00        | 0.00        | 500.27      |
| A-F/YR       | 335.57      | 368.38      | 945.03      | 583.20      | 910.41      | 782.78      | 151.25      | 41.71       | 6.90        | 4125.22     |
|              |             |             |             |             |             |             |             |             |             |             |
| 1995-96      |             |             |             |             |             |             |             |             |             |             |
| Indian Wells |             | 36.90       | 30.51       | 25.97       | 19.66       | 12.90       | 9.83        | 13.56       | 2.28        | 151.62      |
| Freeman      |             | 73.49       | 80.27       | 36.98       | 25.89       | 7.84        | 0.86        | 0.00        | 0.00        | 225.34      |
| Cow Heaven   |             | 49.75       | 29.77       | 11.37       | 11.45       | 11.53       | 4.28        | 0.00        | 0.00        | 118.15      |
| Boulder      |             | 11.07       | 9.07        | 9.75        | 10.63       | 17.96       | 1.90        | 0.00        | 0.00        | 60.38       |
| Sage         |             | 17.36       | 18.09       | 21.08       | 32.46       | 43.86       | 1.41        | 0.00        | 0.00        | 134.26      |
| Horse        |             | 33.34       | 28.94       | 25.09       | 12.30       | 6.71        | 0.97        | 0.00        | 0.00        | 107.34      |
| Bird Spring  |             | 47.40       | 44.61       | 24.38       | 5.30        | 3.57        | 1.41        | 0.00        | 0.00        | 126.67      |
| A-F/YR       |             | 269.31      | 241.26      | 154.62      | 117.69      | 104.37      | 20.67       | 13.56       | 2.28        | 923.76      |

No significant groundwater recharge is believed to occur in areas receiving less than eight inches of annual precipitation (Eakin, Maxey *et al.*, 1951). The lack of recharge at the 4,000 foot level in 1995-96 reflects the 4.13 inches of precipitation gaged at that elevation, well below the eight-inch minimum. A study by Avon and Durbin (1994) postulated a maximum uncertainty of 44% for recharge estimated by the Maxey-Eakin method. Using this percentage as a range of maximum error for the results of this study, the 1994-95 recharge was between 2,191 and 5,940 acre-feet and the 1995-96 recharge was between 517 and 1,331 acre-feet.

Observations were made of plant life in the different canyons of the study area in the course of field work. A consistent pattern emerged, with creosote bush, desert holly, sagebrush, cactus, mountain mahogany and Joshua trees from 3,000 feet to 5,500 feet, and pinon pine, canyon live oak, juniper and cedar above 5,500 feet. Joshua trees become increasingly dominant approaching the 5,000 foot contour. In the stream beds and around the emergence of springs, cottonwood trees and tamarisks flourish. North-facing slopes, which do not receive as much direct sunlight in the winter as the south-facing slopes, hold their snowpack longer and may absorb more water than the south-facing slopes. There is more vegetation on the north-facing slopes than the south, and the tree line generally begins lower, at 5,000-5,200 feet. At the higher elevations above Sage Canyon (approximately 6,500 feet) some Jeffrey pines and sugar pines can be found. The occurrence of these plant species at consistently similar elevations in all of the canyons supports the use of the Freeman Canyon precipitation data for recharge estimates of the entire area.

#### **c. Surface Flow Estimates**

Although pockets of surface water were found in every canyon in all seasons of both years, there were no perennial flowing streams in the study area.

Only Indian Wells and Sage Canyons had streams that ran consistently in the precipitation months of December through May. Flow was occasionally observed below 3,200 feet in Indian Wells Canyon, but in Sage Canyon, the water disappeared into the alluvium at elevations ranging from 3,500 to 3,900 feet. No weirs, continuous stage recorders or crest stage gages are currently in place in any of the watersheds. No historical data on surface flow are available for Sierran streams south of Sand Canyon (Fig. 1). Perennial springs exist along lineaments in Indian Wells, Freeman, Sage and Bird Spring Canyons. Except for Bird Springs Canyon, all of the canyons in the study area include springs that appear upstream from pegmatite and aplite dikes that intersect stream drainages at right angles. These springs appear to be small pools of groundwater brought to the surface by the damming effect of the dikes.

Table 5 lists surface flow measurements taken by the author over the course of the project. Data were separated into 1994-95 and 1995-96 water years and averages were calculated from the measurements. Flows in cubic feet per second were converted to acre-feet per year to simulate a best-case, hypothetical twelve-month scenario for contributions to the valley from surface flow. A total of 6,673 acre-feet could have been produced at these rates over the two-year period. Of this figure, 68%, or 4,456 acre-feet would be attributed to the 1994-95 water year and 32%, or 2,117 acre-feet would be attributed to 1995-96. These figures are not intended to represent actual surface recharge, but rather to emphasize the dry conditions present in these canyons, where streams run less than half the year.

#### **d. Surface Water Chemistry Data**

Forty-five surface water samples were collected for major-ion chemical and stable isotope analysis. Thirty-one of these samples were taken from springs and streams in the conventional surface drainage area. The remaining samples

**Table 5. Ephemeral stream flow measurements projected over hypothetical twelve-month periods illustrate the arid conditions present in the study area's canyons during 1994-95 and 1995-96.**

| Location                   | Elevation (feet) | Longitude/Latitude        | Date     | Flow (cubic feet/second) | Flow (acre-feet/year) | % of Total |
|----------------------------|------------------|---------------------------|----------|--------------------------|-----------------------|------------|
| Indian Wells Canyon Stream | 3950             | 117- 56-00 W / 35-41-45 N | 8/28/94  | 0.800                    | 579.33                | 8.68%      |
| Indian Wells Canyon Stream | 3400             | 117- 54-30 W / 35-40-45 N | 12/20/94 | 1.500                    | 1,086.24              | 16.28%     |
| Indian Wells Canyon Stream | 3400             | 117- 54-30 W / 35-40-45 N | 4/9/95   | 1.875                    | 1,357.80              | 20.35%     |
| Indian Wells Canyon Stream | 4600             | 117- 57-15 W / 35-42-40 N | 7/5/95   | 0.017                    | 12.31                 | 0.18%      |
| Indian Wells Canyon Stream | 3950             | 117- 56-00 W / 35-41-45 N | 11/18/95 | 0.003                    | 2.17                  | 0.03%      |
| Indian Wells Canyon Stream | 3400             | 117- 54-30 W / 35-40-45 N | 3/2/96   | 0.360                    | 260.70                | 3.91%      |
| Indian Wells Canyon Stream | 3400             | 117- 54-30 W / 35-40-45 N | 3/31/96  | 0.150                    | 108.62                | 1.63%      |
| Indian Wells Canyon Stream | 3400             | 117- 54-30 W / 35-40-45 N | 4/20/96  | 0.060                    | 43.45                 | 0.65%      |
| Big Spring                 | 4045             | 117-57-30 W / 35-37-30 N  | 6/22/96  | 0.004                    | 2.90                  | 0.04%      |
| Boulder Canyon Stream      | 4038             | 118-01-30 W / 35-34-45 N  | 11/26/95 | 0.007                    | 5.07                  | 0.08%      |
| Boulder Canyon Stream      | 4038             | 118-01-30 W / 35-34-45 N  | 4/14/96  | 0.050                    | 36.21                 | 0.54%      |
| Sage Canyon Stream         | 4170             | 118-03-30 W / 35-35-00 N  | 10/30/94 | 1.350                    | 977.62                | 14.65%     |
| Sage Canyon Stream         | 4050             | 118-02-45 W / 35-34-45 N  | 11/26/95 | 1.250                    | 905.20                | 13.56%     |
| Sage Canyon Stream         | 4480             | 118-04-30 W / 35-36-00 N  | 5/4/96   | 0.180                    | 130.35                | 1.95%      |
| Sage Canyon Stream         | 4640             | 118-04-30 W / 35-36-15 N  | 5/4/96   | 0.130                    | 94.14                 | 1.41%      |
| Sage Canyon Stream         | 4720             | 118-04-30 W / 35-36-25 N  | 5/4/96   | 0.300                    | 217.25                | 3.26%      |
| Sage Canyon Stream         | 4450             | 118-04-40 W / 35-36-00 N  | 5/4/96   | 0.130                    | 94.14                 | 1.41%      |
| Sage Canyon Stream         | 4200             | 118-03-45 W / 35-35-10 N  | 5/4/96   | 0.260                    | 188.28                | 2.82%      |
| McIvers Spring             | 6680             | 118-04-00 W / 35-37-00 N  | 1/14/96  | 0.009                    | 6.52                  | 0.10%      |
| McIvers Spring             | 6680             | 118-04-00 W / 35-37-00 N  | 4/6/96   | 0.010                    | 7.24                  | 0.11%      |
| Horse Canyon Spring        | 4830             | 118-05-00 W / 35-34-00 N  | 9/10/94  | 0.750                    | 543.12                | 8.14%      |
| Horse Canyon Spring        | 4770             | 118-04-30 W / 35-34-00 N  | 1/15/96  | 0.005                    | 3.62                  | 0.05%      |
| Horse Canyon Well          | 3760             | 118-02-00 W / 35-33-30 N  | 12/16/95 | 0.006                    | 4.34                  | 0.07%      |
| Bird Spring                | 3840             | 118-04-30 W / 35-30-00 N  | 5/25/96  | 0.009                    | 6.52                  | 0.10%      |
|                            |                  |                           |          |                          | <b>TOTAL 6673.13</b>  |            |

came from springs, streams or rivers north and west of the drainage divide. Some locations were sampled more than once to test for repeatability and/or seasonal change. A table listing pertinent data for each sample can be found in Appendix 2.

A fingerprint plot is a graphical means of comparing data which uses a logarithmic scale on the y-axis to display the dissolved concentrations in milliequivalents per liter of the major ions shown on the x-axis. This plot can be used to establish a recognizable visual pattern or water type which can be compared to other sample sets. A similar pattern between samples or sets of samples would suggest a common history or flowpath. The water type is named for the predominant cations and anions as displayed on the plot.

Figure 12 is a fingerprint plot of the eleven spring 1995 surface samples. It indicates a Ca-Na-HCO<sub>3</sub>-SO<sub>4</sub> water type with very little potassium and relatively little chloride in the majority of the surface water. The spring 1995 surface samples had the following average values: a temperature of 15.9 degrees Celsius, a TDS concentration of 525 mg/l, a pH of 7.6 and an alkalinity of 247 mg/l. The average deuterium and oxygen-18 values were -91‰ and -11.8‰, respectively. Log P<sub>CO2</sub> values ranged from -3.71 at Indian Wells Canyon Stream to -0.512 at McIvers Spring (Fig. 13).

Twelve sample analyses from the fall-winter of 1995-96 were fingerprinted in Figure 14. The pattern again showed the Ca-Na-HCO<sub>3</sub>-SO<sub>4</sub> water type, although it was more tightly clustered than the previous group. Mean values for the fall-winter of 1995-96 samples were: a temperature of 15.5 degrees Celsius, a TDS concentration of 382 mg/l, a pH of 7.8 and an alkalinity of 236 mg/l. Deuterium averaged -92‰, oxygen-18 averaged -12.0‰ and Log P<sub>CO2</sub> ranged from -3.153 at Sage Canyon Stream to -1.923 at Cow Heaven Canyon Spring (Fig. 15).

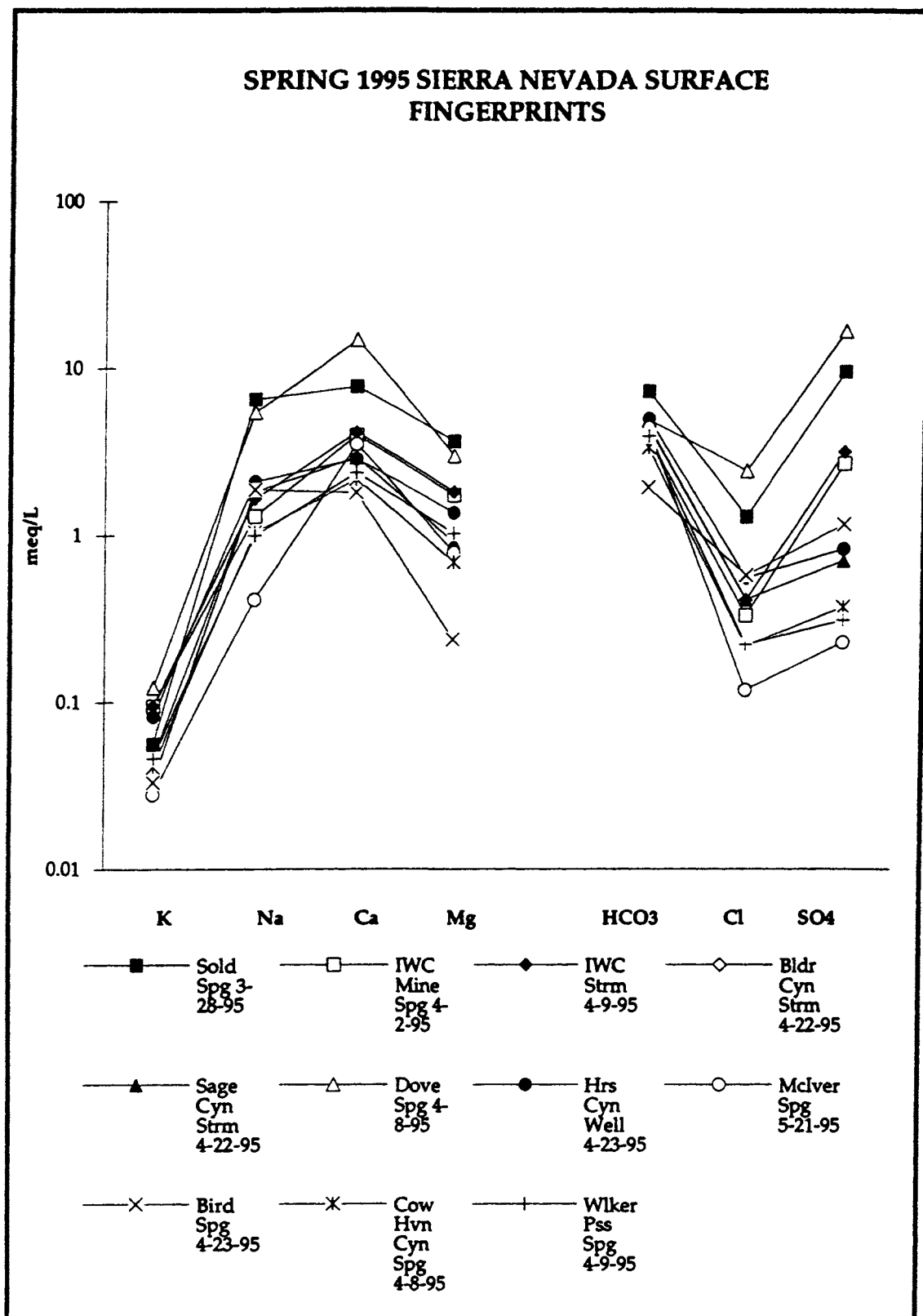


Figure 12. Fingerprint plot of Spring 1995 surface water.

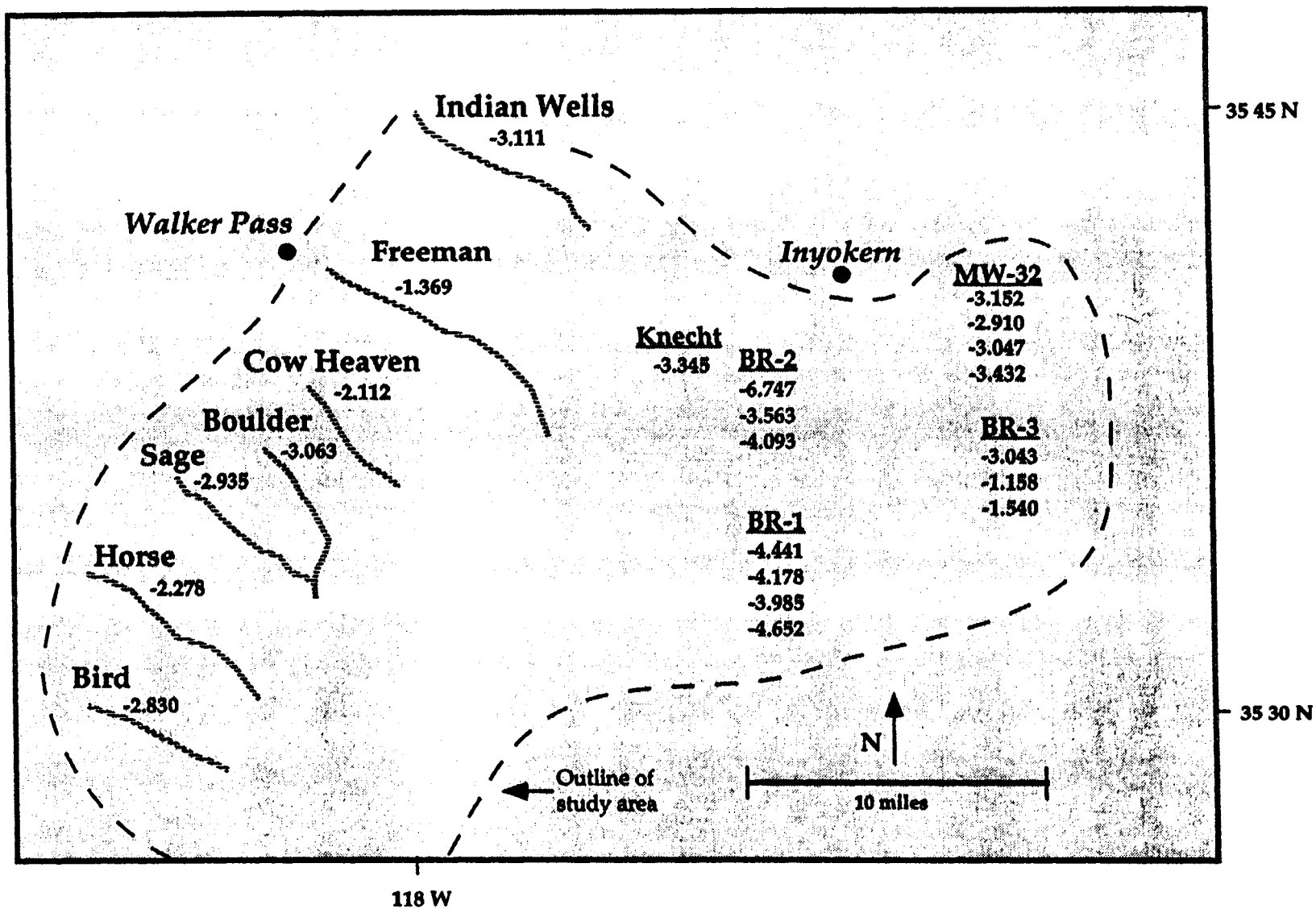


Figure 13. Map of representative log  $P_{CO_2}$  values in the study area canyons and wells from Spring 1995.

# FALL / WINTER 1995-96 SIERRA NEVADA SURFACE FINGERPRINTS

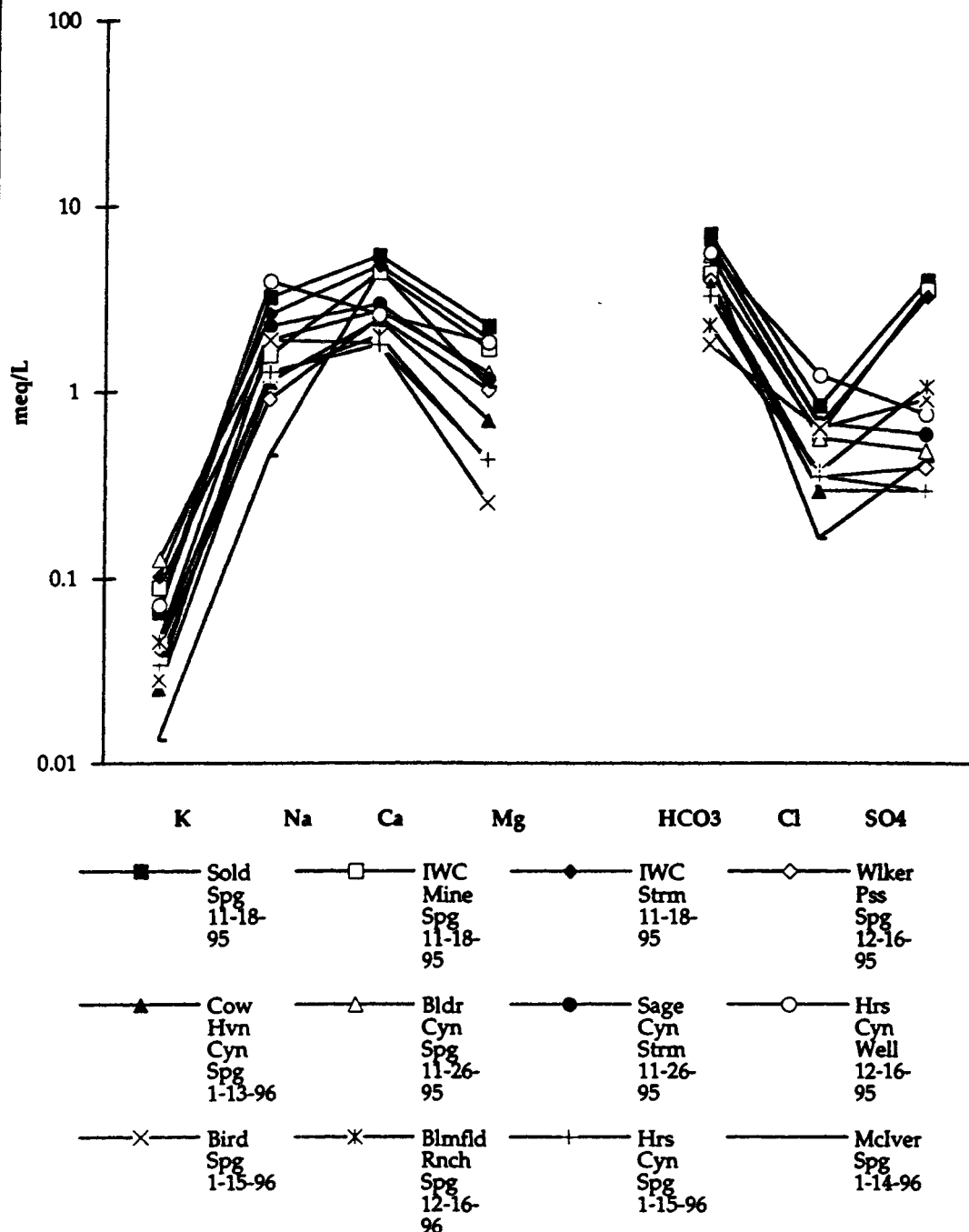


Figure 14. Fingerprint plot of Fall 1995-Winter 1996 Sierra Nevada surface water. 42

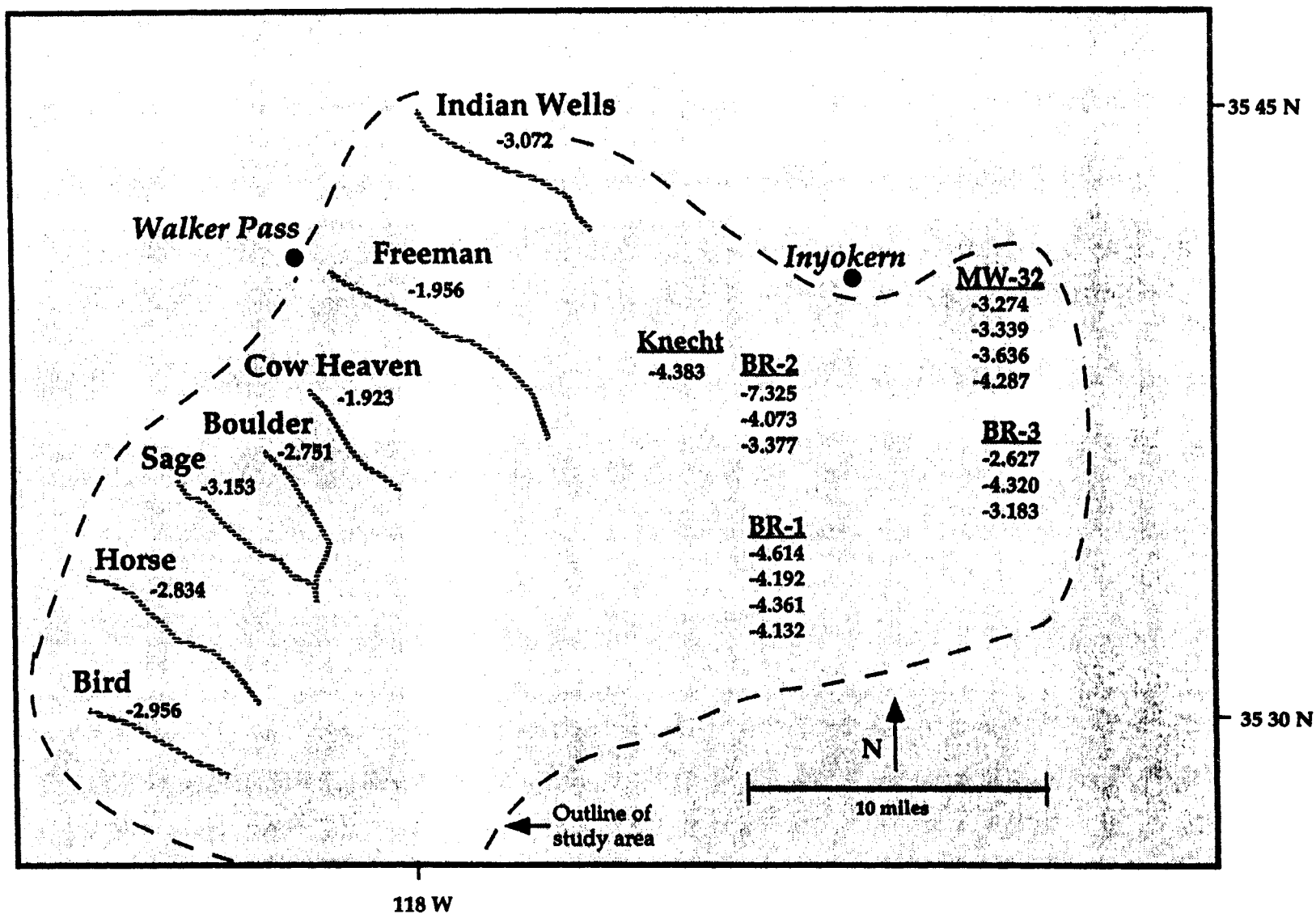


Figure 15. Map of representative log Pco<sub>2</sub> values in the study area canyons and wells from Fall / Winter 1995-1996.

Ten surface samples were collected during the spring of 1996, yielding the same Ca-Na-HCO<sub>3</sub>-SO<sub>4</sub> water type as the first two rounds (Fig. 16). The temperature averaged 21.9 degrees Celsius for these samples, with mean values of 345 mg/l TDS, 7.5 for pH and 218 mg/l for alkalinity. Deuterium and oxygen-18 averaged -96.7‰ and -12.7‰ respectively. Log P<sub>CO2</sub> values ranged from -3.091 at Sage Canyon Spring A to -1.428 at Sage Canyon Spring D (Fig. 17).

Results of the tritium analyses from the surface samples are shown in Table 6. Concentrations of tritium (<sup>3</sup>H), the heavy isotope of hydrogen (half-life = 12.43 years), are reported in tritium units (TU). One TU expresses a tritium to hydrogen ratio of 10<sup>-18</sup>. The margin of error in these analyses is indicated in eTU, where one eTU is one standard deviation.

**Table 6. Surface sample tritium data.**

| <u>Sample</u>                                | <u>Volume</u> | <u>TU</u> | <u>eTU</u> |
|----------------------------------------------|---------------|-----------|------------|
| Bird Spring                                  | 1000 ml       | 0.38      | 0.09       |
| South Fork of the Kern River                 | 1000 ml       | 5.37      | 0.15       |
| Big Spring                                   | 1000 ml       | 0.03      | 0.09       |
| McIvers Spring                               | 1000 ml       | 5.52      | 0.18       |
| Indian Wells Canyon Mine Spring              | 1000 ml       | 1.52      | 0.09       |
| Walker Pass Spring                           | 1000 ml       | 1.33      | 0.09       |
| South Kennedy Meadows<br>(Government Spring) | 1000 ml       | 2.33      | 0.09       |

### **3.2 Southwest Indian Wells Valley Groundwater Recharge**

#### **a. Depth to Water Measurements**

A groundwater hydrograph is a chart depicting the change in groundwater surface elevation relative to a specific datum (mean sea level, in this case) over

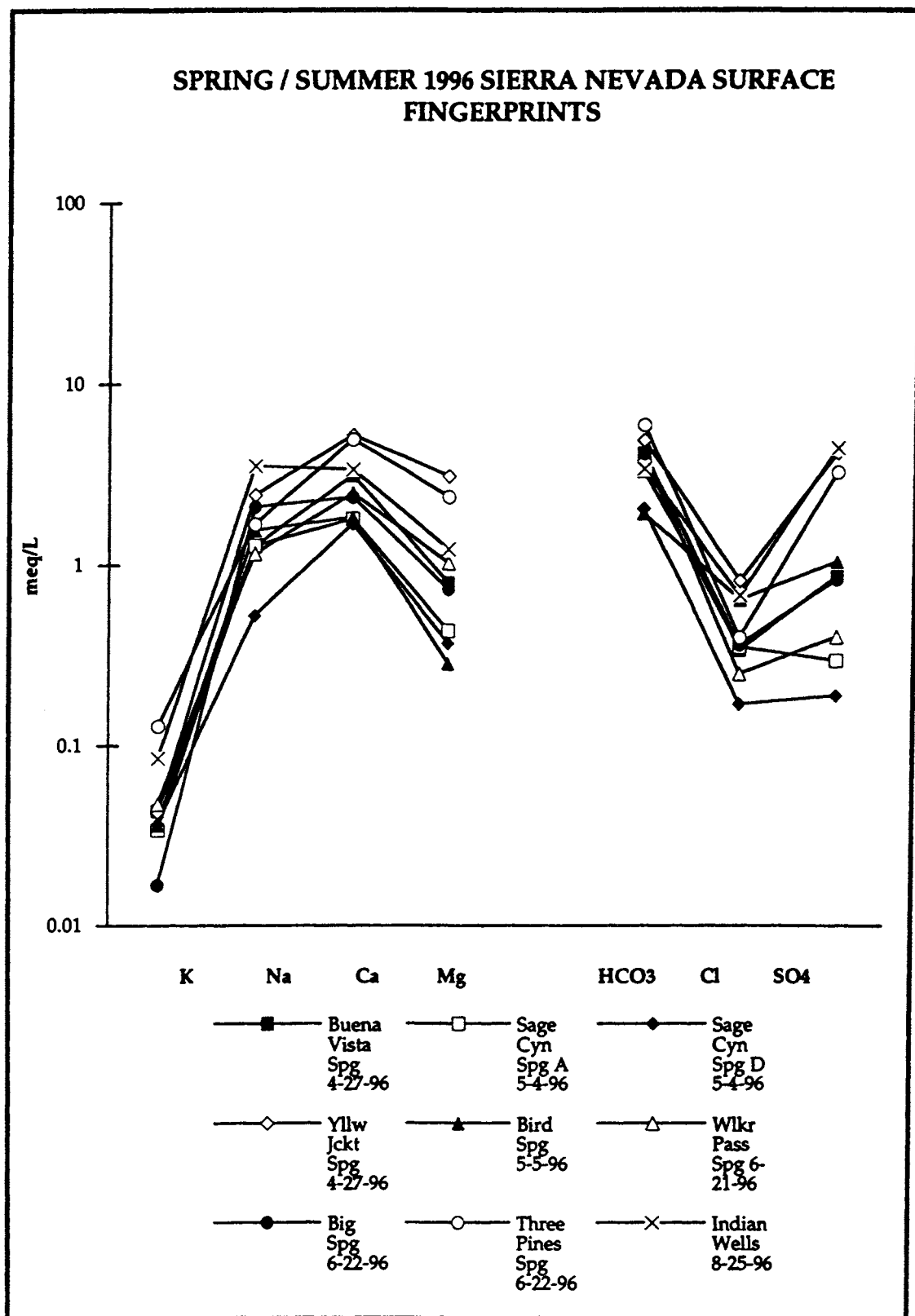


Figure 16. Fingerprint plot of Spring-Summer 1996 surface samples.

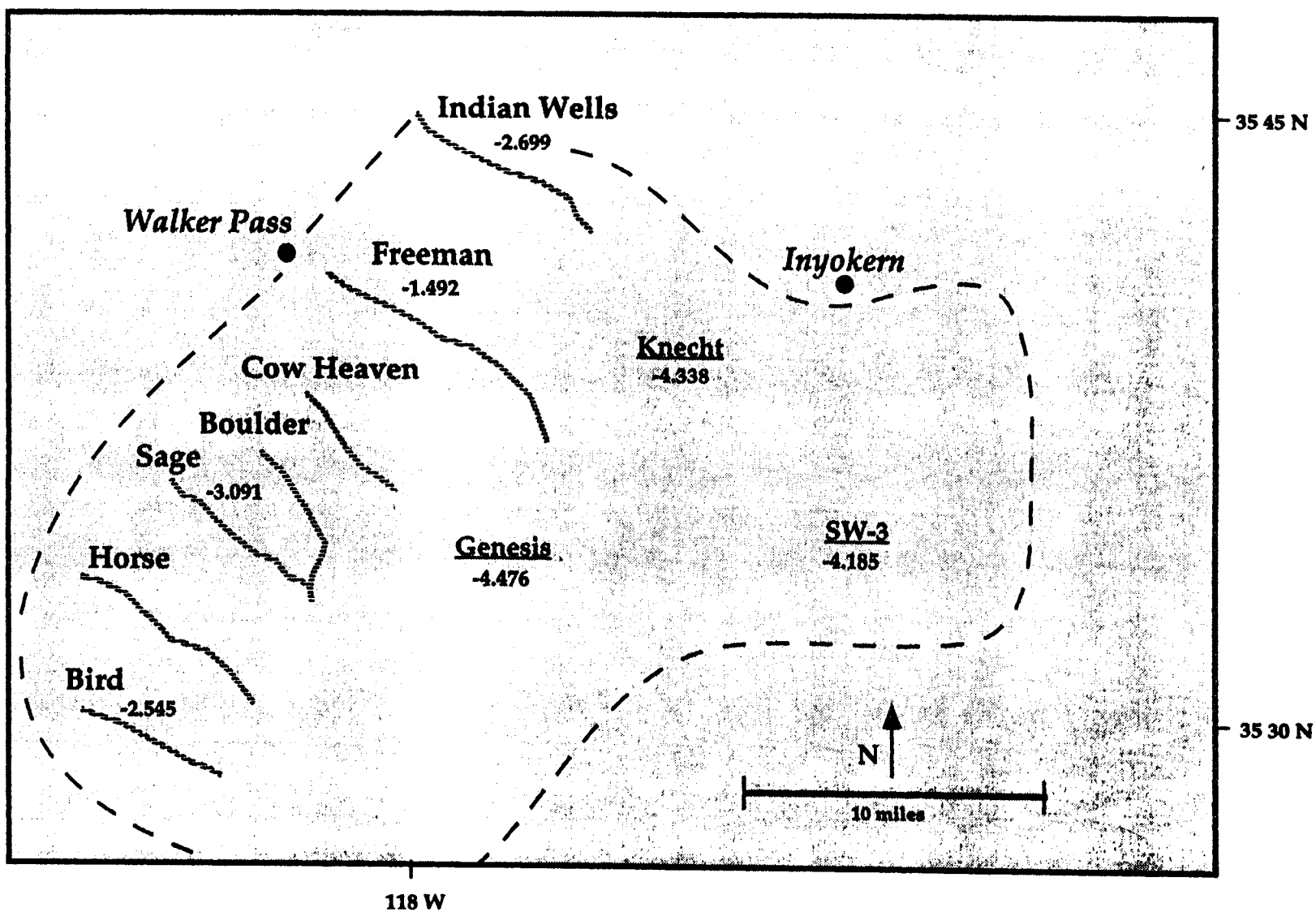
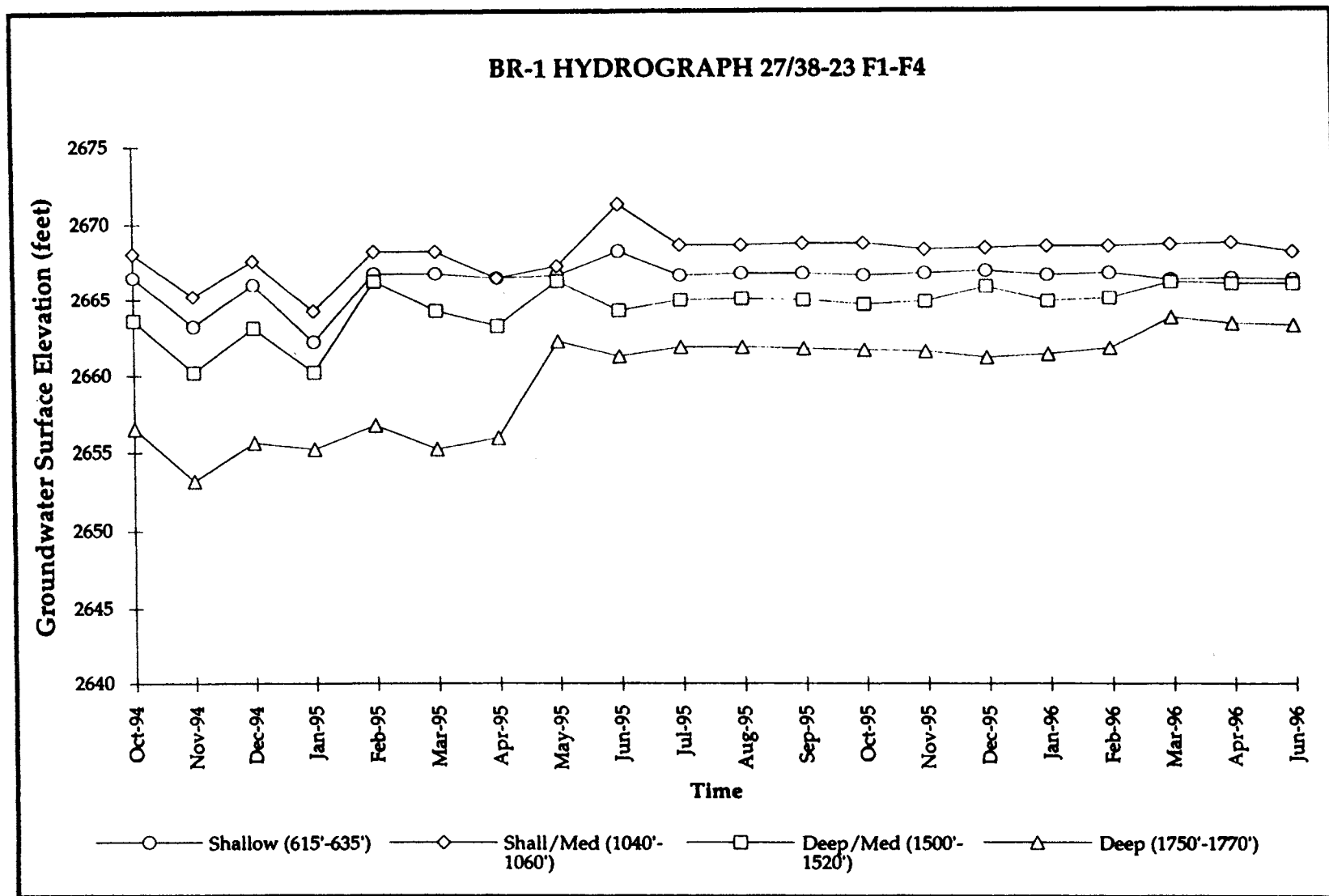


Figure 17. Map of representative log  $P_{CO_2}$  values in the study area canyons and wells from Spring 1996.

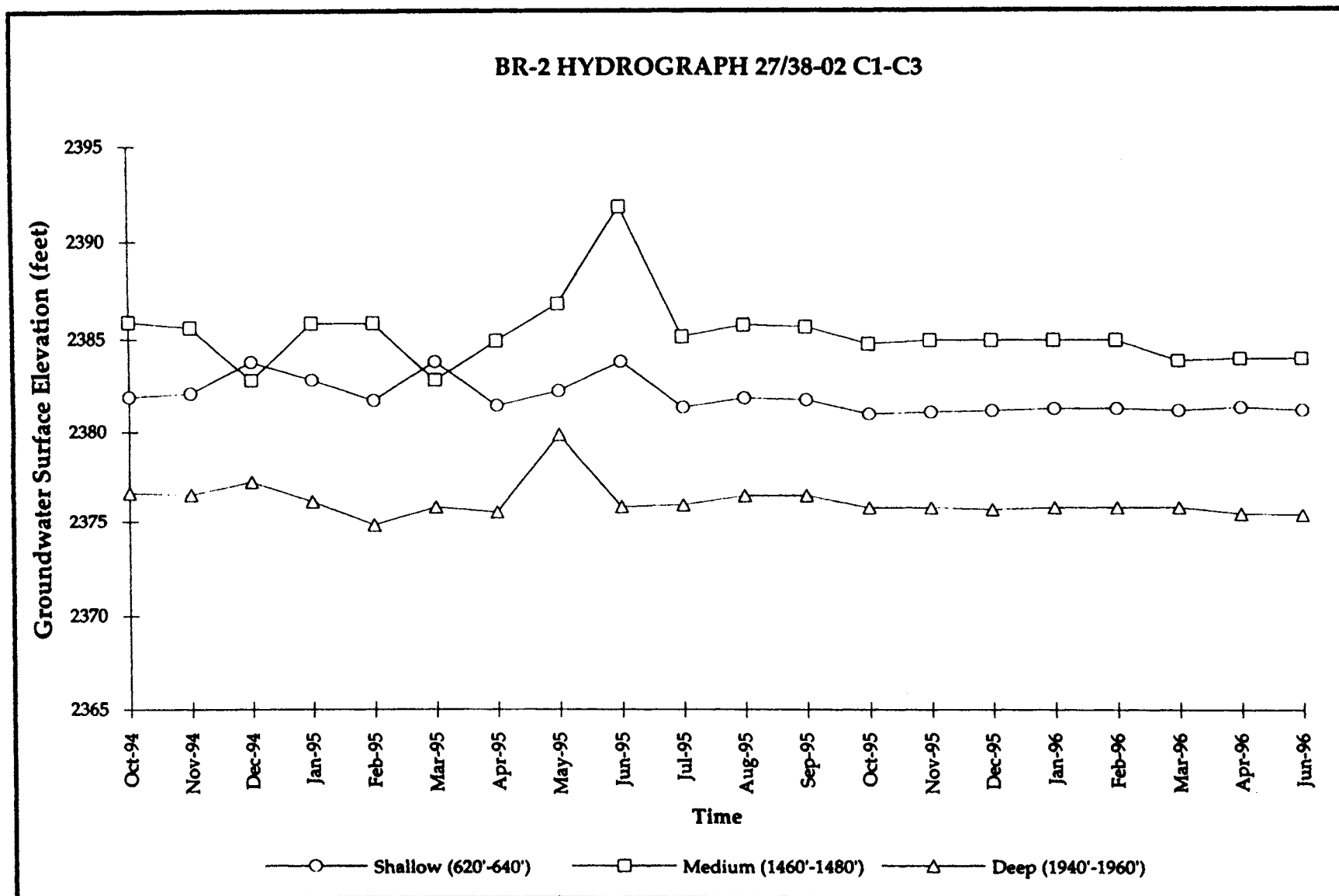
time. Hydrographs were prepared from monthly well-sounding data collected by the author from October, 1994 to June, 1996 in southwest Indian Wells Valley (Figs. 18-21 and Appendix 3). The USBR wells feature multiple nested piezometers perforated at varying depths below the top of each piezometer. The Indian Wells Valley Water District southwest well field monitoring wells, the Knecht domestic well and the two Genesis monitoring wells are each single-unit wells. The perforated interval for each well is indicated on the legend of its hydrograph (Figs. 18-21 and Appendix 3).

Figure 18 illustrates the pattern of change in BR-1 during the course of the investigation. The response over time in the deep piezometers varies from that of the shallow piezometers, showing greater seasonal fluctuation and larger, more rapid increases in elevation. The greatest individual increase occurred in the deep piezometer between April, 1995 and May, 1995. Although depth to water in BR-1 generally increases as the depth of the perforations increases, indicating a recharge zone, there is one exception. There is an upward vertical gradient between the shallow and the shallow-medium piezometers, suggesting the presence of a locally confining or semi-confining layer that separates the two intervals. A similar pattern to that of BR-1 is recognizable in BR-2 (Fig. 19), but BR-3 is decidedly different. Depth to water decreases as the depth of the perforations increases, indicating a discharge zone (Fig. 20). The upward vertical gradient in BR-3 is more pronounced than in either BR-1 or BR-2. The largest rise in the BR-3 deep piezometer occurred between May, 1995 and June, 1995.

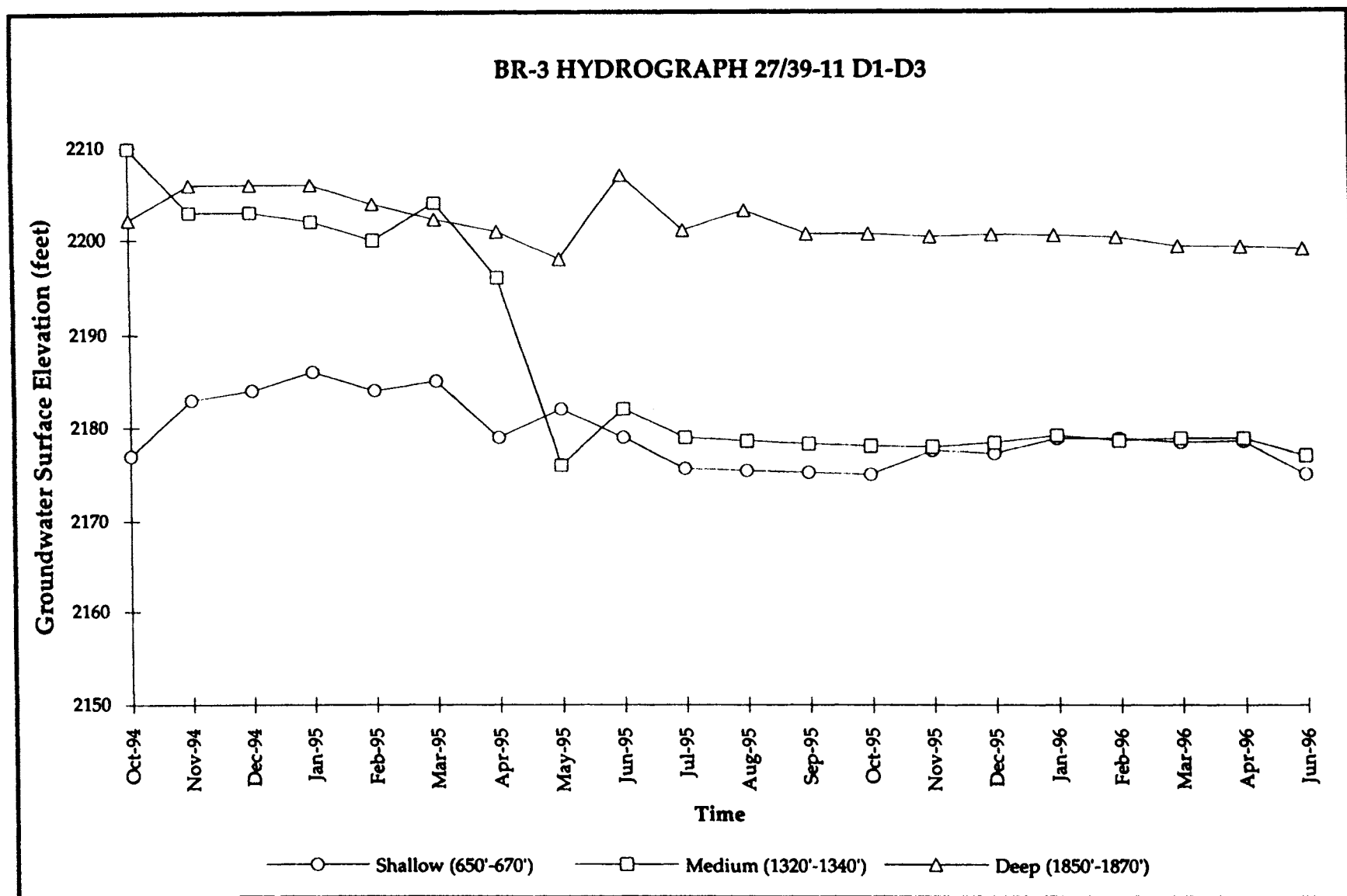
MW-32 (Fig. 21) is located less than a mile from two Indian Wells Valley Water District production wells which are both perforated from 600 to 1,200 feet. The shallow-medium and the deep-medium piezometers at MW-32 show the drawdown effects of the heavy dry season pumping of the production wells between May and November and a corresponding recovery from December



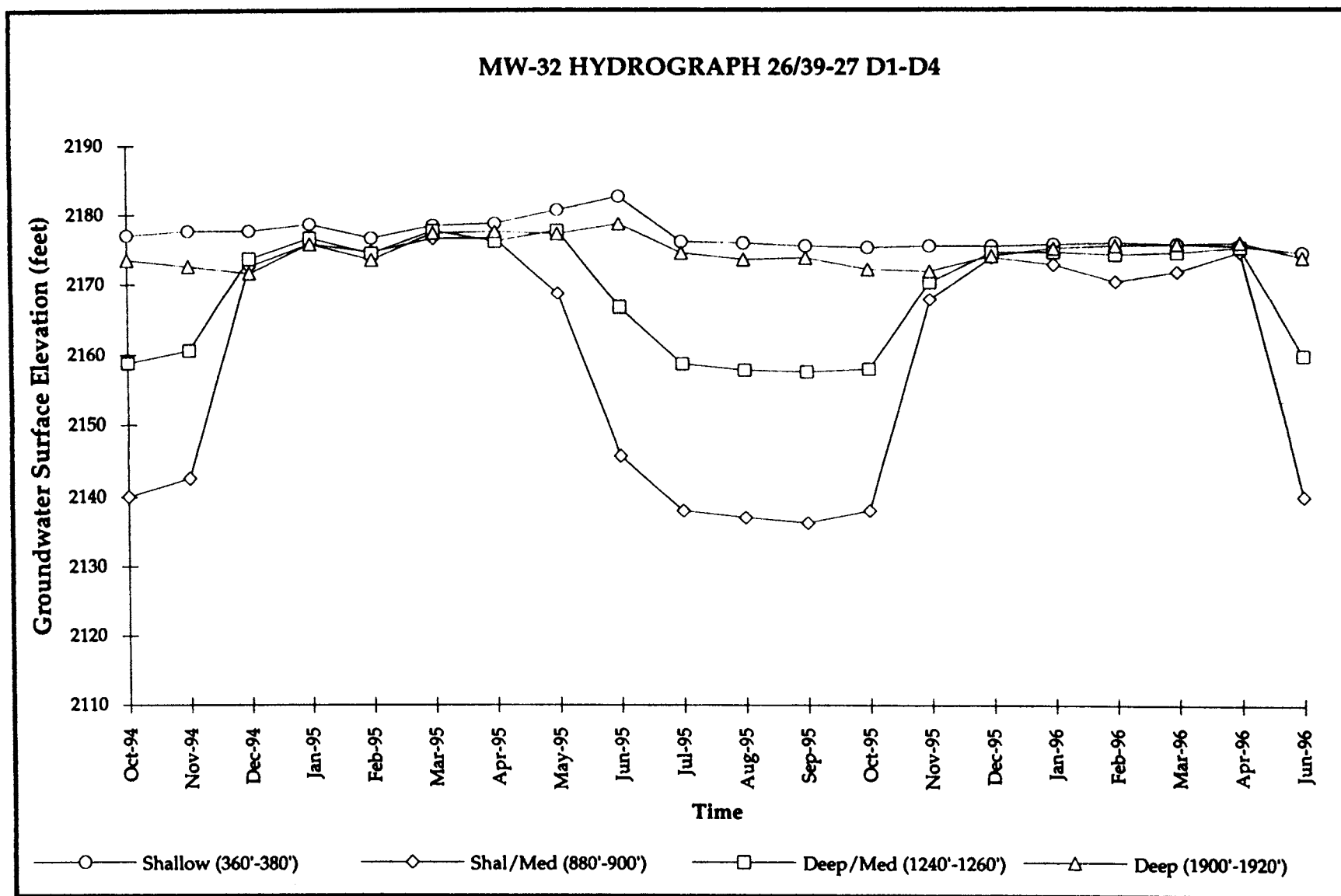
**Figure 18. Hydrograph of the four nested piezometers in well BR-1. Perforation intervals are indicated in parentheses.**



**Figure 19. Hydrograph of the three nested piezometers in well BR-2. Perforation intervals are indicated in parentheses.**



**Figure 20. Hydrograph of the three nested piezometers in well BR-3. Perforation intervals are indicated in parentheses.**



**Figure 21. Hydrograph of the four nested piezometers in well MW-32. Perforation intervals are indicated in parentheses.**

through April. Hydrographs for the remaining wells measured for this study can be found in Appendix 3.

#### **b. Description of Stratigraphic Cross-Sections**

Cross-section A-A' (Plate 1) illustrates a southwest to northeast profile (Fig. 8) of the alluvium in southwest Indian Wells Valley from BR-1 to MW-32. In general, a good correlation exists between the driller's logs and the electric logs. The lithological descriptions indicate gravel, sand and silt deposits typical of coalescing alluvial fans. The largest, cobble-to-boulder size particles lie closest to their presumed Sierran source in BR-1 and SW-3, becoming less and less evident farther northeast in the central part of the valley. Toward the northeast, sand and silt prevail in a more homogenous, relatively well-sorted environment. Exceptions to normal Sierran-derived alluvial deposition are the volcanic ash and basalt chips described in BR-1 below 1,500 feet and in TW-1 at approximately 700 feet. These deposits suggest contributions from the Black Hills, possibly due to Tertiary volcanic eruptions or floods that washed detritus into the valley from the southeast.

The hydraulic gradient in the southwest is steep between SW-3 and the Inyo well (0.029), as the groundwater surface elevation drops from 2,421 feet to 2,179 feet. Between the Inyo well and MW-32, the groundwater surface elevation drops only a few feet, from 2,179 feet to 2,176 feet, as the gradient flattens out to 0.0001. Water quality, however, does not change down the gradient, remaining very fresh at less than 300 mg/l all the way to MW-32.

Cross-section B-B' (Plate 2) bridges a west to east line from the Knecht domestic well to the piezometers at BR-3 (Fig. 8). Again the most poorly sorted materials are closest to the Sierras. The BR-3 log reveals a much different lithology than MW-32, which is 3.2 miles to the north. BR-3 contains a greater proportion of gravel and boulders than MW-32, as well as volcanic ash and basalt

chips in the vicinity of the medium piezometer. This is probably due to its closer proximity to the Black Hills. The water quality in the medium and deep BR-3 piezometers is also profoundly different than any of the other wells, with extremely high sodium, boron and chloride concentrations. BR-2, furthest of all the wells from the Black Hills, shows no evidence of the volcanic material seen in BR-1 and the deep water chemistry is very fresh. The hydraulic gradient is less steep east of BR-2 (0.013) than it is between SW-3 and the Inyo well, dropping from 2,376 feet at BR-2 to 2,179 feet at the Inyo well.

The difficulty encountered in correlating beds from well to well in both cross-sections is probably due to facies heterogeneity characteristic of an alluvial aquifer rather than inaccurate log descriptions. No correlative sequences or continuous marker beds could be found in either of the sections.

#### **c. Groundwater Chemistry Data**

Thirty groundwater samples were collected from the wells and piezometers identified in Figure 8 in two rounds: the spring of 1995 and the winter of 1996. Three additional wells were sampled in June, 1996. The first-round sites were repeated in the second round to determine whether seasonal variations occurred and to aid in further development of the USBR piezometers. All of the samples passed the quality control standard of a  $\pm 10\%$  charge imbalance as calculated by MINTEQA2. The consistently anomalous results from BR-2 shallow, BR-3 medium and BR-3 deep will be considered separately from the rest of the samples. Data tables for each sample can be found in Appendix 1.

Fingerprint plots from both sampling rounds (Fig. 22 and Fig. 23) indicate a predominant Na-HCO<sub>3</sub> water type in the southwest Indian Wells Valley groundwater. These results agree with the both the initial testing by the USBR (1993) and Houghton's (1994) Group A samples from the shallow aquifer. Table 7 compares average values of temperature, TDS, pH, alkalinity and stable isotopes

# SPRING 1995 SOUTHWEST INDIAN WELLS VALLEY GROUNDWATER FINGERPRINTS

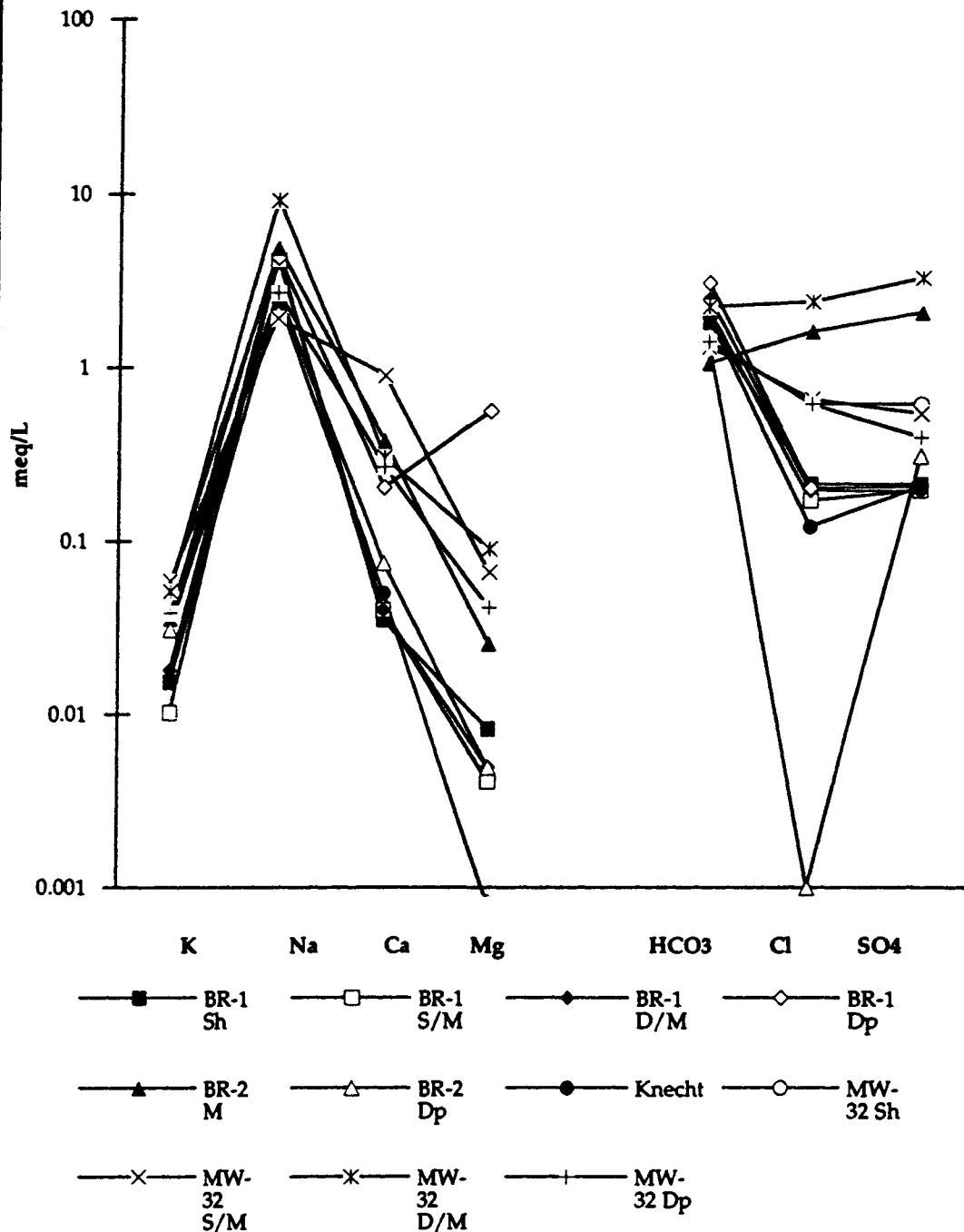
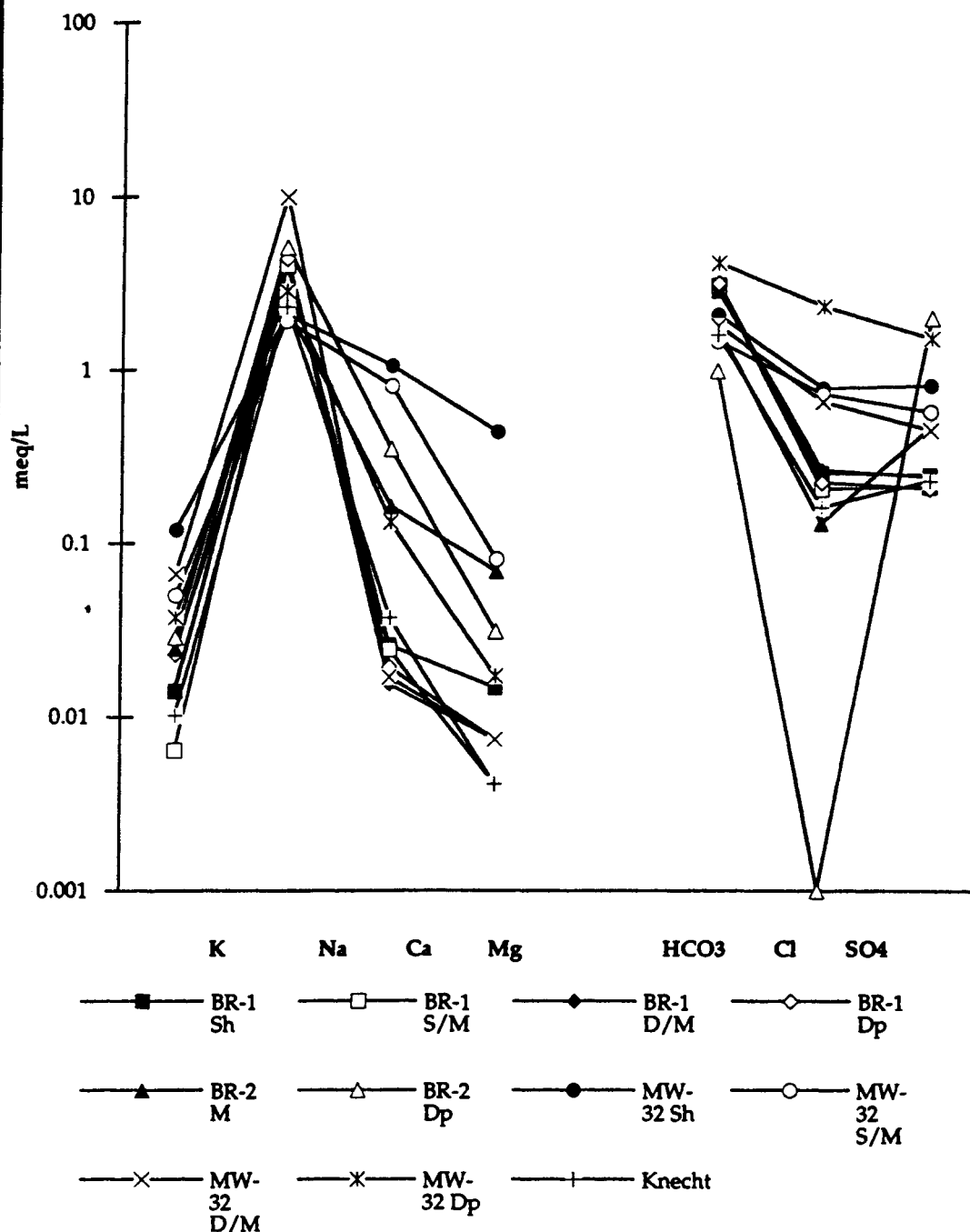


Figure 22. Fingerprint plot of Spring 1995 groundwater samples.

# **WINTER 1996 SOUTHWEST INDIAN WELLS VALLEY GROUNDWATER FINGERPRINTS**



**Figure 23. Fingerprint plot of Winter 1996 groundwater samples.**

from each round. The winter 1996 samples were fresher, had lower alkalinity values and were isotopically lighter than the spring 1995 samples. Log  $P_{CO_2}$  values ranged from -4.652 at BR-1 deep to -2.910 at MW-32 shallow-medium in the spring of 1995 (Fig. 13) and from -4.614 at BR-1 shallow to -2.627 at BR-3 shallow in the winter of 1996 (Fig.15).

**Table 7.** Comparison of average values for southwest Indian Wells Valley groundwater samples, Spring 1995 and Winter 1996.

|                    | <u>Temp</u><br>(° C) | <u>TDS</u><br>(mg/l) | <u>pH</u> | <u>Alkalinity</u><br>(mg/l) | <u>Deuterium</u><br>(‰) | <u>Oxygen-18</u><br>(‰) |
|--------------------|----------------------|----------------------|-----------|-----------------------------|-------------------------|-------------------------|
| <u>Spring 1995</u> | 25.8                 | 294                  | 8.5       | 128                         | -101                    | -12.9                   |
| <u>Spring 1996</u> | 25.4                 | 224                  | 8.9       | 106                         | -102                    | -13.5                   |

The results of tritium analyses of selected southwest Indian Wells Valley groundwater samples taken in June, 1996 are listed in Table 8.

**Table 8.** Southwest Indian Wells Valley groundwater sample tritium data.

| <u>Sample</u>       | <u>Volume</u> | <u>TU</u> | <u>eTU</u> |
|---------------------|---------------|-----------|------------|
| BR-1 Shallow        | 50 ml         | 0.00      | 2.00       |
| BR-1 Shallow/Medium | 50 ml         | 5.00      | 3.00       |
| BR-1 Deep/Medium    | 50 ml         | 2.00      | 2.00       |
| BR-2 Medium         | 50 ml         | 1.00      | 2.00       |
| BR-2 Deep           | 50 ml         | 0.00      | 2.00       |
| Genesis-1           | 1000 ml       | 0.00      | 0.08       |
| Knecht              | 1000 ml       | 0.11      | 0.10       |
| SW-3                | 1000 ml       | 0.04      | 0.09       |

#### **d. Gravity Profiles**

Figure 9 shows the location of the study's three gravity profiles with symbols marking every fifth station. The GRAV2D™ west to east subsurface profile along Bowman Road from highway 14 to Brown Road (point A to point B, Fig. 9) is shown on Figure 24. The basement drops sharply east of highway 14 and abruptly flattens toward Brown Road, consistent with the structure of a down-dropped hanging wall block of a normal fault in extensional terrain. This profile depicts the dominant, first-order structural feature of the west side of Indian Wells Valley, the Sierra Nevada Frontal Fault.

The southwest to northeast profile along the line from BR-1 to Brown Road (BR-1 to point B, Fig. 9) is illustrated in Figure 25. A second-order feature, the sharp rise in the basement evident between stations 1 and 20, peaks at approximately 1,400 feet below ground level and flattens out toward the northeast. The south to north line from BR-1 to highway 178 (BR-1 to point C on Fig. 9) displays a more subdued second-order basement feature approximately 1,700 feet below ground level at station 36 (Fig. 26). This trend may correspond with a buried nose of resistant metamorphic rocks such as those exposed in the roof pendant atop the ridge to the west-northwest between Indian Wells Canyon and Freeman Canyon (Nilsen and Chapman, 1971). At the point of intersection between the south to north line (Station 27, Fig. 9) and the west to east line (Station 21, Fig. 9), depth to basement is approximately 1,850 feet. In sections 1 and 12 of T27 R38 (Fig. 9), the depth to basement is approximately 2,100 feet. In section 7 of T27 R39 (Fig. 9), the basement is approximately 2,000 feet beneath the surface. This is the area identified by previous workers as the location of a possible groundwater flow barrier.

As described in section 2.2d, the gravity profiles were modeled with a simple density contrast of 2.35 g/cc for the aquifer sediments versus 2.67 g/cc for

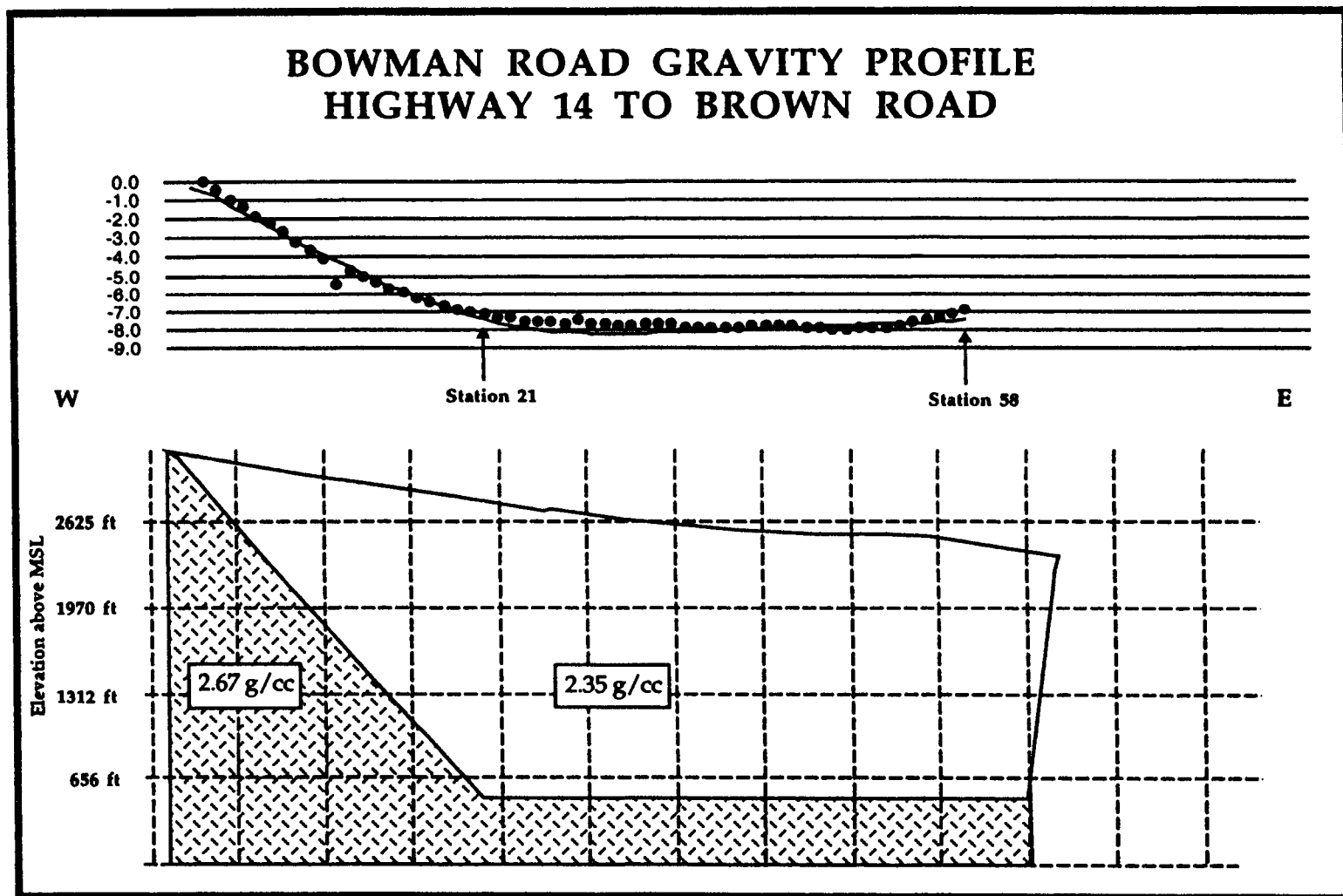
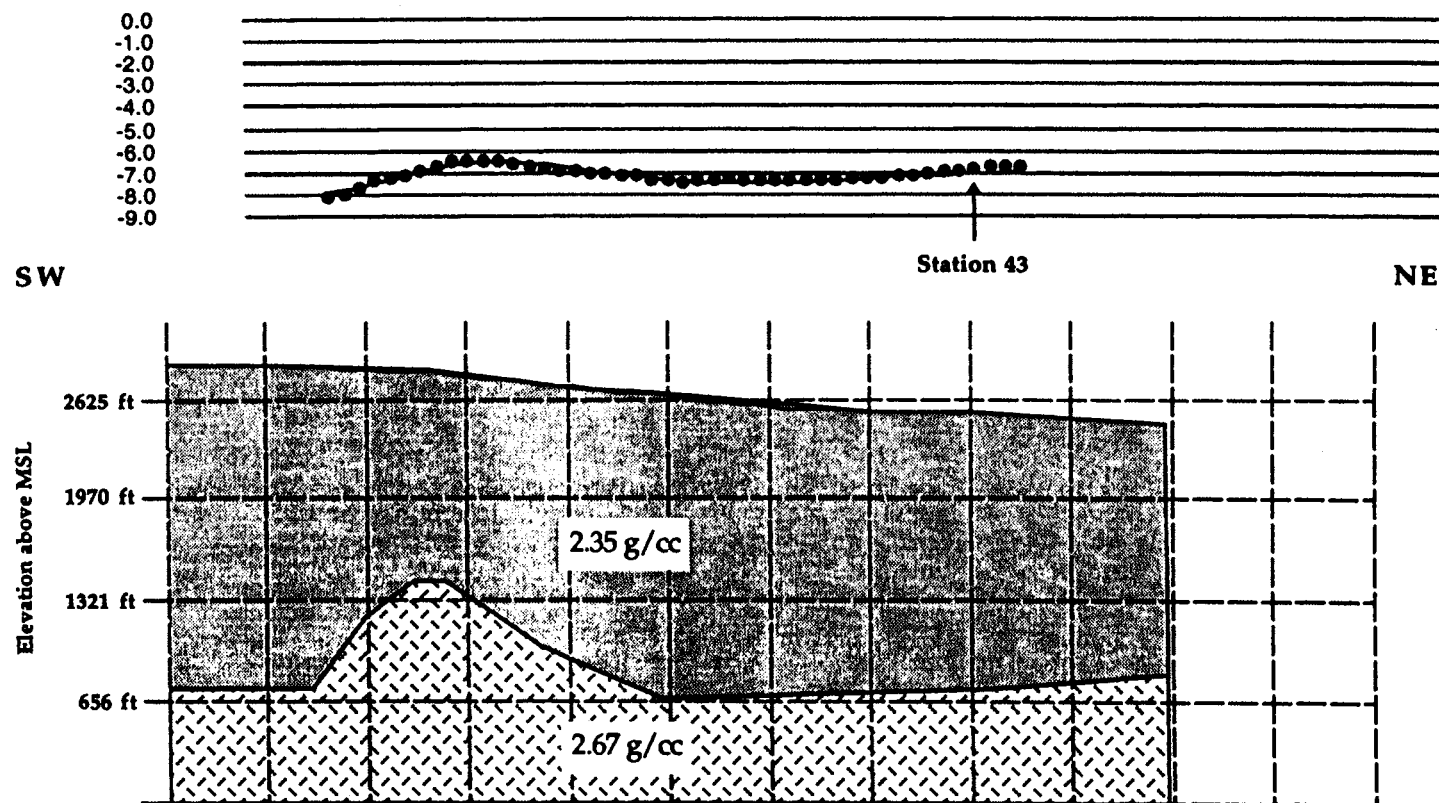


Figure 24. West to east gravity profile along Bowman Road from Highway 14 to Brown Road. Station 21 ties to Station 27 on the south to north line in Figure 26. Station 58 ties to Station 43 on Figure 25.

# **SOUTHWEST - NORTHEAST GRAVITY PROFILE BR-1 TO BROWN ROAD**



**Figure 25. Southwest to northeast gravity profile from BR-1 to Brown Road. Station 43 ties to Station 58 on the west to east line in Figure 24.**

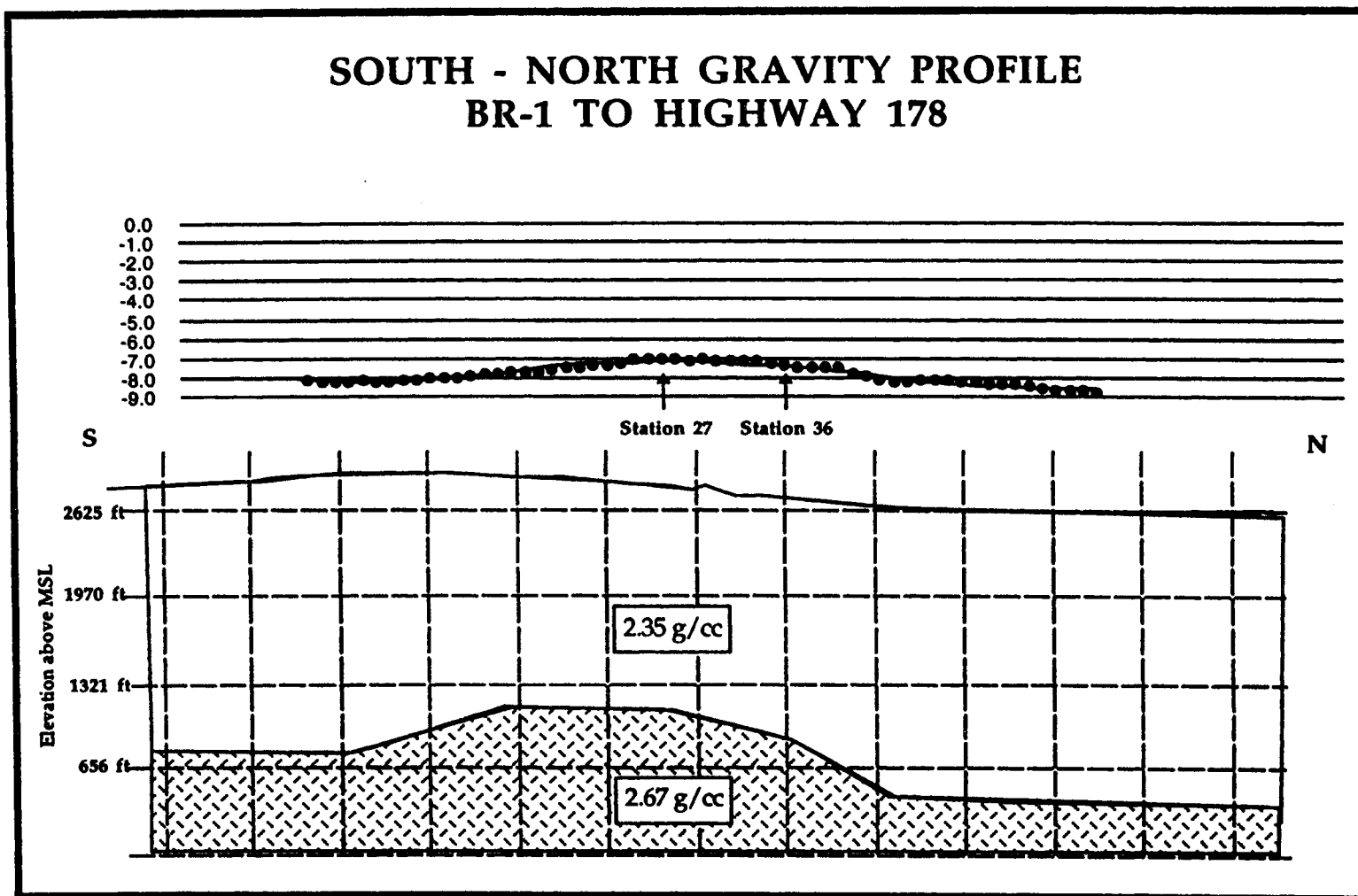


Figure 26. South to north gravity profile from BR-1 to Highway 178. Station 27 ties to Station 21 on Figure 24.

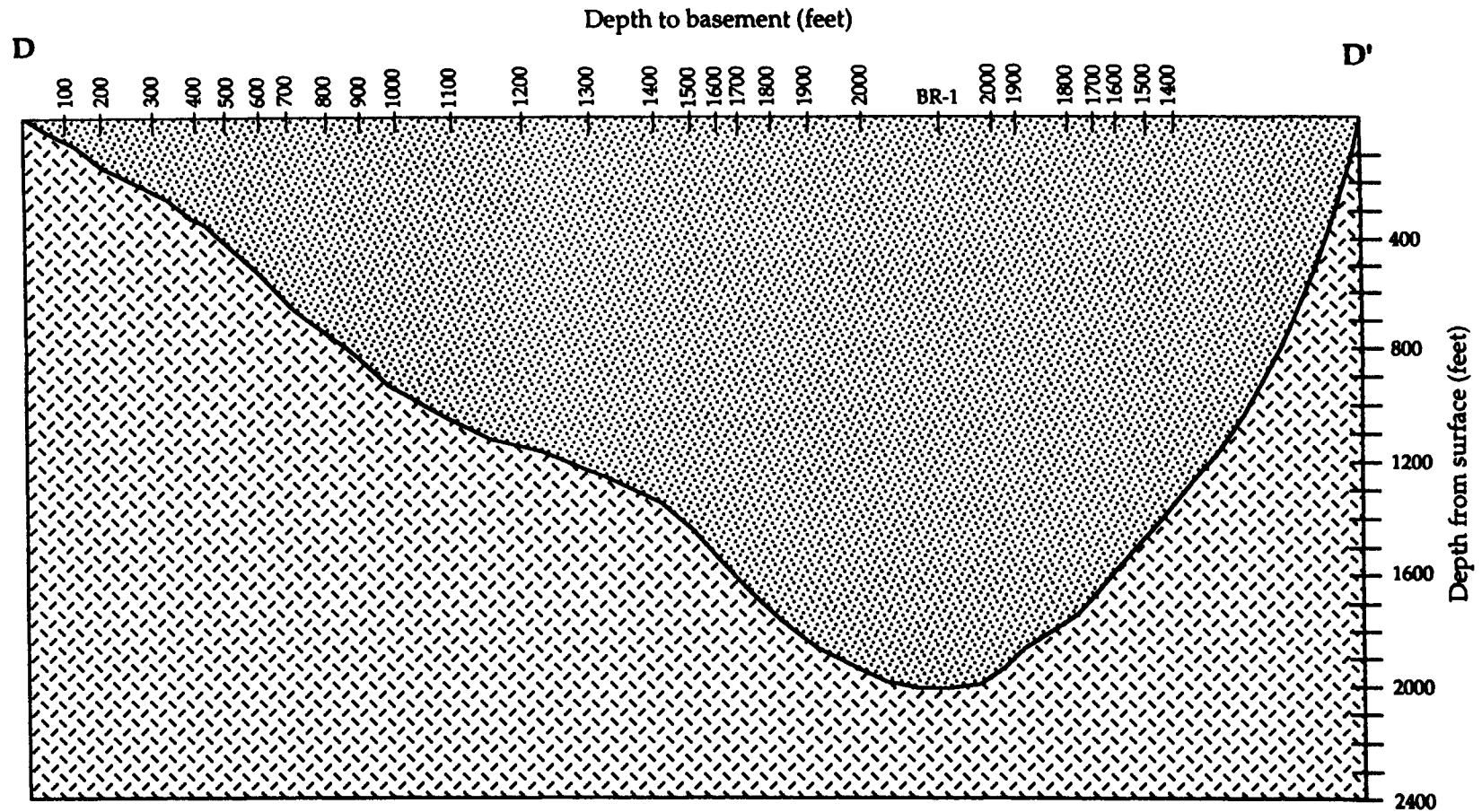
the undifferentiated basement rocks. The depth to undifferentiated basement rock may mark the top of the Ricardo Formation or, in places, the remnants of Sierran granites or metasediments, as suggested by Nilsen and Chapman (1971). If the average density of the aquifer sediments increases with depth (a likely occurrence in a natural setting), thereby reducing the density contrast, then the above estimates of depth to basement are conservative. Both the first- and second-order features in the profiles would then be at greater depths below the surface than they are depicted in this model. The deep, flat west to east profile and the lack of continuity between the two second-order features do not suggest a continuous basement lineament extending southeast across the valley, nor do they appear to represent a continuous subsurface basement high in the vicinity of the proposed groundwater flow barrier.

#### **e. Groundwater Flow Calculations**

The isopach map of the alluvium in southwest Indian Wells Valley (Fig. 9) shows the line D to D' from Freeman Junction to the Black Hills, drawn perpendicular to the direction of groundwater flow (Fig. 6). The profile along this line (Fig. 27) displays the cross-sectional area of aquifer material through which groundwater moves on its way northeast toward the playa. The location of well BR-1 is marked along the horizon of Figure 27 for reference.

Darcy's Law, expressed as  $Q = -KA \, dh/dl$ , where  $Q$  = quantity of groundwater flow,  $K$  = hydraulic conductivity,  $A$  = cross-sectional area and  $dh/dl$  = hydraulic gradient, was used to estimate flow from BR-1 to MW-32 (Fig. 9). Transmissivity values from slug tests (USBR, 1993) for each piezometer in BR-1 and MW-32 were divided by the length of their screened intervals (20 feet) to determine hydraulic conductivity in each piezometer. The average of these values (0.009 feet/minute), representing segments of the aquifer between 615 to 1920 feet, was used for the  $K$  variable. The cross-sectional area (Fig. 27) was

# CROSS-SECTION ALONG LINE D - D' SOUTHWEST INDIAN WELLS VALLEY



**Figure 27. Cross-section of alluvial fill in Southwest Indian Wells Valley between Freeman Junction and the Black Hills. Location of BR-1 is marked for reference. Vertical scale: 1 inch = 500' feet. Horizontal Scale: 1 inch = 0.5 miles.**

approximated from the isopach map data to be  $2.39 \times 10^7 \text{ ft}^2$ . The hydraulic gradient (0.013) was measured by dividing the difference between the 1996 groundwater surface elevations at BR-1 and MW-32 by the distance between the wells. Using a simple Darcy's Law calculation, groundwater flow through the southwest Indian Wells Valley alluvial aquifer from BR-1 to MW-32 (Fig. 9) is approximately 33,750 acre-feet per year, an order of magnitude greater than the recharge estimated from Sierran precipitation (Table 4). The average linear velocity ( $V_x$ ), calculated by the formula  $V_x = (-K \, dh/dl) / \text{porosity}$  (estimated at 25% for an alluvial aquifer) computes to 246 feet per year. At this rate, groundwater would travel from BR-1 to MW-32 in approximately 150 years.

### 3.3 Sierran Lineament Map and Rosette Diagrams

The large difference between the calculations for groundwater flow in the southwest and for surface recharge from the adjacent watershed, along with the differences in chemical and isotopic data, suggest extrabasinal, subsurface sources of recharge for southwest Indian Wells Valley. Geologic maps of the area were examined for faults which could promote infiltration and serve as conduits for flow. A lineament map of the southern Sierra Nevada Mountains region north and west of the study area (Fig. 28) was generated in an attempt to discern potential flowpaths for groundwater recharge to the alluvial aquifer from sources west of the surface water divide through fractured granitic rocks. Lineaments apparent on aerial and satellite photography may represent faults and fractures which are sufficiently permeable to conduct groundwater. Examination of aerial photographs and satellite imagery revealed that such lineaments are widespread throughout the region. Northwest and west northwest-trending features are predominant throughout the area extending

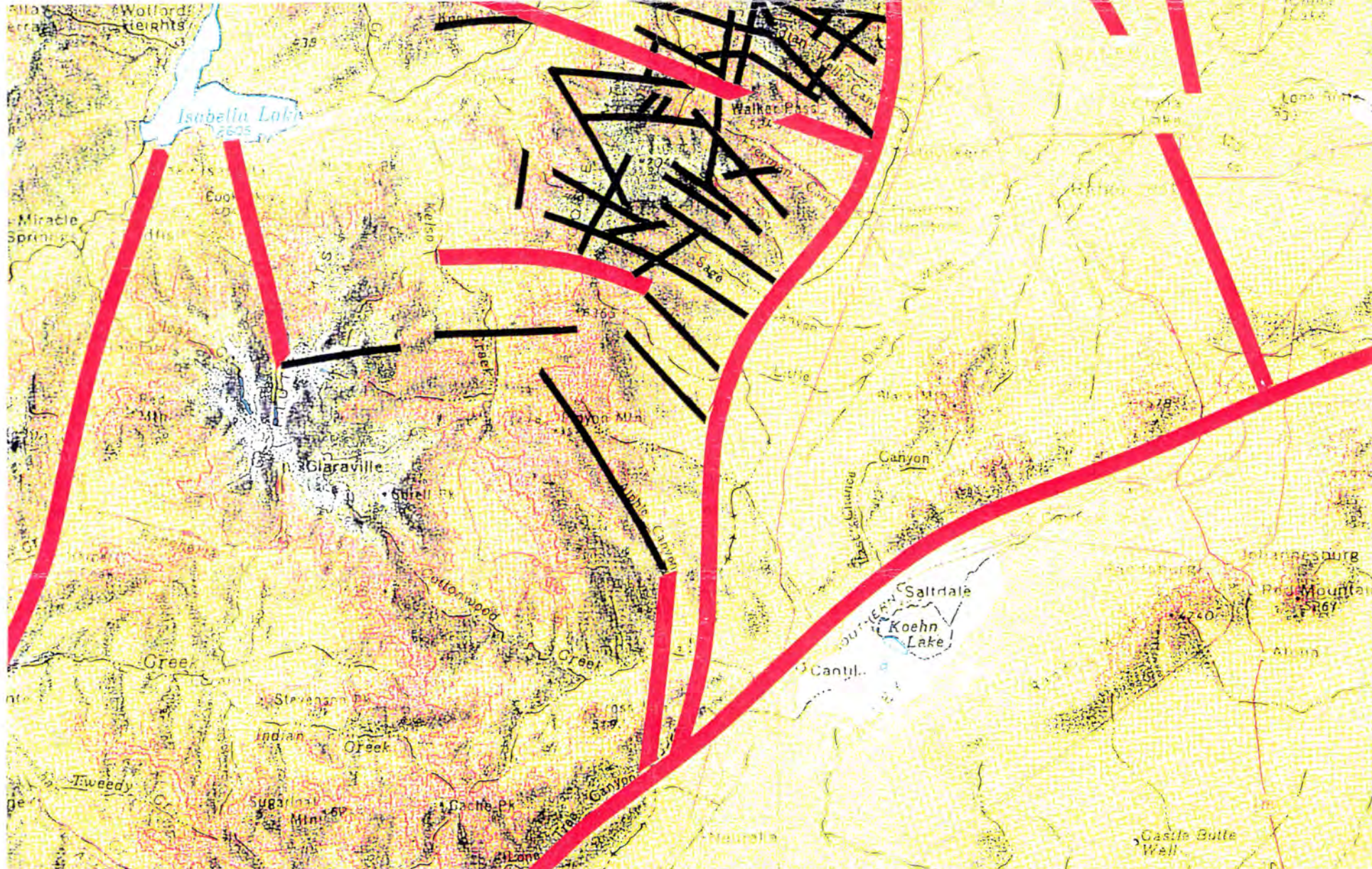
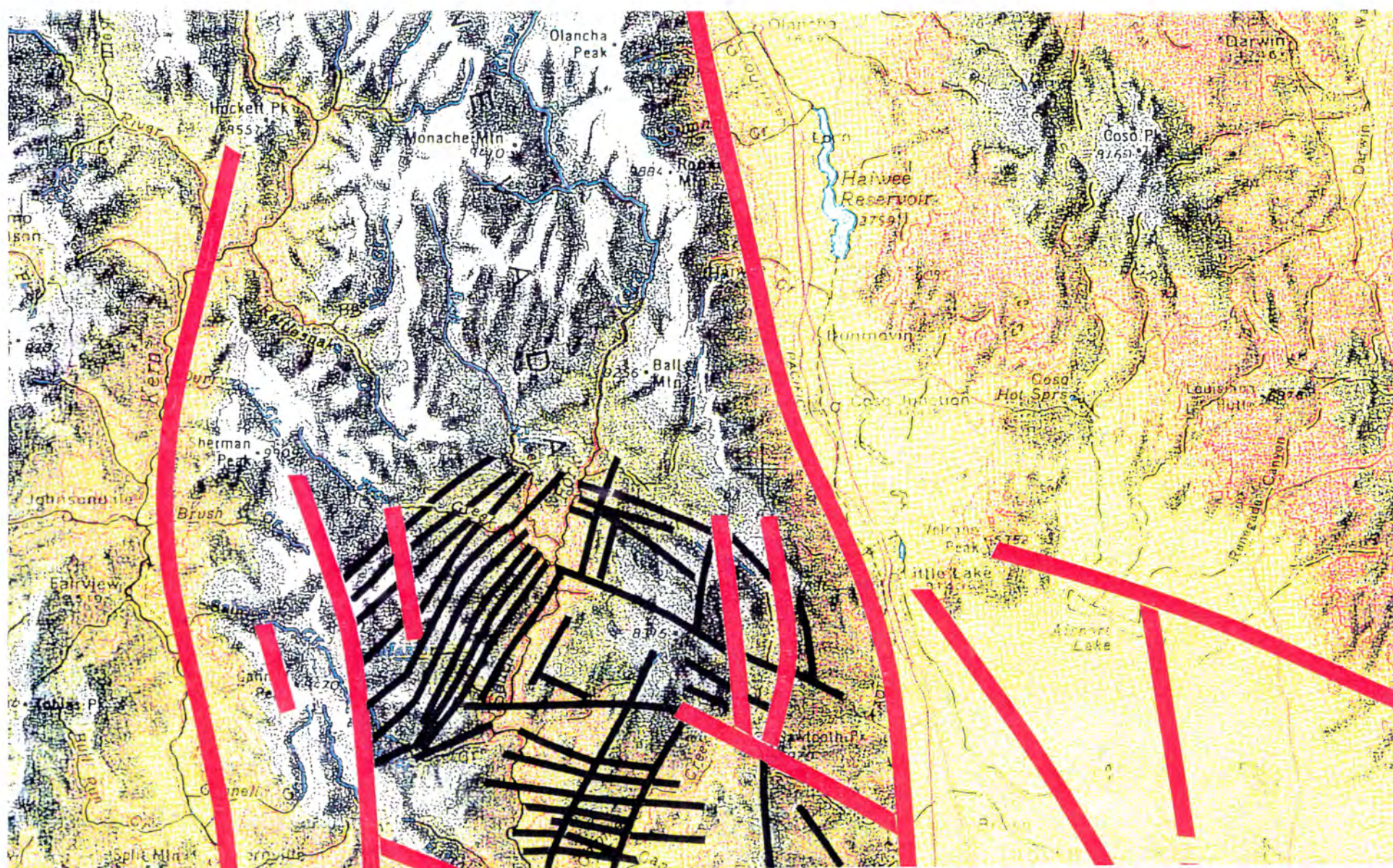


Figure 28. Lineament map of the Sierra Nevada Mountains adjacent to Indian Wells Valley. Red lines are mapped faults. Black lines are lineaments mapped from aerial photos and satellite images. Base map enlarged from the Raven 1:750,000 map of California.

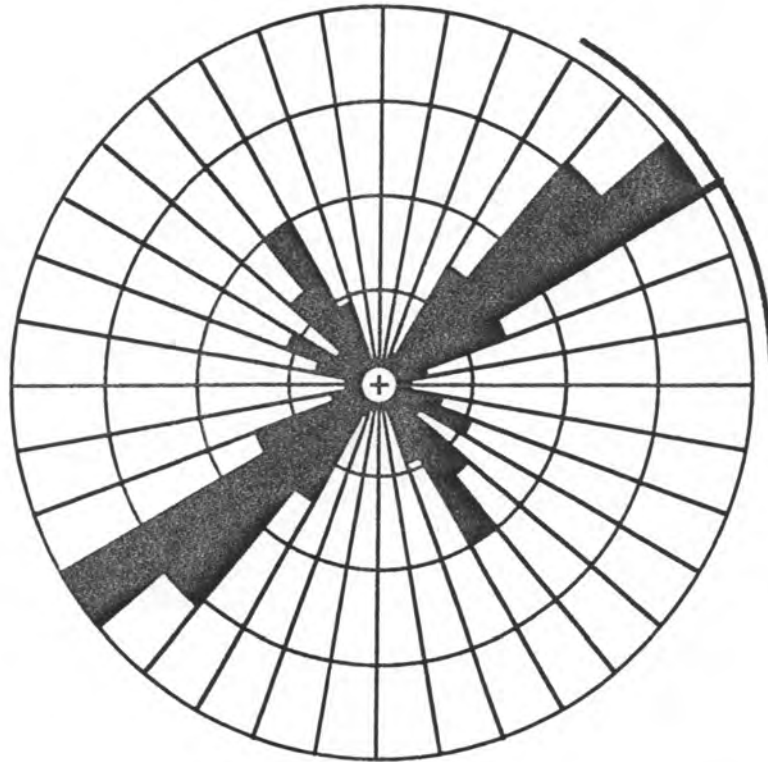


from the drainage of the South Fork of the Kern River into the eastern Sierran canyons adjacent to Indian Wells Valley. North-trending lineaments are also visible in the aerial photos and satellite images. A chaotic swarm of northeast-trending fractures parallels the South Fork in the Rockhouse Basin area. Most significantly, the mapped Pinyon Peak Fault appears to connect the Durrwood Fault (Fig. 2) to Walker Pass and Freeman Canyon, providing an important potential flowpath by which Kern Plateau precipitation could reach the Indian Wells Valley aquifer. Northwest and west northwest lineaments parallel or dissect Freeman Canyon and all of the canyons in the southwest Indian Wells Valley study area.

Strike and dip measurements were taken on fracture sets in each canyon to spot check for possible correlations with the lineament map. Rosette diagrams were prepared from each canyon's data set. Indian Wells Canyon projections (Fig. 29), display dominant N50°E and N40°W trends. The lineament map includes northwest and northeast trending features that match the field data. Freeman Canyon, Cow Heaven Canyon, Boulder Canyon and Bird Spring Canyon projections also show good data correlation (Appendix 4). Indian Wells, Sage and Horse Canyons share very similar vector means of about N50°E-N60°E while vector means for Freeman, Cow Heaven, Boulder and Bird Spring Canyons range from N40°W-N70°W. Lineaments on the map correspond with fracture sets observed to conduct water in Indian Wells, Freeman, Cow Heaven, Sage and Bird Spring Canyons.

#### 4. DISCUSSION

Existing groundwater models for Indian Wells Valley were constructed without benefit of data from the USBR report (1993), the Houghton thesis (1994)



| Indian Wells Canyon Fracture Data Set               | Statistics          |
|-----------------------------------------------------|---------------------|
| N = 102                                             | Vector Mean = 58.9  |
| Class Interval = 10 degrees                         | Conf. Angle = 28.50 |
| Maximum Percentage = 21.6                           | R Magnitude = 0.271 |
| Mean Percentage = 6.25    Standard Deviation = 5.73 | Rayleigh = 0.0005   |

**Figure 29. Rosette diagram of fracture orientations measured in Indian Wells Canyon.**

or recharge and hydrogeochemical data from the conventional surface drainage area. As such, the models are incomplete and in need of revision. This study followed many of the recommendations of previous workers and contributes new information for future models directed toward understanding the source and quantity of recharge in the southwest part of the basin.

#### **4.1 Southern Sierra Nevada Recharge Data**

##### **a. Quantity of Recharge**

To estimate the amount of recharge to southwest Indian Wells Valley from the conventional surface drainage area in the southern Sierra Nevada, precipitation was measured at 500-foot intervals above 4,000 feet in Freeman Canyon (Figs. 10 and 11) and adjusted for evapotranspiration using the Maxey-Eakin method. In 1994-95, recharge was 4,125 acre-feet  $\pm$  1,815 acre-feet; in 1995-96, it was 924 acre-feet  $\pm$  407 acre-feet. There are no other published precipitation data for the study area to use for comparison purposes. The closest California Department of Water Resources snow gaging station is located at Beach Meadow (Fig. 1), north and west of the study area on the Kern Plateau, at an elevation of 7,650 feet. Snow water content data for this station are available from 1930 to the present (California Department of Water Resources, 1996). The historical average of April 1 snow water content is 8.9 inches at Beach Meadow. The April 1, 1995 snow water content was 14.5 inches and the April 1, 1996 snow water content was 9.8 inches. Using the methods described in section 2.1b, projected values for precipitation at 7,650 feet in Freeman Canyon were 22.7 inches in 1994-95 and 15.8 inches in 1995-96. By this analysis, the upper elevation recharge estimates for this study may be inflated. The Bloyd and Robson (1971) figure of 2,870 acre-feet per

year also appears to be too high for an average recharge estimate from the conventional surface drainage area for southwest Indian Wells Valley.

#### **b. Sources and Flowpaths of Sierra Nevadan Recharge**

In the discussion of groundwater flowpaths that follows, the term *mixing* is used in the generic sense to indicate a combination of two or more sources of water. It is not intended to convey a mathematical relationship or a quantitative ratio between chemical constituents or water types.

The stable isotopes of hydrogen (deuterium) and oxygen (oxygen-18) are commonly used to trace sources and flowpaths of groundwater (Mazor, 1991). By laboratory analysis with a mass spectrometer, the composition of a sample can be determined and compared to Standard Mean Ocean Water (SMOW). Deviations from SMOW are expressed as  $\delta D\text{‰}$  for deuterium and  $\delta^{18}O\text{‰}$  for oxygen-18. If the sample contains less deuterium or less oxygen-18 than SMOW, it will be assigned a negative value by the formulas:

$$\delta D\text{‰} = 1000 \times [(D/H)_{\text{sample}} - (D/H)_{\text{SMOW}}] / (D/H)_{\text{SMOW}}$$

and

$$\delta^{18}O\text{‰} = 1000 \times [(^{18}O-^{16}O)_{\text{sample}} - (^{18}O-^{16}O)_{\text{SMOW}}] / (^{18}O-^{16}O)_{\text{SMOW}}.$$

The major factor affecting the composition of the sample in this setting is elevation. Stable isotopes fractionate during condensation, becoming enriched in the heavier hydrogen and oxygen molecules at lower elevations (Mazor, 1991). This occurrence is expressed in more positive values for  $\delta D$  and  $\delta^{18}O$ . The higher the elevation is at the source of the sample, the more negative are the isotope values. Deuterium data are more reliable than oxygen-18 in determining recharge elevations because oxygen is abundant in most rocks while the amount of hydrogen is low (Drever, 1988). After the precipitation infiltrates, the oxygen isotope values may be modified by exchange reactions, but deuterium values are, in most cases, conservative.

Stable isotope data from the precipitation samples collected in Freeman Canyon (Fig. 7) demonstrated the elevation effects described in the above discussion. The precipitation became more enriched in both deuterium and oxygen-18 (values became more positive) as elevation decreased toward 4,000 feet. Deuterium ranged from -77‰ at 6,500 feet to -58‰ at 4,000 feet; oxygen-18 ranged from -8.9‰ at 6,500 feet to -6.3‰ at 4,000 feet. These data were consistent in both the water years studied for this report.

The samples of stream and spring water, however, displayed more negative values than the precipitation samples. The lighter deuterium values in the surface samples (average: -91‰) indicate precipitation that fell at elevations ranging from 7,000 to 9,000 feet, based on the gage data and comparison with Sierran snow core samples from Friedman and Smith (1972). Some mixing with surface runoff may have occurred when the water emerged from the ground in the springs and streams. The fact that no surface or well water was found which matched the isotopic values of the lower elevation precipitation samples supports the Maxey-Eakin (1951) hypothesis that the vast majority of this water evapotranspires without contributing to groundwater recharge. Figure 30 shows the stable isotope data relative to the continental northern hemisphere meteoric water line from Dansgaard (1964).

Based on the analyses of the forty-five surface samples collected for this investigation, there appear to be two groups of water in the springs and streams of the study area. Group I, a  $\text{Ca-Na-HCO}_3\text{-SO}_4$  water, was sampled from springs associated with fractured granite and had an average total dissolved solids concentration of 261 mg/l, an average field alkalinity of 189 mg/l and an average deuterium signature of -95‰. Group II is a  $\text{Ca-Na-HCO}_3\text{-SO}_4$  water, sampled from streams and dike-associated springs, with averages of 585 mg/l total dissolved solids, 289 mg/l field alkalinity and -91‰ deuterium.

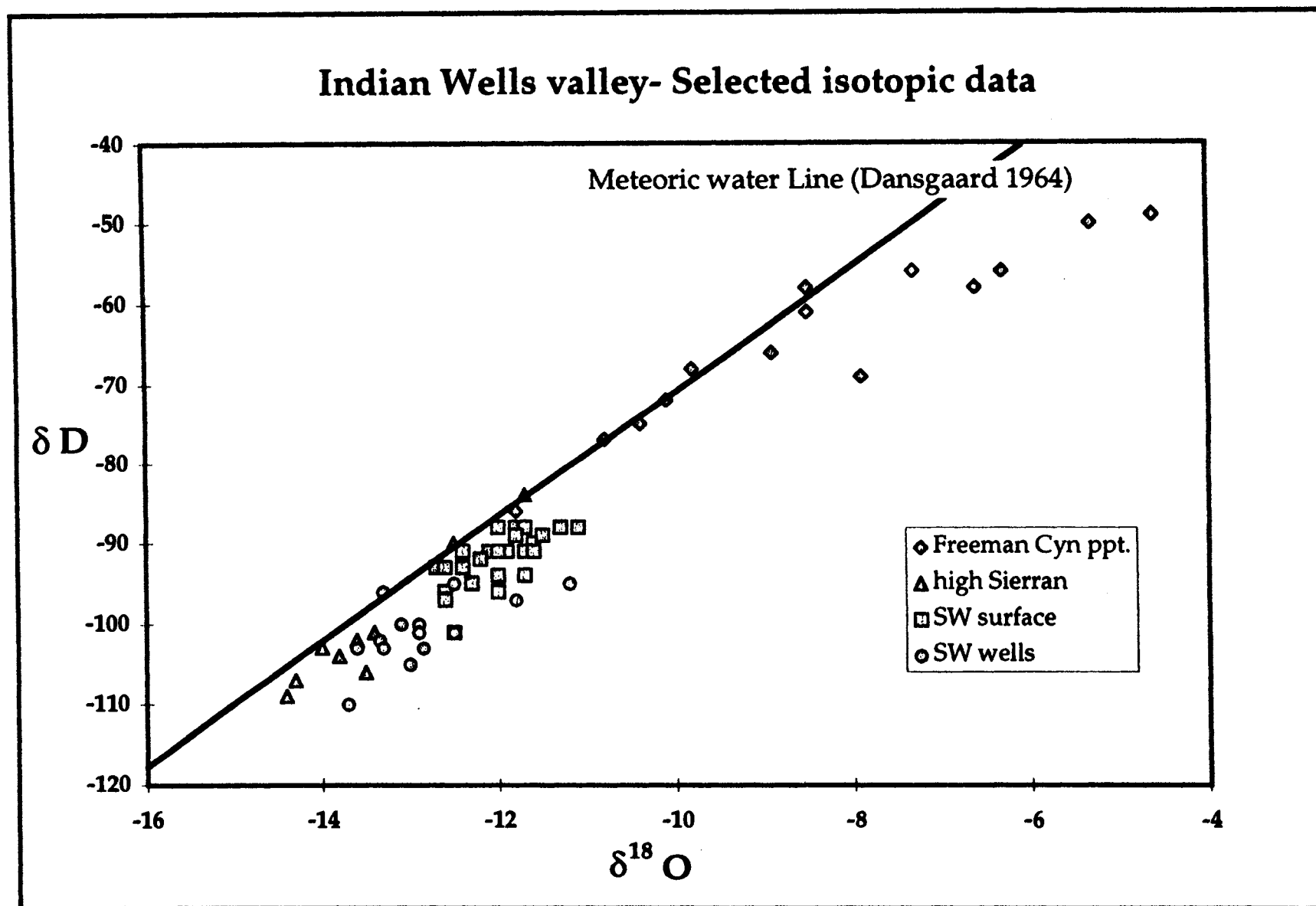


Figure 30. Plot of selected stable isotope data for the study area.

Group I water is interpreted to be derived from both horizontal and vertical fractures in the Sierran granite, with little history of contact with alluvial material, surface runoff or the atmosphere prior to its emergence at the springs. Its recharge elevation is thought to be between 7,000 and 9,000 feet, based on comparison between its deuterium and oxygen-18 values and snow core data from Friedman and Smith (1972). The lower TDS and alkalinity values suggest less rock/water interaction than the Group II waters. Group I water was collected from seven different springs in the study area. The number of analyses for each location (Fig. 7) is indicated in parentheses: Walker Pass Spring (3), Big Spring (1), Cow Heaven Canyon Spring (2), McIvers Spring (2), Sage Canyon Spring (1), Sage Canyon Spring A (1) and Bird Spring (3).

Group II is interpreted to be a combination of Group I fracture-associated water, surface runoff, snowmelt and water that has been in contact with metasedimentary roof pendant material. This water is found in the stream samples, in stream-bed springs that rise to the surface due to downstream damming by low-conductivity dikes and in lower elevation springs close to weathered igneous and metasedimentary outcrops. The greater dissolved solids concentration in Group II waters is due to rock-water interactions brought about by the dissolution of surface detritus, stream-bed gravel and highly mineralized contact metamorphic rocks. The higher alkalinities indicate hydrolysis reactions along the flowpath as the silicate minerals decompose. The recharge elevation is masked by mixing, but the source may be a combination of waters from 6,000 to 8,000 feet, based on the more concentrated deuterium signatures. Group II water (Fig. 7) was collected from Indian Wells Canyon Mine Spring (2), Indian Wells Canyon Stream (2), Three Pines Canyon Spring (1), Buena Vista Canyon Spring (1), Soldier Spring (2), Boulder Canyon Spring (2), Sage Canyon Stream (2), Sage

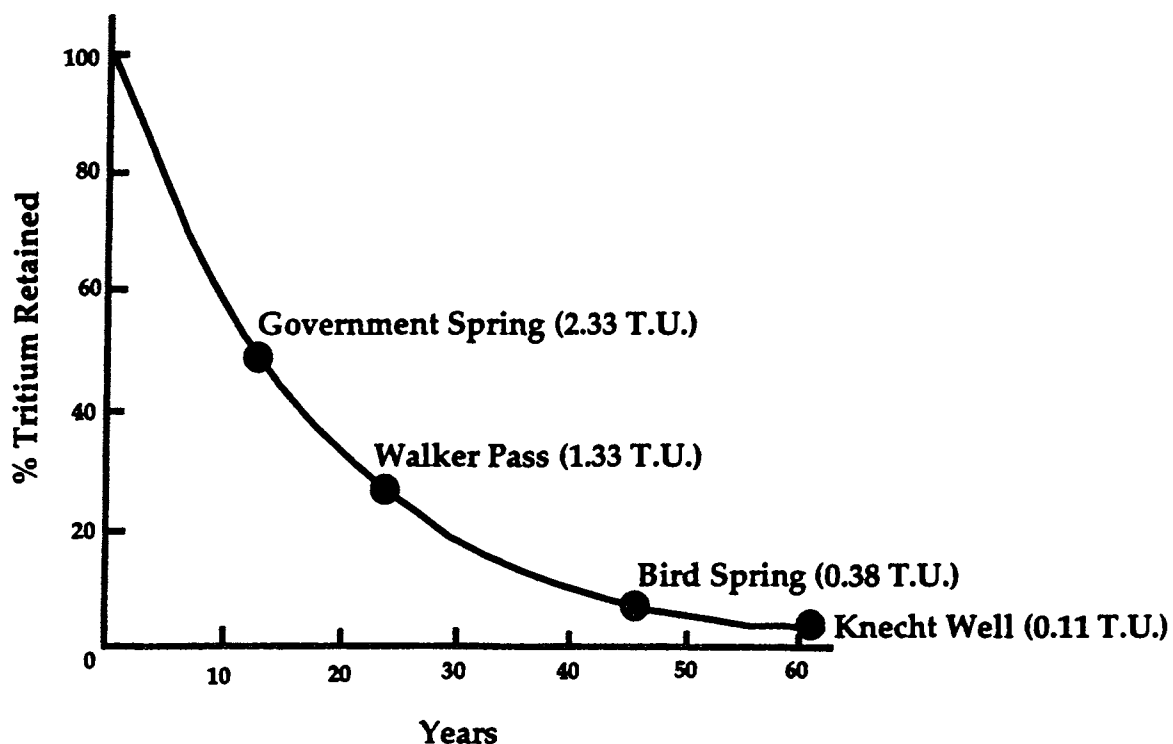
Canyon Spring D (1), Yellow Jacket Spring (1), Horse Canyon Spring (1), Horse Canyon Well (2) and Dove Spring (1).

### c. Age Dates of Surface Samples

The tritium method for dating groundwater was discovered as a result of post-World War II weapons research. Above-ground hydrogen bomb testing introduced anomalously high concentrations of tritium into the atmosphere beginning in 1952 and ending in 1963. Before testing, background tritium values in groundwater were approximately 5 TU (Mazor, 1991). Concentrations peaked at more than 10,000 TU in 1963 and have steadily decreased. An effective age of a groundwater sample can be derived from the rate of radioactive decay of tritium and a measure of its concentration in the sample. Mazor (1991) warned that "complicated mixing takes place in each aquifer, and the mode and extent of mixing of each year's recharge with that of previous years' recharge is unknown. Hence, age determinations accurate to the year are impossible and of no meaning to groundwater studies. However, semi-quantitative dating is possible and very informative." Figure 31 shows the decay curve for tritium from Mazor (1991) and general age estimates for a range of concentrations.

Enriched tritium analyses were conducted by the University of Miami Tritium Laboratory on 1,000-ml samples taken from the South Fork of the Kern River near Onyx, Government Springs at South Kennedy Meadows, Indian Wells Canyon Mine Spring, Walker Pass Spring, Big Spring, McIvers Spring and Bird Spring (Fig. 7 and Fig. 32). The June, 1996 sample from the South Fork of the Kern River, presumably fresh snowmelt, registered 5.37 TU. If this reading represents the current concentration of tritium in the atmosphere, it suggests that most of the bomb tritium has dissipated.

By the parameters given in Figure 31, Bird Spring water, at 0.38 TU, has a pre-1952 date. Assuming the pre-1952 tritium concentration was 5 TU, then 7.6%



**Tritium Concentration (T.U.)**

T.U. < 0.5

T.U. > 10

0.5 < T.U. < 10

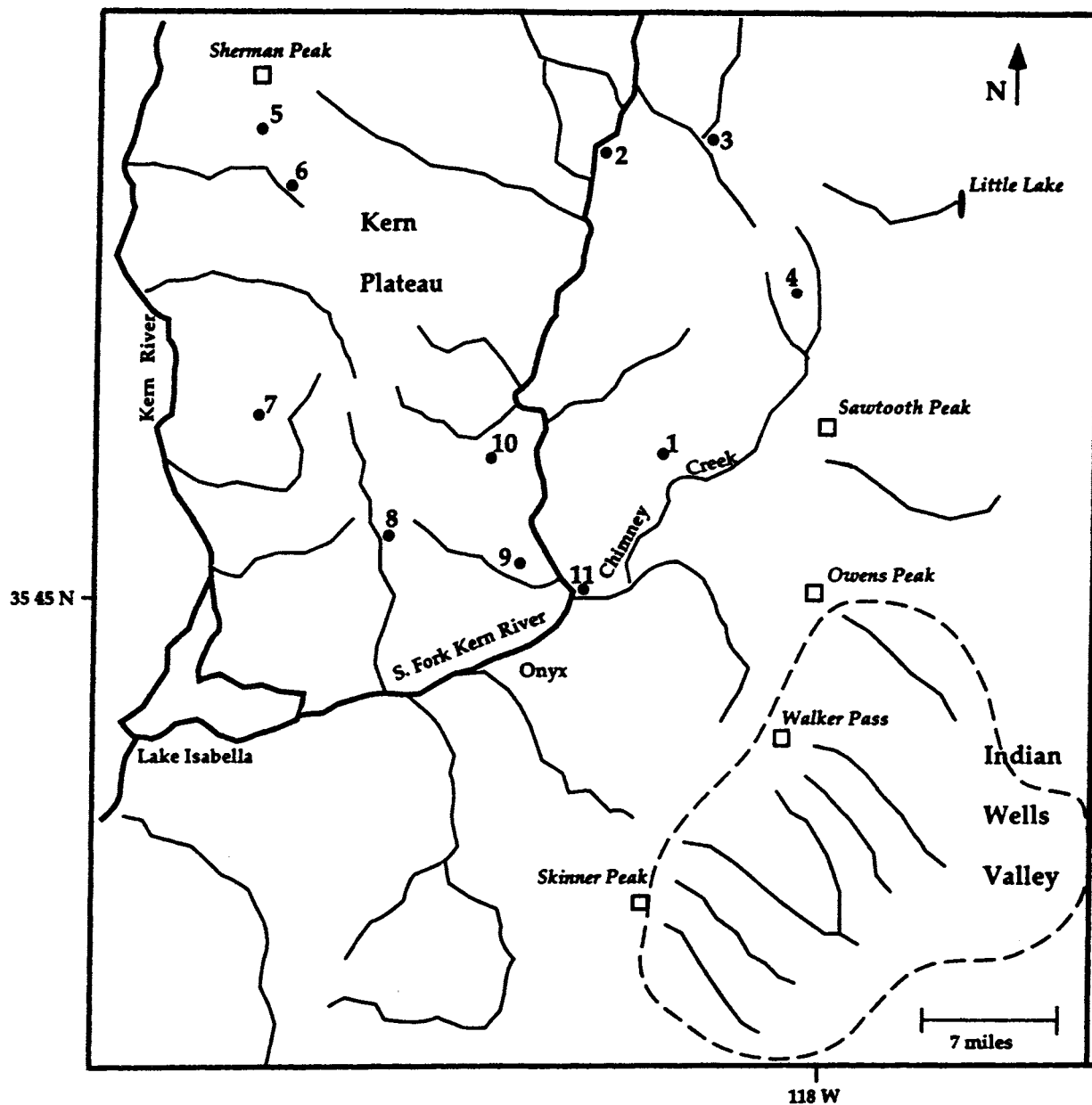
**General Age**

pre-1952

post-1952

mixture of pre-1952 and post-1952

**Figure 31. Radioactive decay curve for tritium after Mazor (1991) (assumes a pre-bomb background concentration of 5 T.U.). Four samples are plotted. Government Spring is in South Kennedy Meadows on the Kern Plateau. Walker Pass and Bird Springs are Group I samples in the conventional recharge area. The Knecht well is in southwest Indian Wells Valley.**



**Figure 32. Location map for unconventional recharge area surface samples. Study area is indicated by dashed line.**

- |                                              |                             |
|----------------------------------------------|-----------------------------|
| 1. Bigfoot Spring                            | 6. Mosquito Meadow Spring   |
| 2. S. Kennedy Meadows<br>(Government Spring) | 7. Cannell Meadows Spring   |
| 3. Sacatar Canyon Spring                     | 8. True Meadow Spring       |
| 4. Edgar's Spring                            | 9. Bartolas Country Spring  |
| 5. Round Meadow Spring                       | 10. Taylor Meadow Spring    |
|                                              | 11. Bloomfield Ranch Spring |

of the original amount of tritium remains in the sample. Plotting 7.6% on the decay curve yields an approximate age of 46 years for the Group I water in Bird Spring.

## **4.2 Southwest Indian Wells Valley Groundwater**

### **a. Quantity of Southwest Groundwater Flow**

Darcy's Law was used to estimate a groundwater flux of 33,750 acre-feet per year through the southwest Indian Wells Valley aquifer from BR-1 to MW-32. The gradient has been well-established from monitoring records of the USBR (1993), the Kern County Water Agency and this study. The gravity profiles and the isopach map from this study furnished a working cross-sectional area for the calculation. Pneumatic slug tests described by the USBR (1993) provided the hydraulic conductivity data. The large discrepancy between the calculated Maxey-Eakin surface recharge (4,125 acre-feet/year) and the calculated Darcy's Law flux through the southwest aquifer (33,750 acre-feet/year) suggests either a) most of the groundwater in the southwest basin is derived from outside the conventional surface drainage area or b) a low-conductivity flow barrier causes an increased gradient through the area. However, a low-conductivity feature has not been defined by field evidence.

The argument for a large flux of groundwater from the southwest appears to hinge upon the conductivity variable in the Darcy equation. To date, there are only three available sources of hydrogeological data that pertain to the permeability of the aquifer sediments. One is the pneumatic slug tests performed on the USBR wells. The second is a 24-hour pump test conducted by Krieger and Stewart Engineering Consultants on the southwest Test Well (TW-1) in June, 1989. The third source is a 21-day pump test at TW-1 by Krieger and Stewart in

the Fall of 1996. TW-1 is located approximately 0.6 miles east of the center of section 7 of T27 R39, in the vicinity of the proposed flow barrier (Fig. 8). None of these data sets supports the presence of a low-conductivity groundwater flow barrier.

Each of the USBR piezometers is screened over a twenty-foot interval that was selected from the electric log data on the basis of its potential for good production. There may be large portions of the southwest aquifer with hydraulic conductivities both lower and higher than the mean slug test value measured from these intervals. Values for K ranged from 0.0002 feet per minute to 0.016 feet per minute, with an average of 0.009 feet per minute. In order for the flux to match an estimated 1994-95 surface drainage recharge of 4,125 acre-feet, the conductivity variable in the Darcy equation must be an order of magnitude smaller than 0.009 feet per minute.

In the 1989 aquifer test, TW-1 was pumped at 3,000 gallons per minute for 24 hours. Drawdown was monitored at SW-1, SW-2 and SW-3 (Fig. 8). Krieger and Stewart (1989) postulated semi-confining conditions below 600 feet based on initial drawdown data. Using both the Jacob straight line method for non-leaky aquifers and the Hantush inflection point method for leaky aquifers, transmissivity was calculated at approximately 293,000 gallons per day per foot. This corresponds to a hydraulic conductivity of 0.068 feet per minute, nearly an order of magnitude greater than the average slug test value.

The rate of drawdown decreased to what Krieger and Stewart (1989) described as "quasi-equilibrium" status in the course of the 24-hour pump test. In this short time period, irrefutable steady state conditions cannot be determined, but the retarded drawdown rate in the latter stages of the test (Fig. 33) indicated a recharge boundary rather than a flow barrier (Fetter, 1994). The data set from Krieger and Stewart is included in Appendix 5. The Fall 1996 preliminary test

INDIAN WELLS VALLEY WATER DISTRICT  
SOUTHWEST WELL FIELD  
MONITORING WELL 1-ACTUAL DRAWDOWN

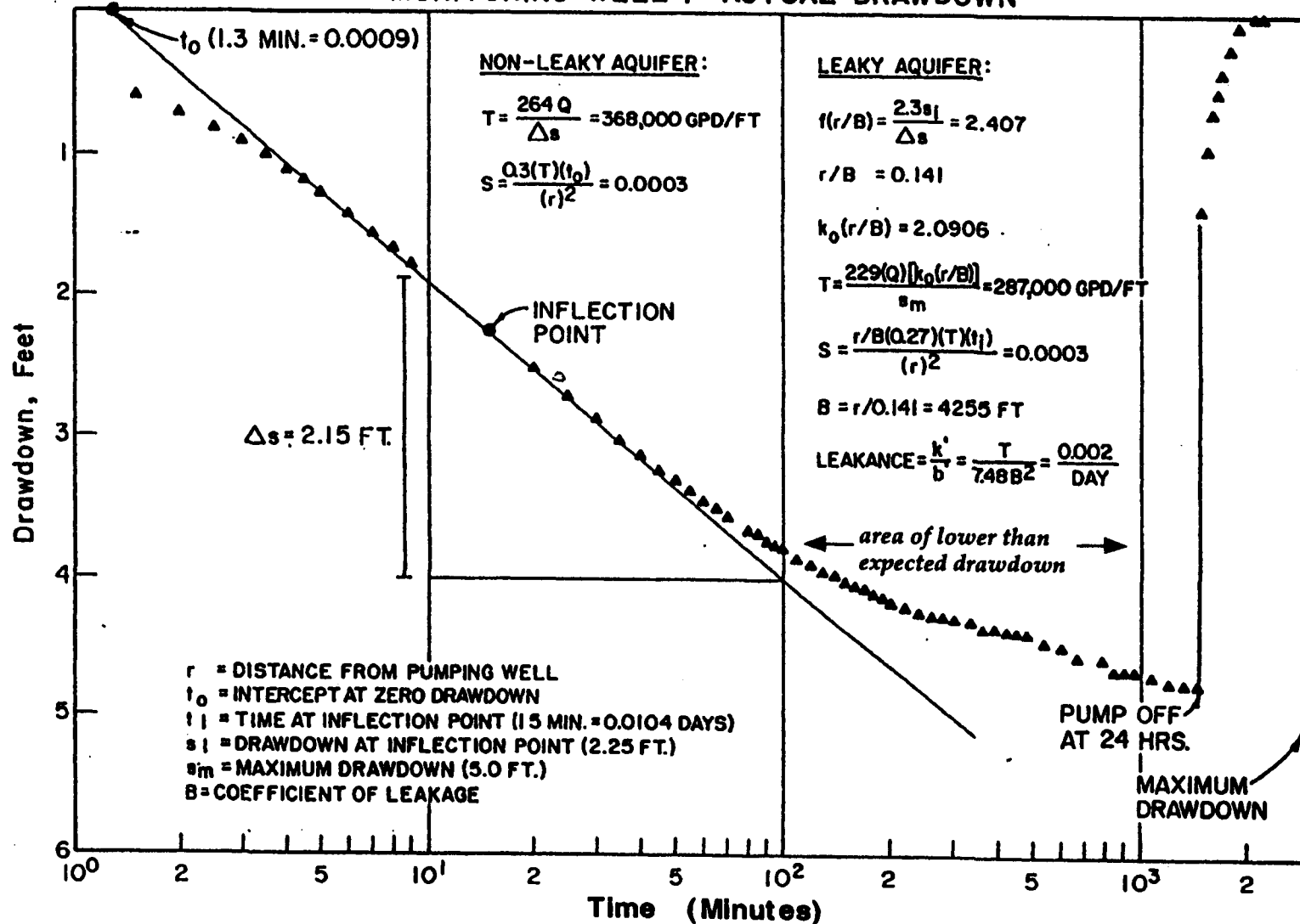


Figure 33. Krieger & Stewart drawdown curve for 1989 pump test at TW-1 (Krieger and Stewart, 1989).

results suggested a transmissivity of approximately 300,000 gallons per day per foot, according to a February, 1997 Krieger and Stewart memorandum to the water district.

The low hydraulic conductivity flow barrier proposed by previous workers is not necessary to explain the basin's steep groundwater gradient. As shown on the isopach map (Fig. 9), the cross-sectional area of the valley expands northeast of the Freeman Junction area parallel to line D-D'. Given constant values for Q and K in Darcy's equation, as the cross-sectional area increases, the gradient must decrease. This relationship is illustrated by the steep gradient between BR-1 and the Inyo well and the flat gradient between the Inyo well and MW-32.

The case for a smaller flux in the southwest, i.e. a flux more in proportion to the estimated amount of available surface recharge, requires speculation about the stratigraphy between BR-1 and TW-1. It is doubtful that any significant lacustrine clay deposits from a Lake China highstand reached this area (Berenbrock and Schroeder, 1994). A more likely scenario for fine-grained sedimentation would be an overlapping series of poorly-sorted mudflows from Pleistocene Freeman Canyon floods. Another possibility might be Tertiary volcanic ash flows from the Black Hills. However, there is not enough electric log data and no shallow seismic data in the literature that would support either of these these hypotheses.

#### **b. Sources and Flowpaths of Groundwater**

Table 9 compares the mean temperature, TDS, pH, alkalinity, deuterium and oxygen-18 values for groundwater from wells and piezometers sampled for this investigation with the Kern Plateau, Group I and Group II surface waters. The basin water type is Na-HCO<sub>3</sub> and the Kern Plateau Group I and Group II Sierran waters are both Ca-Na-HCO<sub>3</sub>-SO<sub>4</sub>. These analyses indicate that southwest Indian Wells Valley groundwater is fresher than the Group II waters in the

conventional watershed and may be derived from a different source. It has many similarities to Kern Plateau and Group I fracture-associated water.

**Table 9.** Comparison of southwest wells, Kern Plateau, Group I and Group II chemistry data.

| <u>Temperature</u><br>(° C) | <u>TDS</u><br>(mg/l) | <u>pH</u> | <u>Alkalinity</u><br>(mg/l) | <u>Deuterium</u><br>(‰) | <u>Oxygen-18</u><br>(‰) |
|-----------------------------|----------------------|-----------|-----------------------------|-------------------------|-------------------------|
| Southwest Wells:            |                      |           |                             |                         |                         |
| 25.9                        | 241                  | 8.5       | 119                         | -102                    | -13.3                   |
| Kern Plateau:               |                      |           |                             |                         |                         |
| 19.1                        | 195                  | 7.2       | 144                         | -102                    | -13.3                   |
| Group I:                    |                      |           |                             |                         |                         |
| 17.4                        | 261                  | 7.5       | 189                         | - 95                    | -12.3                   |
| Group II:                   |                      |           |                             |                         |                         |
| 17.5                        | 585                  | 7.6       | 289                         | - 91                    | -12.0                   |

The change in composition from Ca-Na-HCO<sub>3</sub>-SO<sub>4</sub> water to Na-HCO<sub>3</sub> water can be explained by the exchange of calcium and magnesium cations for sodium cations along the flowpath. Clays present in the alluvium due to the weathering of Sierran feldspars and abundant detrital magnetite provide surfaces for these exchanges to occur. Continuous exchange reactions between the groundwater, fracture surfaces and basin alluvium could result in the Na-HCO<sub>3</sub> water type and the higher pH seen in the samples from BR-1 shallow, medium-shallow, deep-medium and deep; SW-3; the Knecht well; BR-2 medium and deep; BR-3 shallow; MW-32 shallow, medium-shallow, deep-medium and deep. Figure 34 shows the effect of exchanging 90% of the Ca and

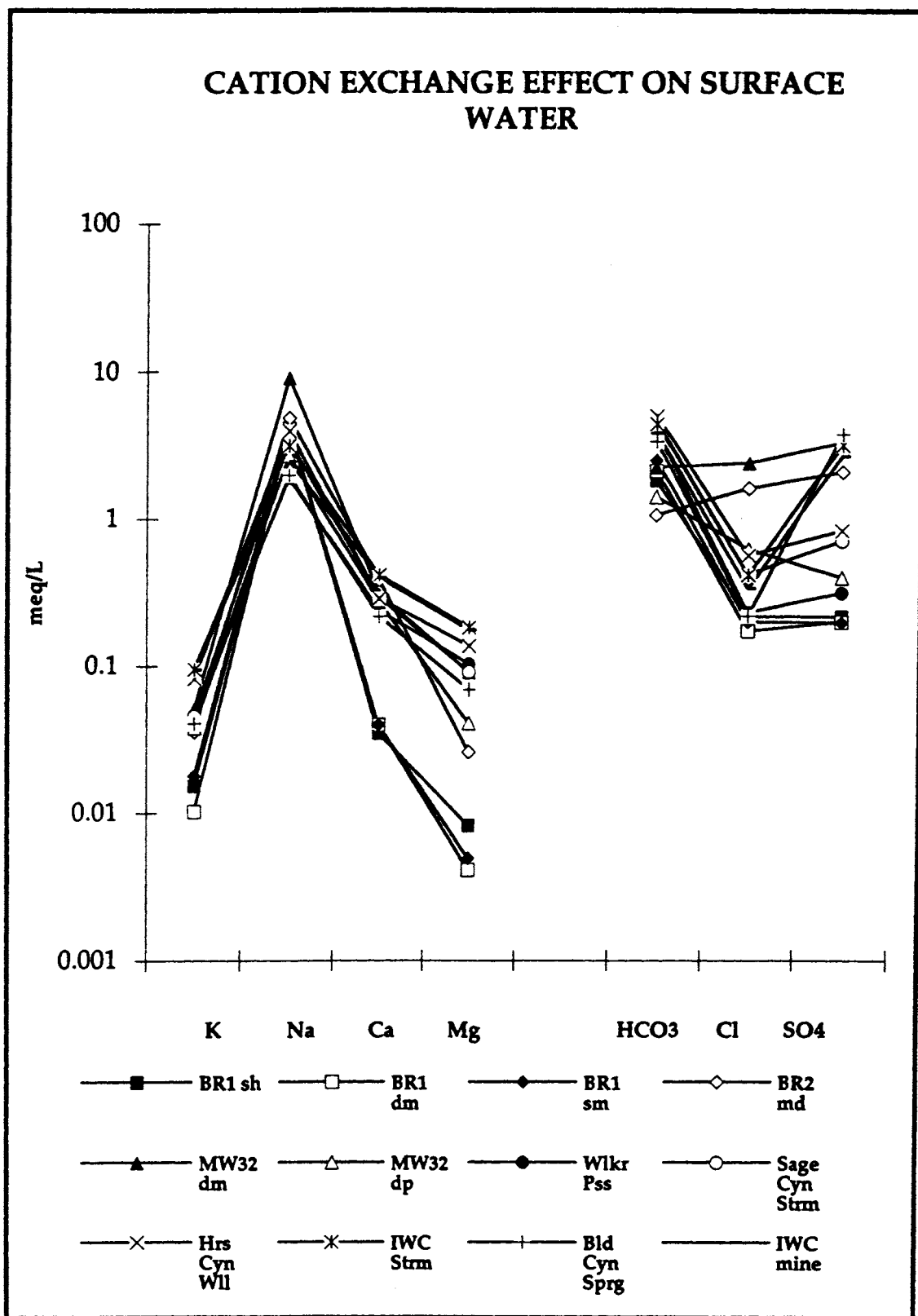


Figure 34. Fingerprint plot showing the effect of exchanging 90% of the Ca and Mg cations for Na cations along the flowpath from the surface samples to the wells.

Mg ions for Na ions in representative surface samples from the study area, creating a Na-HCO<sub>3</sub> water.

The differences in deuterium and alkalinity values between Group I fracture-associated water and the well samples can be attributed to evaporation and mixing with local surface runoff at the Group I sampling points. The portion of this water which does not come to the surface in the Sierras remains unexposed to the atmosphere and may recharge the aquifer in the subsurface without ever being exposed at the surface.

The large difference between Group II TDS concentrations and the well samples, however, remains unresolved. Group II water was not recognized in southwest Indian Wells Valley groundwater. A reasonable explanation may be that this water, which appears to comprise the majority of the surface water in the conventional southern Sierra Nevada drainage area, is diluted by large quantities of Group I water after it enters the subsurface alluvium at the mountain front. If this is correct, slightly elevated TDS and alkalinity values might be expected in the wells in years of abnormally high surface runoff. This hypothesis is supported by more concentrated and higher-alkalinity Spring, 1995 well samples versus fresher, lower-alkalinity Winter, 1996 well samples (Table 7). More information is needed about the velocity of the recharge and the manner in which it is delivered to the aquifer.

Berenbrock and Schroeder (1994) stated that the light deuterium values of the southwest basin indicate "recharge originating either from a higher altitude or during a colder and wetter climate." They chose a Pleistocene origin for the southwest groundwater, which presumably was derived from Sierran runoff during the last Ice Age and stored in the deep alluvium southwest of Inyokern. This groundwater, with an average total dissolved solids concentration of 259 mg/l, is surprisingly fresh after 10,000 years of storage. It is also surprisingly fresh

in comparison with today's surface runoff, which averages over 500 mg/l TDS.

The deuterium plots from this report (Fig. 35) indicate that the recharge elevation of southwest groundwater is 7,000 feet to 9,000 feet. Only 7%, or 1,479 acres, of the conventional surface recharge could provide this water type under modern climatic conditions. Larger areas with these elevations are present west of the surface divide and further north in the Sierras. These data suggest that a source outside the conventional surface drainage area provides a supply of Group I water which travels southeastward through fractures in the conventional drainage area and constitutes the majority of modern recharge to the southwest basin. This extrabasinal recharge may be the source of the majority of the southwest Indian Wells Valley groundwater.

#### **c. Age Dates of Southwest Indian Wells Valley Groundwater**

Direct tritium analyses were performed on 50-ml samples from the BR-1 shallow, shallow-medium and deep-medium and BR-2 medium and deep piezometers. Enriched analyses were performed on 1,000-ml samples from the Knecht well, Genesis I and SW-3. Table 10 summarizes the general and effective age dates based on the techniques from Mazor (1991) as described in section 4.1c. The majority of the samples contained at least some tritium, further establishing Group I water as a modern component of the groundwater in southwest Indian Wells Valley. These tritium data neither prove nor disprove the existence of Pleistocene water in the basin. Rather, the data demonstrate that most of the groundwater had contact with the atmosphere prior to sixty years ago.

New tritium data acquired in the Fall of 1996 by the Indian Wells Valley Water District provides further support for a young age of southwest Indian Wells Valley groundwater. TW-1 (Fig. 8) was sampled at the well head after the pump had been running at 2,400 gallons per minute for eleven days. Analysis by

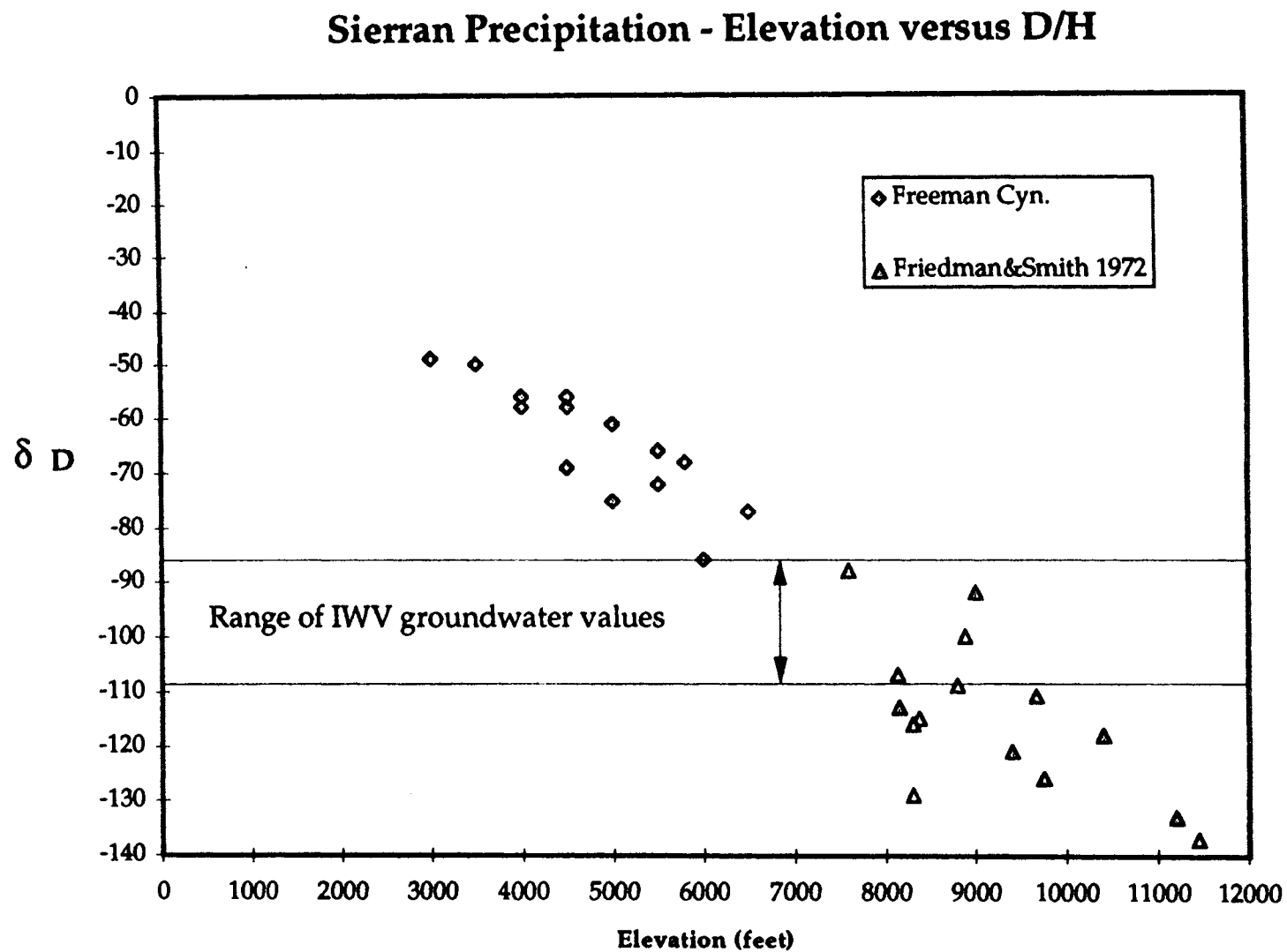


Figure 35. Plot showing elevation range of Indian Wells Valley groundwater isotope values.

Clinical Laboratories of San Bernardino, California showed a count of 232 pCi/l with a counting error of 119 pCi/l. This value converts to 72 T.U.  $\pm$  37 T.U. If similar values are recorded by repeated sampling, then a large portion of the groundwater must have been recharged post-1952.

**Table 10.** Southwest Indian Wells Valley groundwater sample age data.

| <u>Sample</u>       | <u>General Age</u>   | <u>Effective Age</u> |
|---------------------|----------------------|----------------------|
| BR-1 Shallow        | pre-1952             | >60 years            |
| BR-1 Shallow/Medium | pre-1952 & post-1952 | ?                    |
| BR-1 Deep/Medium    | pre-1952 & post-1952 | ?                    |
| BR-2 Medium         | pre-1952 & post-1952 | ?                    |
| BR-2 Deep           | pre-1952             | >60 years            |
| Genesis-1           | pre-1952             | >60 years            |
| Knecht              | pre-1952             | >60 years            |
| SW-3                | pre-1952             | >60 years            |

#### **d. Anomalous Groundwater Samples**

Drever (1988) described water samples from springs associated with ultramafic rocks in California which had pH values between 11 and 12, carbonate species below detection, and low magnesium and silica concentrations. BR-2 data displayed similar characteristics, with mean values of 11.5 for pH, 4.02 mg/l for bicarbonate, 0.09 mg/l for magnesium and 34.9 mg/l for silica. Drever's samples were supersaturated with respect to brucite, serpentine and diopside and undersaturated with respect to forsterite and enstatite. Table 11 shows saturation indices calculated by MINTEQA2 for the Spring, 1995 and Winter, 1996 samples of BR-2 shallow. An index of 0 indicates a solution in equilibrium with the solid phase (saturation), an index >0 means supersaturation and an index <0 means

undersaturation. The range of error is approximately  $\pm 0.5$ . Brucite is the only mineral on the list which does not fit the described profile. However, the most basic rock type described in the region is the Summit gabbro. Lacking evidence of an ultramafic rock source, this example offers a possible explanation, but not a proof, for the hydrogeochemistry of BR-2 shallow.

**Table 11.** Saturation indices of selected minerals at the BR-2 shallow piezometer.

| <u>Mineral</u> | <u>S. I. Spring 1995</u> | <u>S. I. Winter 1996</u> |
|----------------|--------------------------|--------------------------|
| Brucite        | -1.723                   | -0.059                   |
| Serpentine     | 3.865                    | 8.077                    |
| Diopside       | 3.103                    | 5.277                    |
| Forsterite     | -2.823                   | 0.155                    |
| Enstatite      | -0.908                   | 0.395                    |

The BR-3 medium and BR-3 deep piezometers yielded TDS concentrations profoundly dissimilar to the other wells in the study area. Their high sodium, chloride and boron concentrations (Appendix 2) indicate a possible geothermal source (Henry and Gluck, 1981), but the temperature gradients (USBR, 1993) are not extraordinary. If there is a geothermal contribution to these wells, the water temperature is being moderated by mixing with another, cooler source of recharge.

#### **4.3 Sources and Flowpaths of Group I Sierran Recharge**

##### **a. Sources of Group I Water**

Recharge from precipitation in the conventional surface drainage area is insufficient to supply the amount of groundwater calculated to flow through the

southwest aquifer between wells BR-1 and MW-32. Strong hydrogeochemical evidence links Group I fracture-associated water in the Sierra Nevada Mountains to that sampled in the deep-basin wells. If Group I water does not originate in the mountain front adjacent to the basin, as the data suggest, its source must be a higher elevation beyond the conventional surface drainage divide.

The nearest recharge area between 7,000 and 9,000 feet in elevation lies on the Kern Plateau in the drainage area of the South Fork of the Kern River. Surface samples of South Fork water collected for this study agree with data presented by Houghton (1994). They show that water in the Kennedy Meadows/South Fork area has a similar composition and isotopic signature to southwest Indian Wells Valley groundwater. Figure 36 is a fingerprint plot of high Sierran surface samples. All have TDS concentrations and recharge elevations consistent with Group I water. Samples taken directly from snow and from the river are the freshest, while the spring waters show a moderate increase in ionic content engendered by rock/water interaction. Figure 37 compares selected Sierran samples with selected Group I springs and southwest basin wells. The clear differences in ionic concentration between the two groups can be accommodated by cation exchange as demonstrated previously in Figure 34.

#### **b. Flowpaths of Group I Water**

If Kern Plateau water is Group I water, it must reach the Group I springs and southwest basin wells without further evaporation. It must not mix with large quantities of lower elevation recharge. It must travel fast enough to arrive in the conventional drainage area with only moderate increases in dissolved solids.

The hypothesis presented here is that Kern Plateau / Group I recharge passes through a network of fractures associated with regional normal faults and

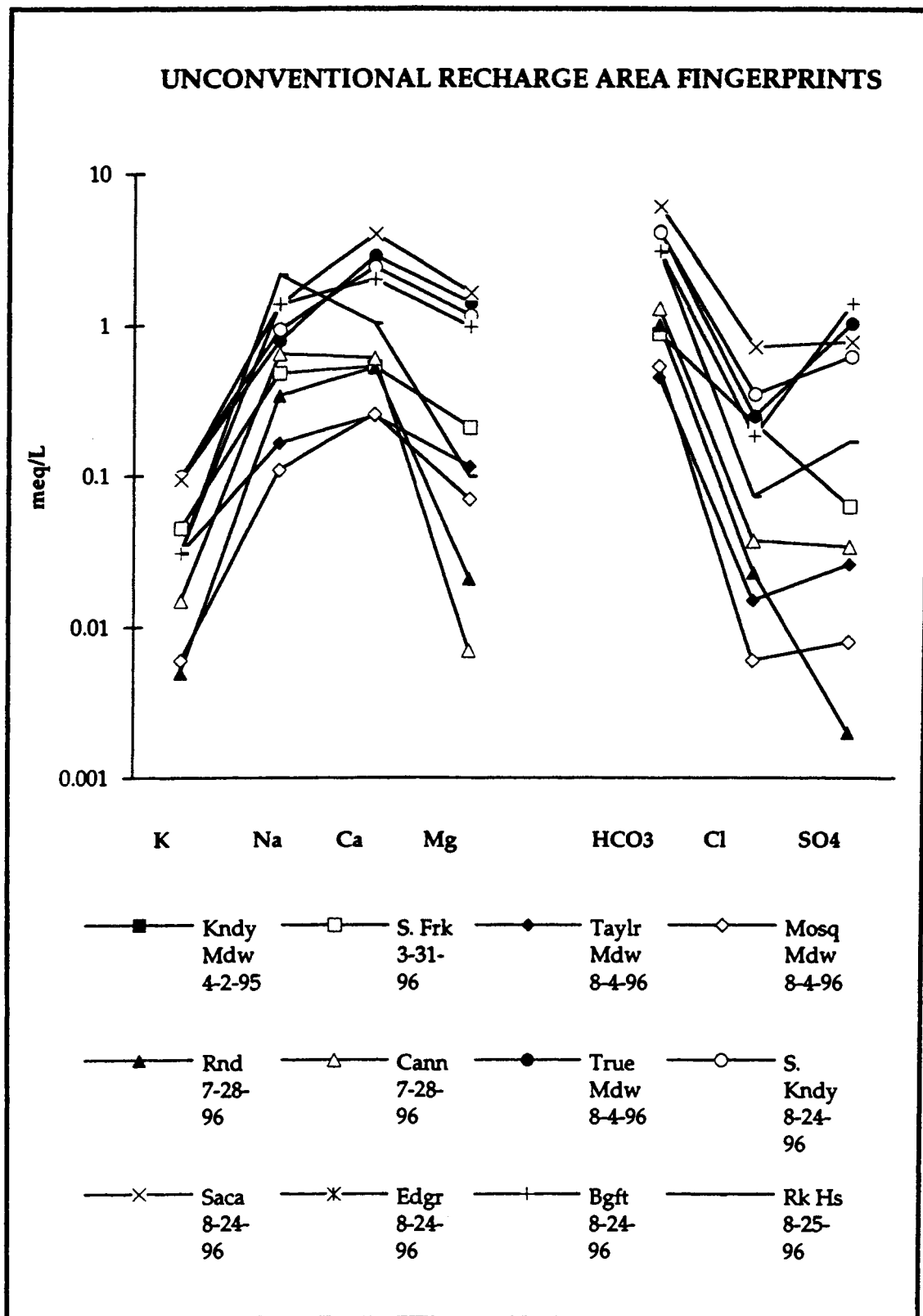


Figure 36. Fingerprint plot of Kern Plateau surface samples.

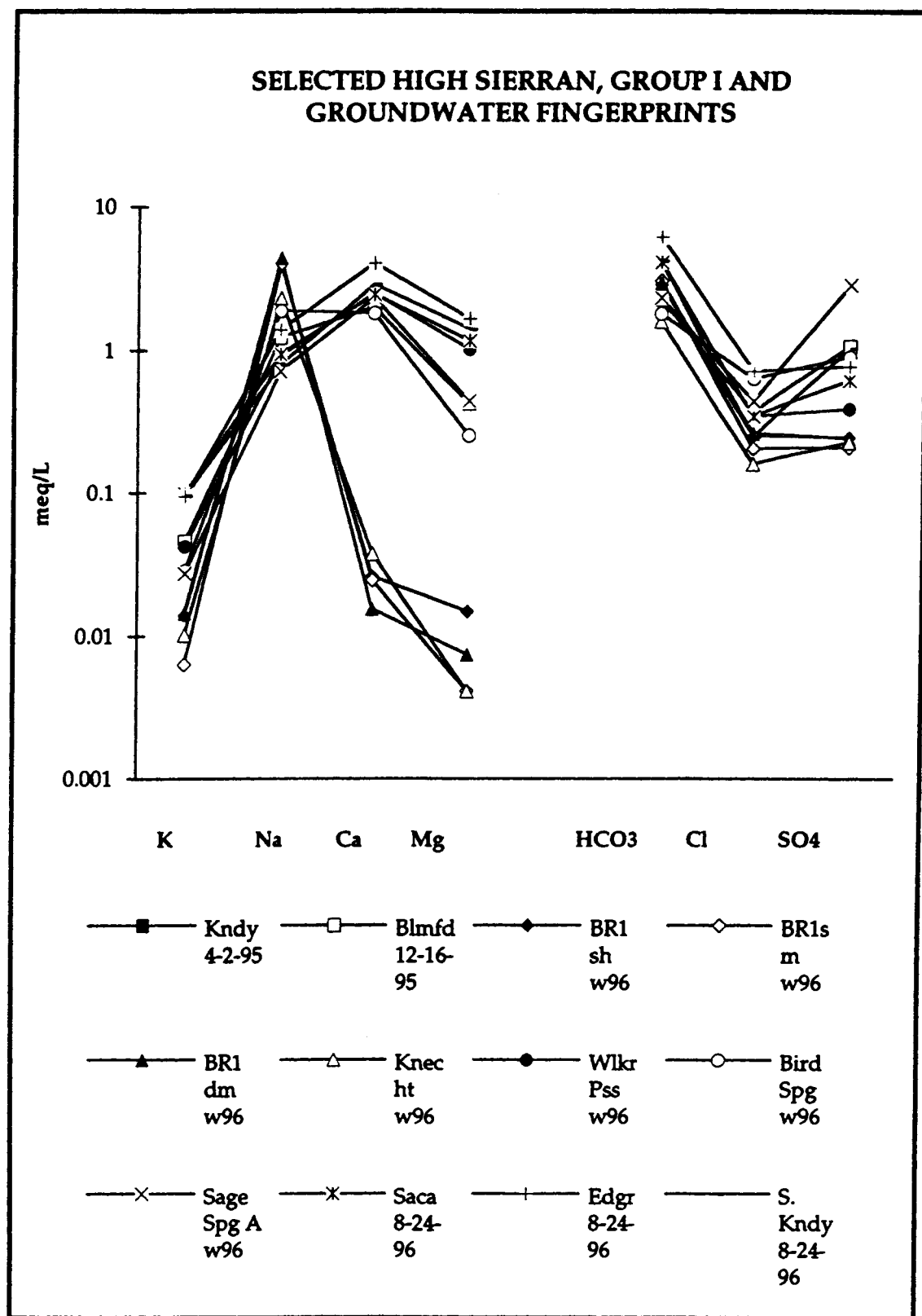


Figure 37. Fingerprint plot of Kern Plateau, Group I and well samples.

local en echelon faults in the southern Sierra Nevada Mountains (Fig. 38). The groundwater occasionally emerges through deep vertical fractures to form springs along the flowpath. It enters southwest Indian Wells Valley through fractured crystalline rocks beneath the coalescing alluvial fans. The water-bearing fractures are part of fault zone structures in the wall rock alongside northwest-trending en echelon faults which may have controlled the opening of the study area's canyons (Diggles, *et al.*, 1985).

Most of the literature on fault zone permeability has focused on localized shallow fault zones, emphasizing faults as flow barriers in sedimentary basins, as targets for exploration for potable water in fractured aquifers or as possible contaminant flowpaths. Deep throughflow along vertical or sub-vertical fractures has not received as much emphasis. However, Huntoon's (1986) observations described fracture permeability which had developed in normally impermeable rocks due to extensional tectonic stresses. Huntoon found maximum permeability in vertical to subvertical anisotropic fractures that were parallel to the strike of faults along which displacement and, therefore, gouge development were minimal. Combining transmissive pathways such as these with Toth and Sheng's (1996) visualization of a regional flow system (Fig. 39) and a steep hydraulic gradient from Kern Plateau recharge yields a very feasible method for delivering fresh, isotopically light groundwater to southwest Indian Wells Valley.

A broad, basin-scale permeability study, necessary to quantify the recharge mechanism proposed by this investigation, faces large problems in both data collection and modeling. The major challenge presented by a regional flow model in this terrain is to quantify the variations in crystalline rock fault zone permeability due to heterogeneity and anisotropy. Smith *et al.* (1990) characterized the temporal evolution of fault zones in crystalline rock. Figure 40

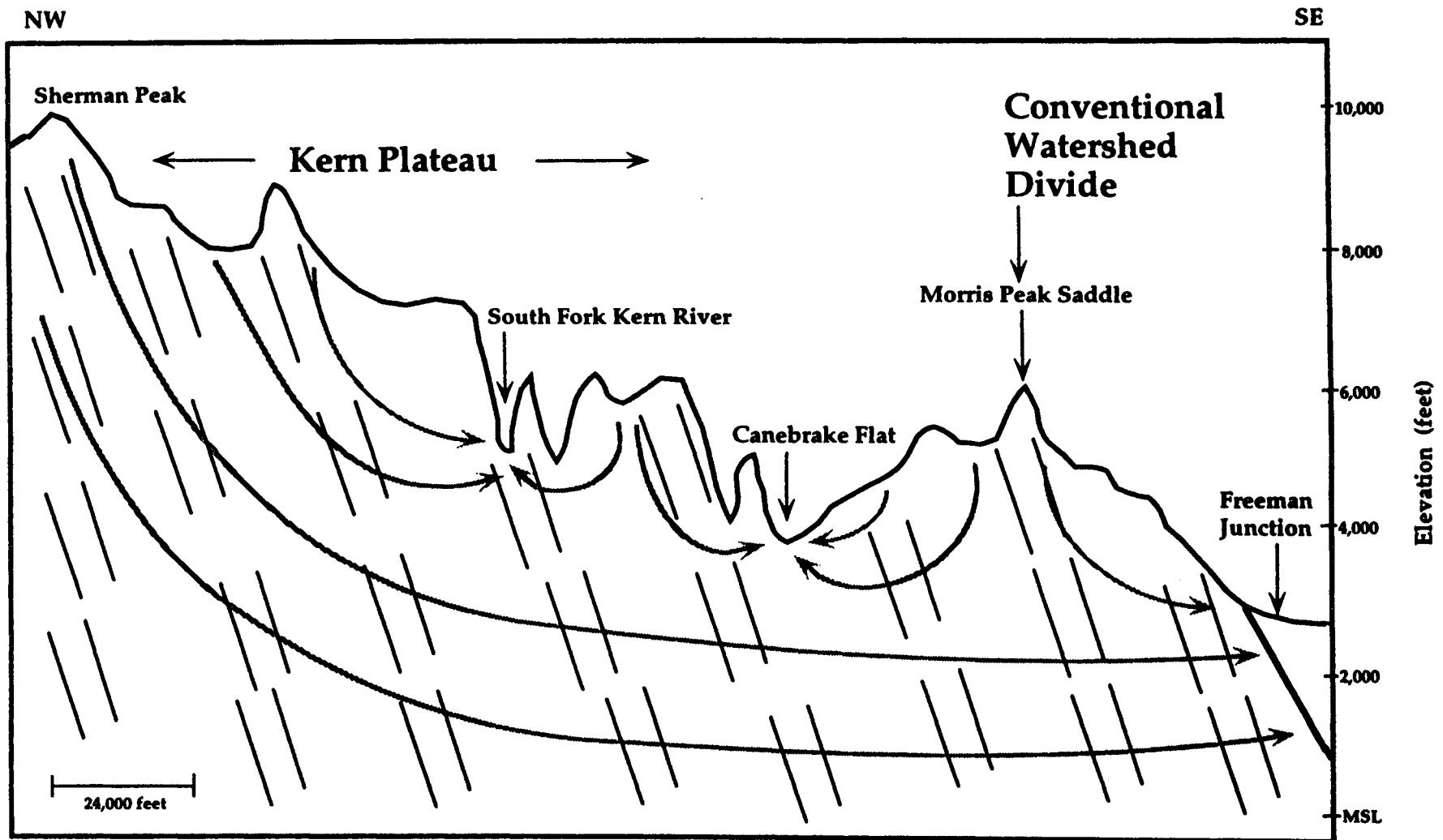
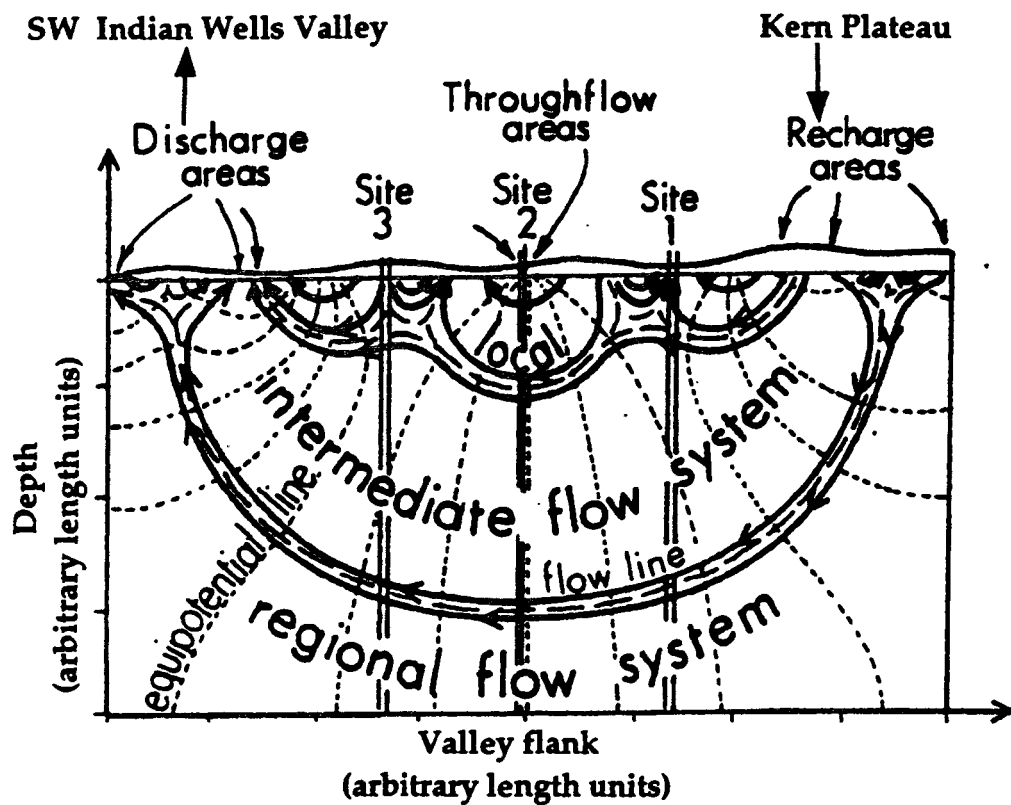
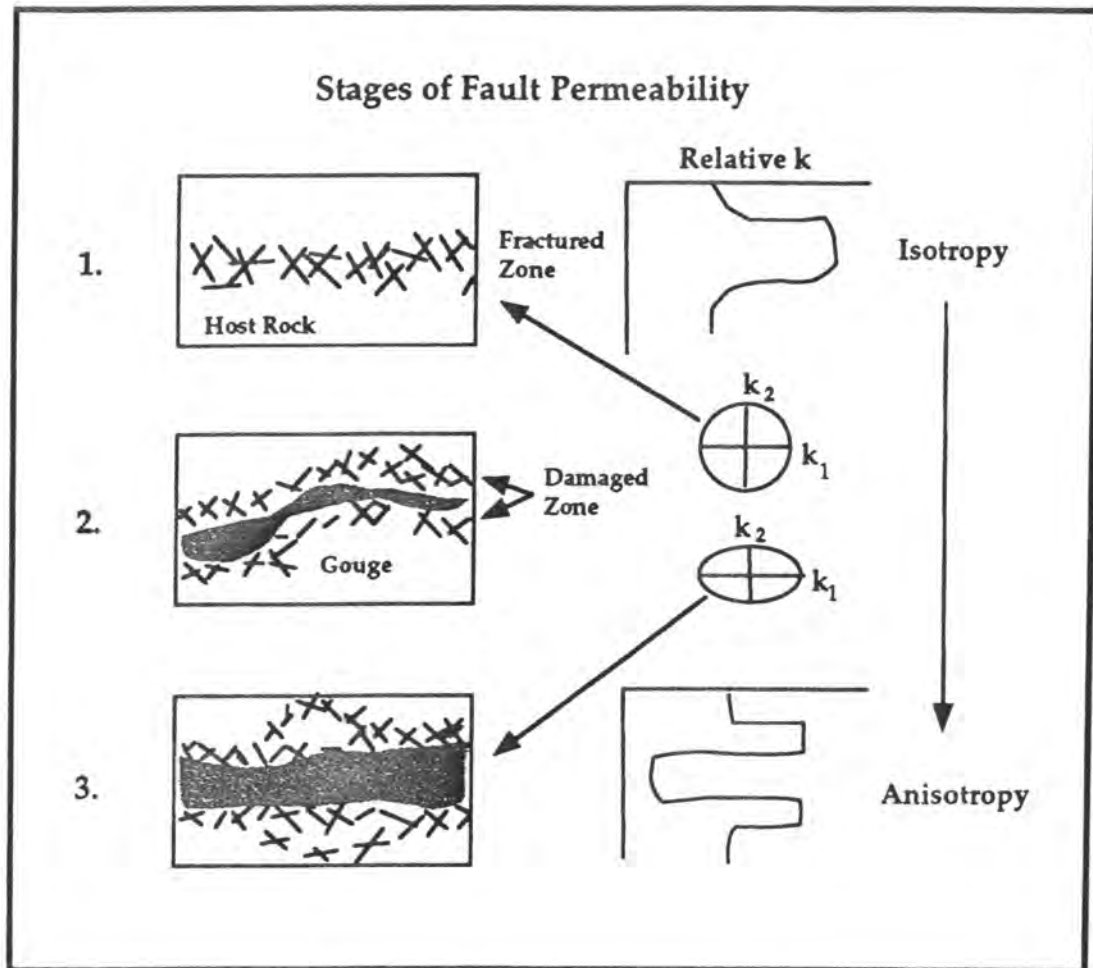


Figure 38. Conceptual drawing of potential groundwater flowpaths through anisotropic fractures in Sierran granites from the Kern Plateau to southwest Indian Wells Valley. Pairs of lines represent subvertical northeast-trending fractures. Their conjugate pairs, which trend northwesterly, are not visible in cross-section. Vertical exaggeration is approximately 12x.



**Figure 40. Schematic illustration of a regional recharge area concept from Toth and Sheng (1996). A deep regional flow system such as the one depicted here may deliver groundwater from the Kern River Plateau to southwest Indian Wells Valley via highly permeable fractured crystalline rocks.**



**Figure 40.** Conceptual picture of the development of permeability along a fault zone after Smith et al. (1990). Original fractures are isotropic in stage one and develop relatively impermeable clay gouge zones in stage two. Permeability increases as anisotropy increases in stage three. Permeability is greatest along fault zones where displacement is small and gouge development is minimal.

illustrates three stages of permeability development, from a fractured, nearly isotropic protolith through the formation of clay and mica fault gouge flanked by anisotropic, highly permeable damage zones. The thickness of the damage zones may change both along strike and in the dip direction of the fault and permeability may vary by four orders of magnitude over a span of fifteen to twenty feet (Smith *et al.*, 1990). Smith *et al.* (1990) suggested that fault zones such as these may capture 50% of the regional groundwater.

Both normal and strike-slip fault zones exhibit segments whose boundaries change abruptly or splay away from the main trace to accommodate stress. The Group I springs may be associated with segment boundaries which force groundwater to the surface along vertical fractures.

Group I water is not found in the valley aquifers adjacent to the Sierran canyons north of the study area (USBR, 1993; Houghton, 1994). The northern canyons, geomorphically younger than those in the southwest (Baker, 1912), appear to be less affected by fracturing and erosion associated with the clockwise rotation of the southernmost Sierra Nevada. The lineaments on Figure 28, derived from aerial photographs and satellite imagery, suggest that groundwater from the Kern Plateau has many possible avenues to the southwest canyons and hence, to the wells in southwest Indian Wells Valley. Chief among these are the north-northeast traces associated with Basin and Range extension and the older west-northwest to northwest trends (Mayo, 1947).

A manmade tunnel at Bird Spring serves as a microcosm of the proposed transport mechanism for groundwater to southwest Indian Wells Valley. From a distance, the spring, at elevation 3,840 feet (site 22, Fig. 7), is not remarkable. A stagnant puddle at the base of two withered cottonwood trees rarely yields enough water to sample. Although a fault is mapped through Bird Spring Pass and a distinct northwest lineament is visible in the vicinity of the spring on

aerial photos and remote sensing images, the surrounding canyon is very dry. A few hundred feet northwest of the spring, however, cut into the granite ridge, is a small tunnel approximately 8 feet high, 4 feet wide and 10 feet long. A 2-inch pipe leads from the bottom of the tunnel down the hillside, carrying water year-round to a cattle trough and a stock tank. Inside the tunnel, water drips from the northwest wall through tight (apertures to 0.1 inch) vertical and horizontal fractures in the granodiorite and forms a pool on the floor two feet deep. Three sample analyses of the  $\text{Ca-Na-HCO}_3\text{-SO}_4$  water averaged 229 mg/l TDS, 86 mg/l for alkalinity and -95‰ for deuterium. Tritium data suggest recharge that is less than fifty years old. The Bird Spring tunnel produces Group I water moving quickly through highly permeable, fractured, crystalline rock in the damage zone of a northwest-trending fault-controlled canyon.

A simplified regional recharge model for southwest Indian Wells Valley would feature Group I groundwater, driven by a steep hydraulic gradient from higher elevations on the Kern Plateau, being transported through highly permeable damage zones along intersecting segments of regional strike-slip and normal faults. Along the flowpath, where the damage zones intersect the surface and the head in these zones is higher than the elevation of the land surface, small quantities of Group I water emerge as springs. The majority of the Group I water recharges the southwest aquifer through damage zones flanking the canyons at the base of the mountains, buried beneath the alluvium. The small amount of Group II water that enters the basin is diluted and not apparent in deep well samples. The fresh, isotopically light,  $\text{Na-HCO}_3$  water with measurable amounts of tritium flows through the narrow channel between Freeman Junction and the Black Hills, causing a steep gradient. As the valley widens to the northeast, the gradient flattens and the Group I recharge mixes with the main body of Indian Wells Valley groundwater.

## 5. CONCLUSIONS

The majority of the southwest Indian Wells Valley groundwater appears to be derived from outside the conventional surface drainage area. The isotope and water chemistry data suggest that the most likely source is the Kern Plateau drainage area of the South Fork of the Kern River. The following results support this conclusion:

- The surface recharge estimated from precipitation gages placed within the conventional surface drainage area of southwest Indian Wells Valley is insufficient to supply the amount of groundwater calculated to flow through the southwest aquifer between wells BR-1 and MW-32.
- The majority of the southwest groundwater has a lower dissolved solids concentration than the majority of the surface water in the conventional drainage area.
- A portion of the surface water associated with seven fracture-associated springs has a similar dissolved solids concentration to the majority of the southwest groundwater. Differences in chemical composition between the springs and the basin can be accommodated by cation exchange.
- Deuterium isotope values for the southwest groundwater and the fracture-associated springs indicate that this water was derived from precipitation which fell at elevations from 7,000 to 9,000 feet. These elevations comprise only 7% of the conventional drainage area of southwest Indian Wells Valley.

The transport mechanism for Kern Plateau recharge to southwest Indian Wells Valley appears to be a network of high-permeability fractures associated with regional Basin and Range north-northeast normal faults and local northwest-trending en echelon faults.

## 6. RECOMMENDATIONS

Because the results of this study raise important questions regarding the quantity, the source, the flowpaths and the age of recharge to southwest Indian Wells Valley, the proposed model must be tested thoroughly before any development occurs that requires the use of groundwater. The following recommendations are designed to provide such a test.

- Until the hypothetical groundwater flow barrier in the southwest is proved or disproved, all calculations of flux must be considered with caution. Three more deep monitoring wells are needed in the southwest well field (see open circles, Fig. 8). The wells should be perforated at the same intervals as the other district monitoring wells (SW-2 and SW-3) and they should be equipped with continuous data loggers and sampling pumps. With these wells in place, an aquifer test of at least thirty days in duration should provide the necessary data to characterize the conductivity of the well field.
- At least one more monitoring well is needed southwest of BR-1 (see open circle, Fig. 8) to confirm the gradient from the 2,800-foot contour shown on the head map ( Fig. 6) in the deep southwest.
- Geophysical logs (spontaneous potential and electrical resistivity) should be run in the new wells to further investigate the basin stratigraphy.
- The deep seismic line NAWS 92-01, shot by the Geothermal Program Office through the southwest basin, should be reprocessed for shallow reflectors to help define the top of the Ricardo Formation (consolidated sediments) and to compare with this study's gravity interpretation of the depth to undifferentiated basement. Possible facies discontinuities in the alluvium, which may be associated with faulting, may be detected with this method.

- Tritium sampling should be repeated in the southwest monitoring wells and the BR wells to confirm the dominance of modern water in the aquifer.
- The use of rare earth elements as tracers of groundwater movement should be studied for its applicability in this regime.
- Permanent precipitation gaging stations at varying elevations should be monitored and sampled regularly for stable isotope analysis to establish local norms for precipitation and storm patterns. New (1996) remote stations in Horse Canyon, Walker Pass and the station in Indian Wells Canyon will provide data to compare with the recharge estimates of this study.
- The surface water flow measurements for this study were limited by time and expense problems, as well as the ephemeral nature of their discharge. The installation and long-term monitoring of crest stage gages and weirs in Sage Canyon and Indian Wells Canyon would improve these estimates.
- Further investigation of the Kern Plateau and the conventional drainage area should include more sampling of the Group I springs and an expanded effort to field map fracture patterns associated with them.
- Frequent, regular monitoring of Group I spring flow may provide information about the seasonal response to recharge, groundwater velocity and fracture permeability.
- The drainage area of the South Fork of the Kern River should be calculated and recharge estimated from precipitation measured in the catchment basin. These results should be compared to flow measured at the USGS South Fork gaging station on the Bloomfield Ranch near Onyx.
- A study of the hydrogeology and structure of the southern and eastern boundaries of the valley may provide important information regarding the possible flow of groundwater from Indian Wells Valley to other basins.

- The groundwater model for Indian Wells Valley should be revised using data acquired from the USBR report, the CSUB studies and the above-recommended projects. The revised model could then be used as a tool to simulate the consequences of planned development projects on the groundwater supply.

## REFERENCES

Avon, L. and Durbin, T. J., 1994, Evaluation of the Maxey-Eakin method for estimating recharge to ground-water basins in Nevada: Water Resources Bulletin, vol. 30, no. 1, February, 1994, p. 99-111.

Baker, C. L., 1912, Physiography and structure of the western El Paso Range and the southern Sierra Nevada: Univ. Calif. Pub., Bull. Dept. of Geol., vol. 7, p.117-142.

Bean, R. T., 1989, Hydrogeologic conditions in Indian Wells Valley and vicinity: California Department of Water Resources Contract Number DWR B-56783, 51 p.

Berenbrock, C. and P. Martin, 1991, The ground water flow system in the Indian Wells Valley, Kern, Inyo and San Bernardino Counties, California: USGS Water-Resources Investigations Report 89-4191, 67 p.

Berenbrock, C. and R. A. Schroeder, 1994, Ground-water flow and quality, and geochemical processes, in Indian Wells Valley, Kern, Inyo and San Bernardino Counties, California, 1987-88: USGS Water-Resources Investigations Report 93-4003, 59 p.

Blaney, H. F., 1952, Determining evapotranspiration by phreatophytes from climatological data: American Geophysical Union Transcript, v. 33, p.61-65.

Bloyd, R. M., Jr. and S. G. Robson, 1971, Mathematical ground water model of Indian Wells Valley, California: USGS Open File Report, 36 p.

Brown, D. S. and J. Allison, 1987, MINTEQA1. Equilibrium Metal Speciation Model: User's Manual, US Environmental Protection Agency, Athens, Georgia.

California Department of Water Resources, 1996, California cooperative snow surveys, snow courses no. 258 and 265, Kern River drainage.

Chase, C. G. and T. C. Wallace, 1886, Uplift of the Sierra Nevada of California: Geology, v14, p.703-733.

Dansgaard, W., Stable isotopes in precipitation: Tellus, v.15, p.336-339.

Dibblee, Jr., T. W. and T. E. Gay, Jr., 1952, Geology of the Saltdale Triangle, California and Mineral Deposits of the Saltdale Quadrangle: California Division of Mines Bulletin 160, 65p.

Diggles, M. F., R. E. Tucker, A. Griscom, J. D. Causey and R. S. Gaps, 1985, Mineral Resources of the Owens Peak and Little Lake Canyon Wilderness Study Areas, Inyo and Kern Counties, California: USGS Bulletin 1708-B, 12p.

Drever, J. I., 1988, The geochemistry of natural waters, 2nd edition, Prentice Hall, 1988, 437 p.

Dutcher, L. C. and W. R. Moyle, Jr., 1973, Geologic and hydrologic features of Indian Wells Valley, California: USGS Water Supply Paper 2007, 30 p.

Eakin, T. E., G. B. Maxey, J. C. Robinson, R. Fredericks and O. J. Loeltz, 1951, Contributions to the hydrology of eastern Nevada: Water Resources Bulletin No. 12, State of Nevada, 34 p.

Ersine, M. C., 1989, Review of the geohydrology of the Indian Wells Valley Region, Kern, Inyo and San Bernardino Counties, California: Report for the Eastern Kern County Resource Conservation District, 47 p.

Fetter, C. W., 1994, Applied Hydrogeology, 3rd edition, Prentice-Hall, 691 p.

Friedman, I. and G. I. Smith, 1972, Deuterium content of snow as an index to winter climate in the Sierra Nevada area: Science, volume 176, pp. 790-793.

Harner, J. L., M. A. Chaffee, J. F. Seitz and D. O. Capstick, 1983, Mineral resource potential of the Scodies Roadless Area, Kern County, California: USGS Open-File Report 83-510, 14 p.

Henry, C.D. and J. K. Gluck, 1981, A preliminary assessment of the geologic setting, hydrology, and geochemistry of the Hueco Tanks Geothermal Area, Texas and New Mexico: University of Texas at Austin Bureau of Economic Geology Geological Circular 81-1, p. 1-34

Houghton, B. D., 1994, Groundwater geochemistry of the Indian Wells Valley: M.S. thesis, California State University, Bakersfield, 85 p.

Huntoon, Peter W., 1986, Incredible tale of Texasgulf Well 7 and fracture permeability, Paradox Basin, Utah: Ground Water, Vol. 24, No. 5.

Kanter, L. R. and M. O. McWilliams, 1982, Rotation of the southernmost Sierra Nevada, California: Journal of Geophysical Research, v. 87, number B5, p. 3819-3830.

Kern County Water Agency, 1997, Water Supply Report 1996.

Krieger, R. A., 1989, Indian Wells Valley Water District southwest well field test and monitoring wells construction and development, Krieger and Stewart Engineering Consultants, September, 1989, 20 p.

Kunkel, F. and G. H. Chase, 1969, Geology and ground water in Indian Wells Valley, California: USGS Open File Report, 84 p.

Lee, C. H., 1913, Ground water resources of Indian Wells Valley, California: California State Conservation Commission Report, p. 403-429.

Lipinsky, P. and D. D. Knochenmus, 1981, A 10-year plan to study the aquifer system of Indian Wells Valley, California: USGS Open File Report 81-404, 16 p.

Nilsen, T. H. and R. H. Chapman, 1971, Bouguer Gravity Map of California, Trona Sheet, scale 1:250,000: California Division of Mines and Geology.

Rantz, S. E., 1967, Mean annual precipitation in the California region: USGS map.

Saint-Amand, P., 1986, Water supply of Indian Wells Valley, California: NWC Technical Publication 6404, 71 p.

Smith, G. I., I. Friedman, J. D. Gleason and A. Warden, 1992, Stable isotope composition of waters in southeastern California: 2. groundwaters and their relation to modern precipitation: *Journal of Geophysical Research*, v.97, number D5, p. 5813-5823.

Smith, L., C.B. Forster and J. P. Evans, 1990, Interaction of fault zones, fluid flow and heat transfer at the basin scale, in: *Hydrogeology of Low Permeability Environments*, International Association of Hydrogeologists, v. 2, p. 41-67.

Thompson, D. G., 1929, The Mojave Desert region, California: Water Supply Paper 578, U.S. Department of the Interior, p. 144-170.

Toth, J. and G. Sheng, 1996, Enhancing safety of nuclear waste disposal by exploiting regional groundwater flow: the recharge area concept; *Hydrogeology Journal*, Vol. 4, No. 4.

U.S. Bureau of Reclamation, 1993, Indian Wells Valley Groundwater Project: Technical Report Vols. I and II.

von Huene, R. E., 1960, Structural geology and gravimetry of Indian Wells Valley, southeastern California: Ph.D. Thesis, University of California at Los Angeles, 78 p.

Whelan, J. A., R. Baskin and A. M. Katzenstein, 1989, A water geochemistry study of Indian Wells Valley, Inyo and Kern Counties, California, Vols. I and II: NWC Technical Paper 7019, 54 p.

Winter, T. C., 1981, Uncertainties in estimating the water balance of lakes: Water Resources Bulletin, v. 17, number 1, p. 82-115.

Wright, L., 1976, Late Cenozoic fault patterns and westward displacement of the Sierra Nevada block: Geology, v. 4, p. 489-494.

Zbur, R. T., 1963, A geophysical investigation of Indian Wells Valley, California: NOTS Technical Publication 2795, 98 p.

## **APPENDIX ONE**

### **Gravity Data**

| Bowman Rd |                |               |                | bedrock      | bedrock       | alluvial     | alluvial      |
|-----------|----------------|---------------|----------------|--------------|---------------|--------------|---------------|
| Station   | Gravity (mgal) | surface el(m) | surface el(ft) | surf elev(m) | surf elev(ft) | thickness(m) | thickness(ft) |
| 1         | -105.72        | 960           | 3149           | 951          | 3120          | 9            | 30            |
| 2         | -106.19        | 953           | 3127           | 943          | 3094          | 10           | 33            |
| 3         | -106.68        | 946           | 3105           | 920          | 3019          | 26           | 85            |
| 4         | -107.07        | 941           | 3086           | 863          | 2830          | 78           | 256           |
| 5         | -107.56        | 934           | 3063           | 830          | 2722          | 104          | 341           |
| 6         | -107.96        | 930           | 3051           | 799          | 2621          | 131          | 430           |
| 7         | -108.35        | 925           | 3035           | 760          | 2494          | 165          | 541           |
| 8         | -108.87        | 920           | 3019           | 729          | 2393          | 191          | 627           |
| 9         | -109.36        | 916           | 3004           | 698          | 2289          | 218          | 715           |
| 10        | -109.76        | 912           | 2991           | 634          | 2079          | 278          | 912           |
| 11        | -111.26        | 906           | 2974           | 619          | 2032          | 287          | 942           |
| 12        | -110.44        | 902           | 2959           | 597          | 1958          | 305          | 1001          |
| 13        | -110.77        | 897           | 2944           | 558          | 1831          | 339          | 1112          |
| 14        | -111.07        | 893           | 2930           | 545          | 1788          | 348          | 1142          |
| 15        | -111.38        | 888           | 2915           | 505          | 1658          | 383          | 1257          |
| 16        | -111.69        | 884           | 2900           | 449          | 1473          | 435          | 1427          |
| 17        | -111.99        | 879           | 2885           | 427          | 1402          | 452          | 1483          |
| 18        | -112.22        | 875           | 2870           | 396          | 1298          | 479          | 1572          |
| 19        | -112.44        | 871           | 2858           | 349          | 1146          | 522          | 1713          |
| 20        | -112.63        | 868           | 2847           | 320          | 1049          | 548          | 1798          |
| 21        | -112.8         | 865           | 2837           | 299          | 980           | 566          | 1857          |
| 22        | -112.89        | 860           | 2822           | 264          | 867           | 596          | 1955          |
| 23        | -113.04        | 855           | 2805           | 246          | 807           | 609          | 1998          |
| 24        | -113.11        | 853           | 2798           | 214          | 701           | 639          | 2097          |
| 25        | -113.29        | 847           | 2780           | 190          | 625           | 657          | 2156          |
| 26        | -113.34        | 842           | 2764           | 185          | 608           | 657          | 2156          |
| 27        | -113.33        | 838           | 2750           | 181          | 594           | 657          | 2156          |
| 28        | -113.4         | 834           | 2736           | 177          | 580           | 657          | 2156          |
| 29        | -113.22        | 829           | 2719           | 172          | 563           | 657          | 2156          |
| 30        | -113.39        | 831           | 2725           | 174          | 569           | 657          | 2156          |
| 31        | -113.38        | 828           | 2715           | 175          | 573           | 653          | 2142          |
| 32        | -113.56        | 822           | 2696           | 169          | 553           | 653          | 2142          |
| 33        | -113.57        | 818           | 2684           | 170          | 558           | 648          | 2126          |
| 34        | -113.42        | 813           | 2669           | 169          | 556           | 644          | 2113          |
| 35        | -113.38        | 809           | 2655           | 161          | 529           | 648          | 2126          |
| 36        | -113.46        | 805           | 2640           | 157          | 514           | 648          | 2126          |
| 37        | -113.6         | 801           | 2629           | 157          | 516           | 644          | 2113          |
| 38        | -113.59        | 797           | 2616           | 153          | 503           | 644          | 2113          |
| 39        | -113.63        | 793           | 2603           | 149          | 490           | 644          | 2113          |
| 40        | -113.62        | 792           | 2598           | 153          | 502           | 639          | 2097          |
| 41        | -113.59        | 790           | 2593           | 155          | 510           | 635          | 2083          |
| 42        | -113.56        | 788           | 2587           | 153          | 503           | 635          | 2083          |
| 43        | -113.53        | 786           | 2580           | 151          | 497           | 635          | 2083          |
| 44        | -113.54        | 784           | 2571           | 149          | 488           | 635          | 2083          |
| 45        | -113.56        | 779           | 2556           | 148          | 486           | 631          | 2070          |
| 46        | -113.6         | 780           | 2560           | 149          | 490           | 631          | 2070          |
| 47        | -113.62        | 778           | 2554           | 147          | 484           | 631          | 2070          |
| 48        | -113.69        | 777           | 2550           | 142          | 466           | 635          | 2083          |
| 49        | -113.7         | 778           | 2551           | 143          | 468           | 635          | 2083          |
| 50        | -113.68        | 777           | 2550           | 142          | 466           | 635          | 2083          |
| 51        | -113.62        | 776           | 2546           | 141          | 462           | 635          | 2083          |
| 52        | -113.58        | 773           | 2538           | 138          | 454           | 635          | 2083          |
| 53        | -113.48        | 773           | 2537           | 138          | 453           | 635          | 2083          |
| 54        | -113.35        | 773           | 2536           | 147          | 482           | 626          | 2054          |
| 55        | -113.22        | 773           | 2536           | 147          | 482           | 626          | 2054          |
| 56        | -113.09        | 773           | 2537           | 147          | 483           | 626          | 2054          |
| 57        | -112.85        | 772           | 2534           | 146          | 480           | 626          | 2054          |
| 58        | -112.63        | 772           | 2532           | 146          | 478           | 626          | 2054          |

| BR1-Brown |               |               |                | bedrock      | bedrock       | alluvial     | alluvial      |
|-----------|---------------|---------------|----------------|--------------|---------------|--------------|---------------|
| Station   | Gravity(mgal) | surface el(m) | surface el(ft) | surf elev(m) | surf elev(ft) | thickness(m) | thickness(ft) |
| 1         | -113.83       | 868           | 2848           | 224          | 735           | 644          | 2113          |
| 2         | -113.73       | 866           | 2842           | 222          | 729           | 644          | 2113          |
| 3         | -113.38       | 866           | 2843           | 222          | 730           | 644          | 2113          |
| 4         | -113.11       | 865           | 2839           | 256          | 840           | 609          | 1998          |
| 5         | -113.01       | 862           | 2828           | 301          | 988           | 561          | 1841          |
| 6         | -112.85       | 861           | 2825           | 335          | 1099          | 526          | 1726          |
| 7         | -112.69       | 860           | 2821           | 373          | 1223          | 487          | 1598          |
| 8         | -112.45       | 858           | 2814           | 397          | 1301          | 461          | 1513          |
| 9         | -112.25       | 857           | 2810           | 422          | 1383          | 435          | 1427          |
| 10        | -112.15       | 855           | 2805           | 429          | 1407          | 426          | 1398          |
| 11        | -112.16       | 854           | 2801           | 428          | 1403          | 426          | 1398          |
| 12        | -112.19       | 849           | 2786           | 427          | 1402          | 422          | 1385          |
| 13        | -112.32       | 846           | 2777           | 411          | 1350          | 435          | 1427          |
| 14        | -112.38       | 843           | 2766           | 386          | 1266          | 457          | 1499          |
| 15        | -112.49       | 842           | 2762           | 372          | 1219          | 470          | 1542          |
| 16        | -112.67       | 839           | 2754           | 352          | 1156          | 487          | 1598          |
| 17        | -112.69       | 835           | 2740           | 330          | 1083          | 505          | 1657          |
| 18        | -112.72       | 832           | 2731           | 310          | 1018          | 522          | 1713          |
| 19        | -112.72       | 829           | 2720           | 298          | 977           | 531          | 1742          |
| 20        | -112.82       | 825           | 2707           | 277          | 909           | 548          | 1798          |
| 21        | -112.85       | 822           | 2696           | 274          | 898           | 548          | 1798          |
| 22        | -113.06       | 817           | 2680           | 251          | 823           | 566          | 1857          |
| 23        | -113.11       | 813           | 2667           | 239          | 784           | 574          | 1883          |
| 24        | -113.17       | 813           | 2668           | 261          | 857           | 552          | 1811          |
| 25        | -113.08       | 811           | 2661           | 219          | 718           | 592          | 1942          |
| 26        | -113.03       | 806           | 2645           | 201          | 660           | 605          | 1985          |
| 27        | -112.98       | 803           | 2634           | 194          | 636           | 609          | 1998          |
| 28        | -113.08       | 800           | 2624           | 191          | 625           | 609          | 1998          |
| 29        | -113.07       | 795           | 2610           | 186          | 611           | 609          | 1998          |
| 30        | -113.08       | 792           | 2598           | 183          | 600           | 609          | 1998          |
| 31        | -113.03       | 789           | 2589           | 180          | 591           | 609          | 1998          |
| 32        | -113.06       | 786           | 2580           | 177          | 581           | 609          | 1998          |
| 33        | -113.1        | 782           | 2566           | 182          | 597           | 600          | 1969          |
| 34        | -113.1        | 780           | 2560           | 180          | 592           | 600          | 1969          |
| 35        | -113.1        | 779           | 2557           | 179          | 588           | 600          | 1969          |
| 36        | -113.02       | 778           | 2553           | 178          | 585           | 600          | 1969          |
| 37        | -112.95       | 778           | 2551           | 178          | 583           | 600          | 1969          |
| 38        | -113.02       | 777           | 2549           | 177          | 580           | 600          | 1969          |
| 39        | -112.89       | 777           | 2551           | 177          | 582           | 600          | 1969          |
| 40        | -112.83       | 776           | 2546           | 176          | 578           | 600          | 1969          |
| 41        | -112.74       | 775           | 2544           | 166          | 545           | 609          | 1998          |
| 42        | -112.69       | 774           | 2539           | 165          | 541           | 609          | 1998          |
| 43        | -112.6        | 773           | 2538           | 164          | 540           | 609          | 1998          |
| 44        | -112.49       | 774           | 2539           | 165          | 541           | 609          | 1998          |
| 45        | -112.47       | 773           | 2535           | 164          | 537           | 609          | 1998          |
| 46        | -112.39       | 771           | 2529           | 162          | 530           | 609          | 1998          |

| BR1-178 |               |               |                | bedrock      | bedrock       | alluvial     | alluvial      |
|---------|---------------|---------------|----------------|--------------|---------------|--------------|---------------|
| Station | Gravity(mgal) | surface el(m) | surface el(ft) | surf elev(m) | surf elev(ft) | thickness(m) | thickness(ft) |
| 1       | -113.87       | 869           | 2850           | 234          | 766           | 635          | 2083          |
| 2       | -113.91       | 871           | 2858           | 236          | 774           | 635          | 2083          |
| 3       | -113.93       | 874           | 2867           | 235          | 771           | 639          | 2097          |
| 4       | -113.92       | 877           | 2877           | 251          | 823           | 626          | 2054          |
| 5       | -113.8        | 878           | 2882           | 252          | 828           | 626          | 2054          |
| 6       | -113.93       | 880           | 2887           | 254          | 833           | 626          | 2054          |
| 7       | -113.93       | 884           | 2899           | 266          | 872           | 618          | 2028          |
| 8       | -113.86       | 885           | 2904           | 267          | 877           | 618          | 2028          |
| 9       | -113.82       | 887           | 2911           | 269          | 883           | 618          | 2028          |
| 10      | -113.72       | 888           | 2914           | 279          | 916           | 609          | 1998          |
| 11      | -113.74       | 888           | 2912           | 279          | 914           | 609          | 1998          |
| 12      | -113.69       | 889           | 2915           | 289          | 947           | 600          | 1969          |
| 13      | -113.61       | 887           | 2910           | 287          | 941           | 600          | 1969          |
| 14      | -113.53       | 887           | 2910           | 287          | 942           | 600          | 1969          |
| 15      | -113.48       | 885           | 2903           | 298          | 977           | 587          | 1926          |
| 16      | -113.41       | 884           | 2900           | 297          | 974           | 587          | 1926          |
| 17      | -113.4        | 883           | 2897           | 300          | 984           | 583          | 1913          |
| 18      | -113.36       | 881           | 2892           | 302          | 992           | 579          | 1900          |
| 19      | -113.25       | 881           | 2891           | 307          | 1008          | 574          | 1883          |
| 20      | -113.21       | 880           | 2889           | 310          | 1019          | 570          | 1870          |
| 21      | -113.17       | 878           | 2881           | 312          | 1024          | 566          | 1857          |
| 22      | -113.12       | 877           | 2876           | 311          | 1019          | 566          | 1857          |
| 23      | -113.1        | 875           | 2871           | 309          | 1014          | 566          | 1857          |
| 24      | -112.98       | 873           | 2864           | 307          | 1007          | 566          | 1857          |
| 25      | -112.77       | 872           | 2860           | 311          | 1019          | 561          | 1841          |
| 26      | -112.74       | 869           | 2851           | 312          | 1024          | 557          | 1828          |
| 27      | -112.75       | 867           | 2846           | 310          | 1018          | 557          | 1828          |
| 28      | -112.74       | 865           | 2839           | 308          | 1011          | 557          | 1828          |
| 29      | -112.82       | 859           | 2817           | 302          | 990           | 557          | 1828          |
| 30      | -112.8        | 858           | 2815           | 301          | 987           | 557          | 1828          |
| 31      | -112.86       | 854           | 2801           | 310          | 1016          | 544          | 1785          |
| 32      | -112.84       | 848           | 2784           | 313          | 1029          | 535          | 1755          |
| 33      | -112.88       | 843           | 2766           | 304          | 998           | 539          | 1768          |
| 34      | -112.91       | 844           | 2770           | 300          | 985           | 544          | 1785          |
| 35      | -113.01       | 837           | 2748           | 306          | 1005          | 531          | 1742          |
| 36      | -113.09       | 833           | 2733           | 311          | 1020          | 522          | 1713          |
| 37      | -113.14       | 832           | 2729           | 293          | 960           | 539          | 1768          |
| 38      | -113.16       | 829           | 2720           | 285          | 935           | 544          | 1785          |
| 39      | -113.15       | 826           | 2712           | 269          | 884           | 557          | 1828          |
| 40      | -113.22       | 822           | 2698           | 261          | 857           | 561          | 1841          |
| 41      | -113.52       | 820           | 2690           | 246          | 806           | 574          | 1883          |
| 42      | -113.67       | 815           | 2673           | 228          | 747           | 587          | 1926          |
| 43      | -113.87       | 810           | 2657           | 205          | 672           | 605          | 1985          |
| 44      | -113.98       | 806           | 2644           | 180          | 590           | 626          | 2054          |
| 45      | -113.92       | 804           | 2639           | 169          | 556           | 635          | 2083          |
| 46      | -113.88       | 803           | 2635           | 150          | 493           | 653          | 2142          |
| 47      | -113.81       | 800           | 2625           | 139          | 456           | 661          | 2169          |
| 48      | -113.9        | 796           | 2613           | 126          | 415           | 670          | 2198          |
| 49      | -113.97       | 795           | 2609           | 125          | 411           | 670          | 2198          |
| 50      | -114.01       | 794           | 2606           | 124          | 408           | 670          | 2198          |
| 51      | -114.05       | 792           | 2600           | 122          | 402           | 670          | 2198          |
| 52      | -114.08       | 792           | 2600           | 122          | 402           | 670          | 2198          |
| 53      | -114.03       | 794           | 2605           | 124          | 407           | 670          | 2198          |
| 54      | -114.14       | 796           | 2611           | 126          | 413           | 670          | 2198          |
| 55      | -114.29       | 796           | 2611           | 126          | 412           | 670          | 2198          |
| 56      | -114.39       | 794           | 2607           | 124          | 408           | 670          | 2198          |
| 57      | -114.4        | 796           | 2610           | 126          | 412           | 670          | 2198          |
| 58      | -114.44       | 796           | 2612           | 126          | 414           | 670          | 2198          |
| 59      | -114.47       | 796           | 2611           | 126          | 413           | 670          | 2198          |

**APPENDIX TWO**  
**Water Sampling Data**

**Conventional recharge area surface sample location key for Figure 7:**

1. Indian Wells Canyon Mine Spring
2. Indian Wells Canyon Stream
3. Indian Wells (Lodge Spring)
4. Three Pines Canyon Spring
5. Buena Vista Canyon Spring
6. Walker Pass Spring
7. 5500' rain gage
8. 5000' rain gage
9. 4500' rain gage
10. 4000' rain gage
11. Big Spring
12. Soldier Spring (Soldier Wells)
13. Cow Heaven Canyon Spring
14. Boulder Canyon Spring
15. McIvers Spring
16. Yellow Jacket Spring
17. Sage Canyon Spring "D"
18. Sage Canyon Spring "A"
19. Sage Canyon Stream
20. Horse Canyon Spring
21. Horse Canyon Well
22. Bird Spring
23. Dove Spring

**Unconventional recharge area surface sample location key for Figure 32:**

1. Bigfoot Spring
2. South Kennedy Meadows Government Spring
3. Sacatar Canyon
4. Edgar's Spring
5. Round Meadow
6. Mosquito Meadow
7. Cannell Meadows
8. True Meadow
9. Bartolas Country
10. Taylor Meadow
11. Bloomfield Ranch Spring

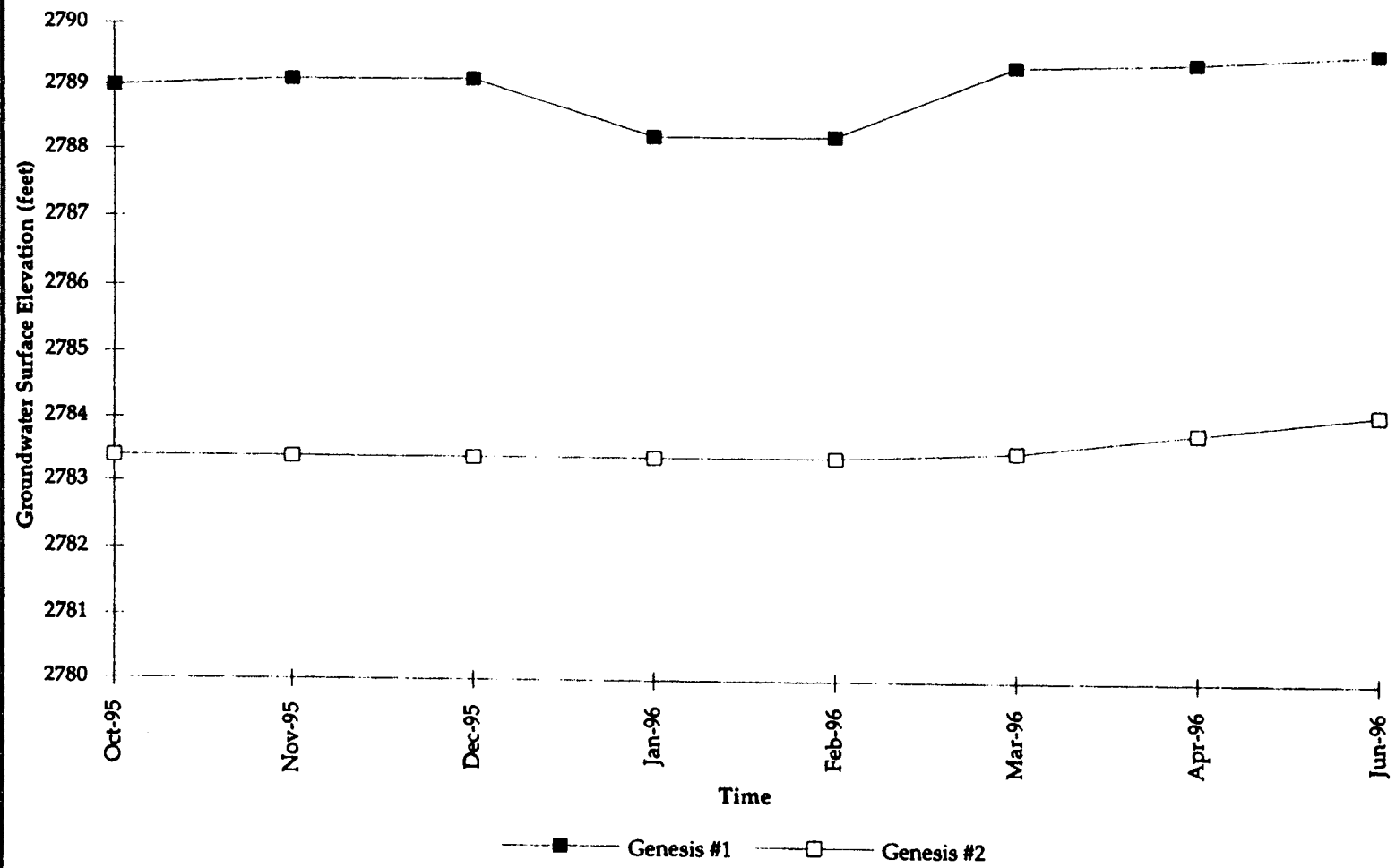


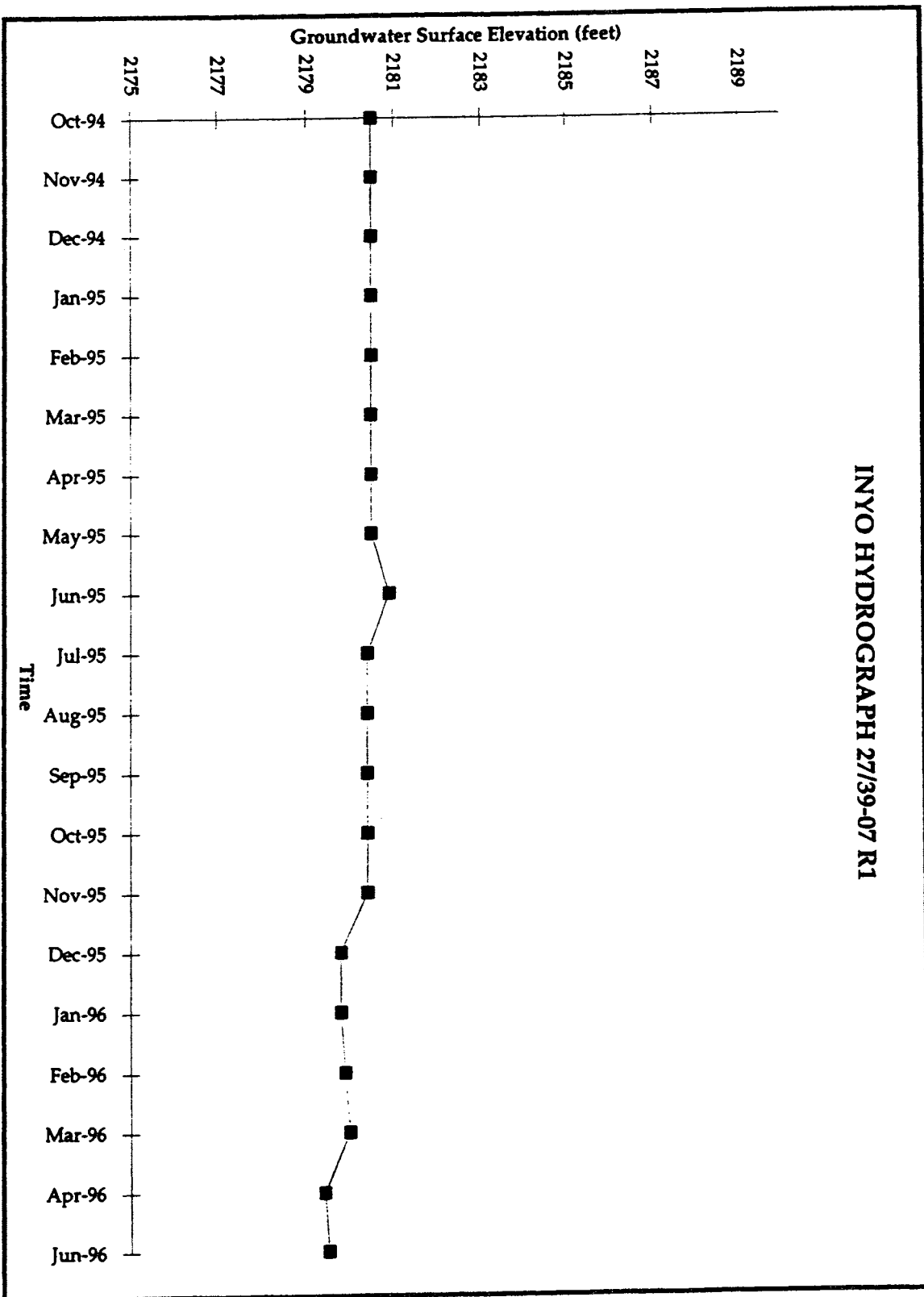
| Sample Name | Date    | Well Numb   | Ca     | Mg    | Na       | K     | CO3   | HCO3   | Cl       | SO4    | NO3  | F    | Br   | Lab pH | Lab TDS | Lab Alk | Cations | Anions | Chg. Bal | Fid pH | Fid Alk | Fid Temp | Deuterium | Oxygen-18 | Log p CO2 |
|-------------|---------|-------------|--------|-------|----------|-------|-------|--------|----------|--------|------|------|------|--------|---------|---------|---------|--------|----------|--------|---------|----------|-----------|-----------|-----------|
|             |         |             | mg/L   | mg/L  | mg/L     | mg/L  | mg/L  | mg/L   | mg/L     | mg/L   | mg/L | mg/L | mg/L |        | mg/L    | mg/L    | meq/L   | meq/L  |          |        | mg/L    | Celsius  | per mil   | per mil   |           |
| BR-1 Sh     | 2/19/96 | 27/38-23 F1 | 0.52   | 0.18  | 91.50    | 0.55  | 13.40 | 175.00 | 8.96     | 11.80  | 1.34 | 0.33 | 0.15 | 9.2    | 249     | 188     |         |        |          | 9.7    | 187     | 18.4     | -103      | -13.7     | -4.614    |
|             |         |             | 0.03   | 0.01  | 3.98     | 0.01  | 0.45  | 2.87   | 0.25     | 0.25   | 0.02 | 0.02 | 0.00 |        |         |         | 4.03    | 3.85   | 2.28%    |        |         |          |           |           |           |
| BR-1 ShMd   | 2/19/96 | 27/38-23 F2 | 0.49   | 0.05  | 93.00    | 0.25  | 11.90 | 187.00 | 7.28     | 10.10  | 2.04 | 0.12 | 0.14 | 9.1    | 240     | 199     |         |        |          | 9.5    | 124     | 28.0     | -103      | -13.9     | -4.192    |
|             |         |             | 0.02   | 0.00  | 4.05     | 0.01  | 0.40  | 3.07   | 0.21     | 0.21   | 0.03 | 0.01 | 0.00 |        |         |         | 4.08    | 3.92   | 2.01%    |        |         |          |           |           |           |
| BR-1 DpMd   | 2/19/96 | 27/38-23 F3 | 0.31   | 0.06  | 102.00   | 0.57  | 12.20 | 180.00 | 9.35     | 11.60  | 1.38 | 0.60 | 0.15 | 9.2    | 241     | 192     |         |        |          | 9.6    | 229     | 27.0     | -103      | -13.6     | -4.361    |
|             |         |             | 0.02   | 0.00  | 4.44     | 0.01  | 0.41  | 2.95   | 0.26     | 0.24   | 0.02 | 0.03 | 0.00 |        |         |         | 4.47    | 3.92   | 6.60%    |        |         |          |           |           |           |
| BR-1 Dp     | 2/19/96 | 27/38-23 F4 | 0.39   | 0.09  | 101.00   | 0.90  | 9.10  | 193.00 | 7.89     | 9.90   | 1.42 | 0.40 | 0.14 | 9.0    | 245     | 202     |         |        |          | 9.5    | 261     | 25.0     | -100      | -13.6     | -4.132    |
|             |         |             | 0.02   | 0.01  | 4.39     | 0.02  | 0.30  | 3.16   | 0.22     | 0.21   | 0.02 | 0.02 | 0.00 |        |         |         | 4.44    | 3.94   | 5.98%    |        |         |          |           |           |           |
| BR-2 Sh     | 2/16/96 | 27/38-02 C1 | 8.12   | 0.09  | 166.00   | 3.83  | 84.90 | 8.03   | 23.80    | 35.50  | 0.04 | 0.14 | 0.16 | 11.4   | 485     | 93      |         |        |          | 11.3   | 202     | 23.0     | -100      | -13.6     | -7.325    |
|             |         |             | 0.41   | 0.01  | 7.22     | 0.15  | 2.83  | 0.47   | 0.67     | 1.16   | 0.00 | 0.01 | 0.00 |        |         |         | 7.78    | 5.14   | 4.30%    |        |         |          |           |           |           |
| BR-2 Md     | 2/16/96 | 27/38-02 C2 | 3.28   | 0.84  | 52.00    | 0.97  | 7.06  | 106.00 | 4.60     | 22.20  | 0.30 | 0.01 | 0.05 | 9.2    | 171     | 113     |         |        |          | 9.2    | 145     | 28.5     | -102      | -13.6     | -4.073    |
|             |         |             | 0.16   | 0.07  | 2.26     | 0.02  | 0.24  | 1.74   | 0.13     | 0.46   | 0.00 | 0.00 | 0.00 |        |         |         | 2.52    | 2.57   | -1.02%   |        |         |          |           |           |           |
| BR-2 Dp     | 2/16/96 | 27/38-02 C3 | 6.99   | 0.38  | 117.00   | 1.13  | 0.68  | 60.00  | 56.60    | 96.30  | 0.09 | 8.61 | 0.21 | 8.4    | 329     | 60      |         |        |          | 8.5    | 79      | 28.5     | -99       | -13.1     | -3.377    |
|             |         |             | 0.35   | 0.03  | 5.09     | 0.03  | 0.02  | 0.98   | 1.60     | 2.01   | 0.00 | 0.45 | 0.00 |        |         |         | 5.50    | 5.07   | 4.09%    |        |         |          |           |           |           |
| BR-3 Sh     | 2/9/96  | 27/39-11 D1 | 18.40  | 3.76  | 90.90    | 5.10  | 0.79  | 127.00 | 30.20    | 74.90  | 1.80 | 0.47 | 0.33 | 8.1    | 326     | 127     |         |        |          | 6.7    | 11      | 25.7     | -100      | -13       | -2.627    |
|             |         |             | 0.92   | 0.31  | 3.93     | 0.13  | 0.03  | 2.08   | 1.42     | 1.56   | 0.03 | 0.02 | 0.00 |        |         |         | 5.31    | 5.14   | 1.62%    |        |         |          |           |           |           |
| BR-3 Md     | 2/9/96  | 27/39-11 D2 | 388.00 | 10.80 | 1,540.00 | 17.10 | 0.03  | 20.10  | 2,990.00 | 369.00 | 0.07 | 1.86 | 3.55 | 7.5    | 5680    | 20      |         |        |          | 8.5    | 15      | 24.1     | -91       | -12.1     | -4.32     |
|             |         |             | 19.36  | 0.89  | 66.99    | 0.44  | 0.00  | 0.33   | 84.34    | 7.69   | 0.00 | 0.10 | 0.07 |        |         |         | 87.67   | 92.52  | -2.69%   |        |         |          |           |           |           |
| BR-3 Dp     | 2/9/96  | 27/39-11 D3 | 616.00 | 40.00 | 1,970.00 | 30.80 | 0.02  | 18.90  | 4,240.00 | 77.30  | 0.09 | 2.65 | 7.14 | 7.4    | 7780    | 19      |         |        |          | 7.3    | 15      | 20.8     | -90       | -11.6     | -3.183    |
|             |         |             | 30.74  | 3.29  | 83.69    | 0.79  | 0.00  | 0.31   | 119.59   | 1.61   | 0.00 | 0.14 | 0.09 |        |         |         | 120.51  | 121.75 | -0.51%   |        |         |          |           |           |           |
| MW-32 Sh    | 2/8/96  | 26/39-27 D1 | 21.20  | 5.31  | 48.00    | 4.68  | 0.64  | 127.00 | 27.60    | 38.70  | 1.24 | 0.94 | 0.32 | 8.0    | 245     | 128     |         |        |          | 8.3    | 100     | 23.9     | -99       | -12.6     | -3.274    |
|             |         |             | 1.06   | 0.44  | 2.09     | 0.12  | 0.02  | 2.08   | 0.78     | 0.81   | 0.02 | 0.05 | 0.00 |        |         |         | 3.70    | 3.76   | -0.00%   |        |         |          |           |           |           |
| MW-32 ShN   | 2/8/96  | 26/39-27 D2 | 16.10  | 0.98  | 44.20    | 1.97  | 0.42  | 89.60  | 25.60    | 27.30  | 3.03 | 0.09 | 0.28 | 8.0    | 210     | 90      |         |        |          | 8.3    | 92      | 23.9     | -99       | -13.1     | -3.399    |
|             |         |             | 0.80   | 0.08  | 1.92     | 0.05  | 0.01  | 1.47   | 0.72     | 0.57   | 0.05 | 0.00 | 0.00 |        |         |         | 2.86    | 2.83   | 0.46%    |        |         |          |           |           |           |
| MW-32 Dp    | 2/9/96  | 26/39-27 D3 | 0.34   | 0.09  | 227.00   | 2.61  | 1.36  | 110.00 | 23.10    | 21.50  | 3.18 | 0.10 | 0.28 | 8.4    | 220     | 111     |         |        |          | 8.7    | 90      | 24.0     | -99       | -13.5     | -3.636    |
|             |         |             | 0.02   | 0.01  | 9.87     | 0.07  | 0.05  | 1.80   | 0.65     | 0.45   | 0.05 | 0.01 | 0.00 |        |         |         | 9.96    | 3.01   | 4.90%    |        |         |          |           |           |           |
| MW-32 Dp    | 2/9/96  | 26/39-27 D4 | 2.64   | 0.21  | 65.60    | 1.47  | 29.80 | 251.00 | 81.90    | 73.00  | 0.03 | 5.61 | 0.31 | 9.4    | 596     | 281     |         |        |          | 9.4    | 141     | 26.0     | -104      | -13.5     | -4.287    |
|             |         |             | 0.13   | 0.02  | 2.85     | 0.04  | 0.99  | 4.11   | 2.31     | 1.52   | 0.00 | 0.30 | 0.00 |        |         |         | 3.04    | 9.24   | 4.90%    |        |         |          |           |           |           |
| Knecht Wel  | 1/13/96 | 27/38-35 N1 | 0.75   | 0.05  | 53.30    | 0.48  | 5.03  | 97.20  | 5.70     | 11.00  | 3.29 | 0.13 | 0.06 | 9.1    | 155     | 102     |         |        |          | 9.3    | 85      | 24.6     | -110      | -14.3     | -4.38     |
|             |         |             | 0.04   | 0.00  | 2.32     | 0.01  | 0.17  | 1.59   | 0.16     | 0.23   | 0.05 | 0.01 | 0.00 |        |         |         | 2.37    | 2.21   | 3.46%    |        |         |          |           |           |           |
| Genesis 1   | 6/29/96 | 27/38-30 K1 | 2.28   | 0.15  | 75.10    | 0.65  | 6.80  | 64.40  | 12.10    | 20.20  | 1.35 | 9.15 | 0.34 | 9.4    | 175     | 73      |         |        |          | 9.2    | 55      | 29.1     | -111      | -13.6     | -4.476    |
|             |         |             | 0.11   | 0.01  | 3.27     | 0.02  | 0.23  | 1.06   | 0.34     | 0.42   | 0.02 | 0.48 | 0.00 |        |         |         | 3.41    | 2.55   | 1.90%    |        |         |          |           |           |           |
| SW-3        | 6/30/96 | 27/39-19 E1 | 2.62   | 0.11  | 87.10    | 0.47  | 9.07  | 74.80  | 20.90    | 28.50  | 0.09 | 3.99 | 0.19 | 9.4    | 190     | 84      |         |        |          | 9.3    | 131     | 23.8     | -105      | -13.1     | -4.185    |
|             |         |             | 0.13   | 0.01  | 3.79     | 0.01  | 0.30  | 1.23   | 0.59     | 0.59   | 0.00 | 0.21 | 0.00 |        |         |         | 3.94    | 2.93   | 5.60%    |        |         |          |           |           |           |
| Knecht      | 6/29/96 | 27/38-35 N1 | 0.87   | 0.09  | 66.20    | 0.52  | 10.20 | 80.10  | 5.30     | 17.60  | 3.09 | 0.43 | 0.07 | 9.4    | 187     | 90      |         |        |          | 9.3    | 95      | 29.7     | -115      | -14.4     | -4.338    |
|             |         |             | 0.04   | 0.01  | 2.88     | 0.01  | 0.34  | 1.31   | 0.16     | 0.37   | 0.05 | 0.02 | 0.00 |        |         |         | 2.94    | 2.25   | 1.10%    |        |         |          |           |           |           |

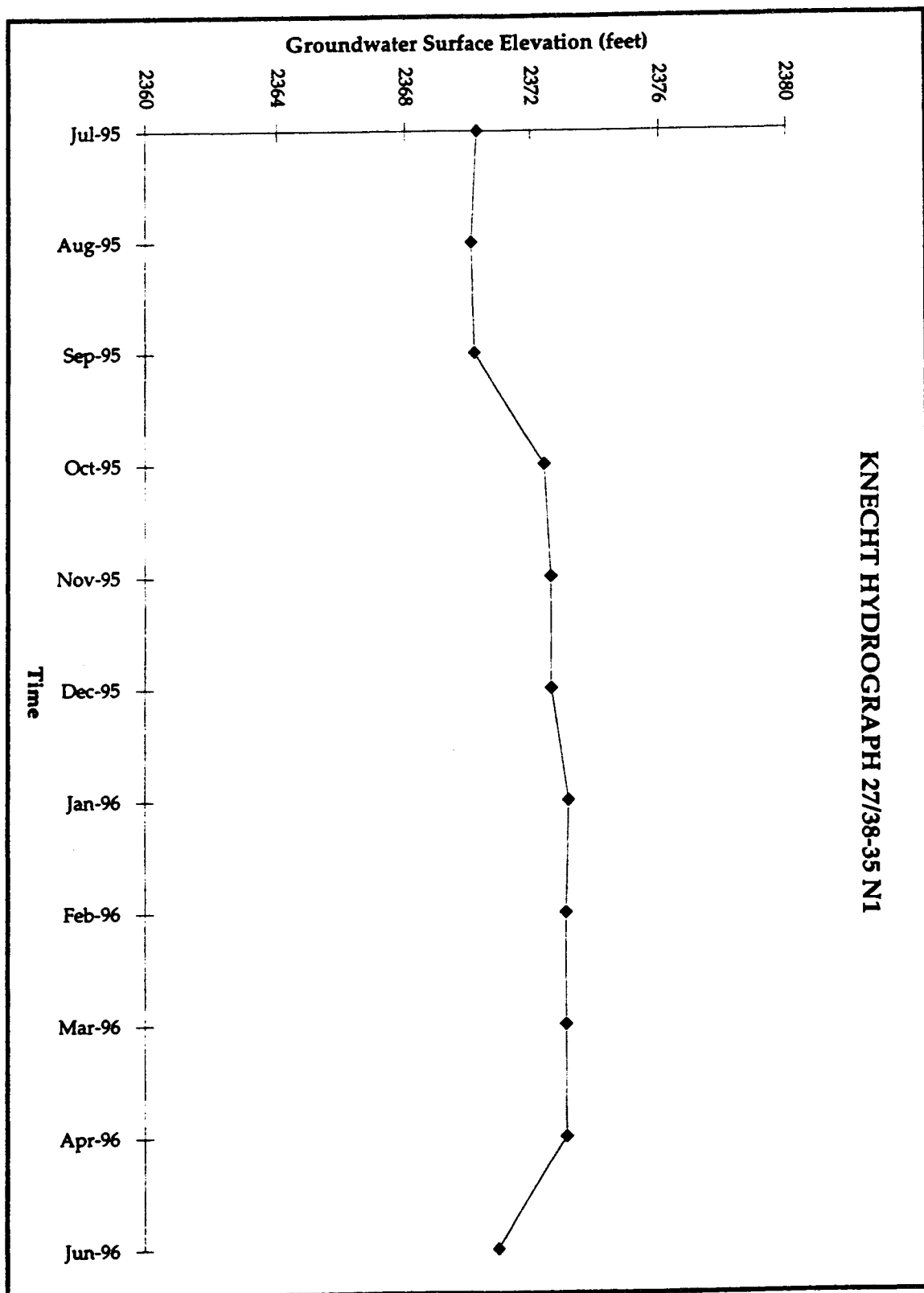
## **APPENDIX THREE**

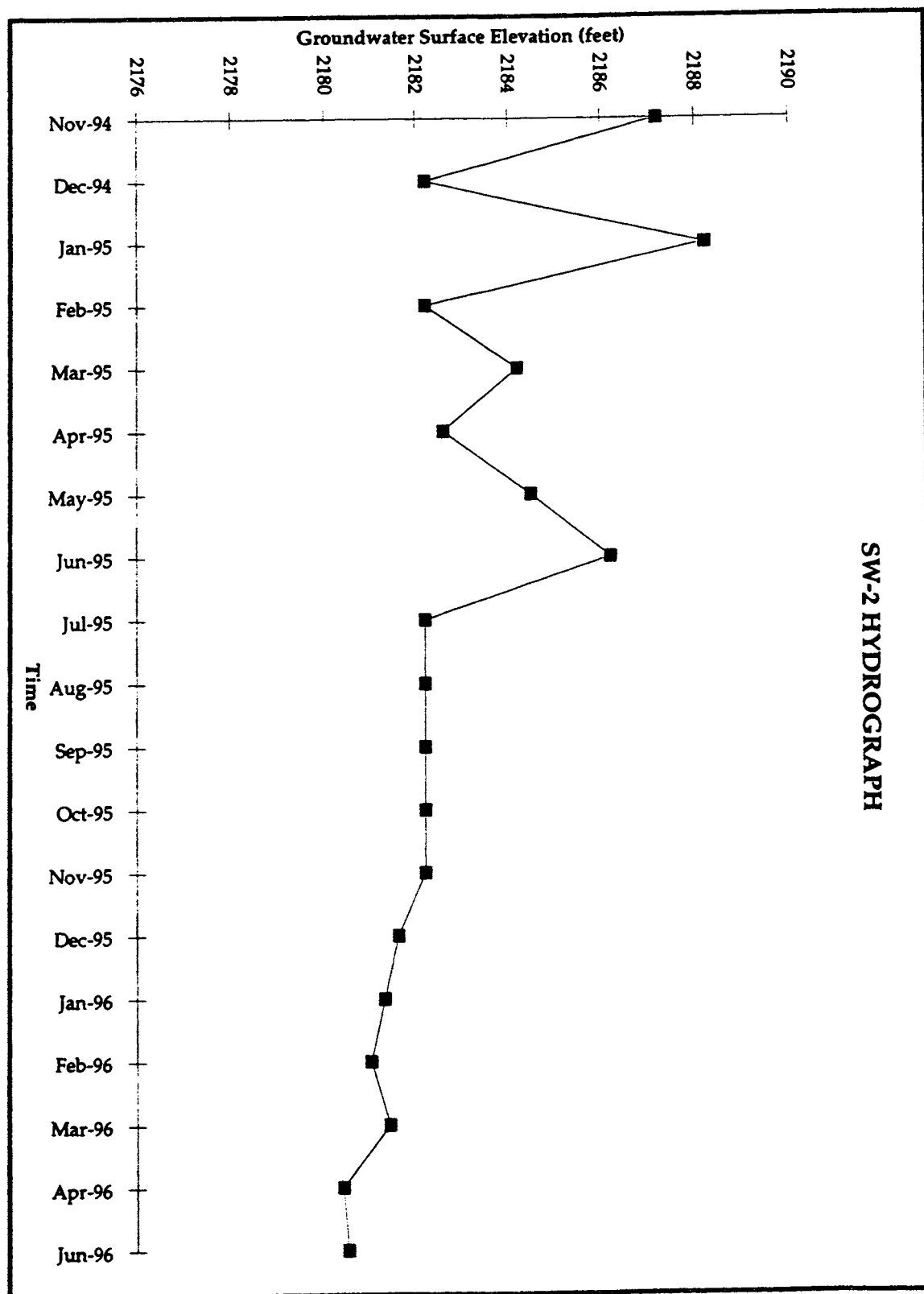
### **Hydrographs**

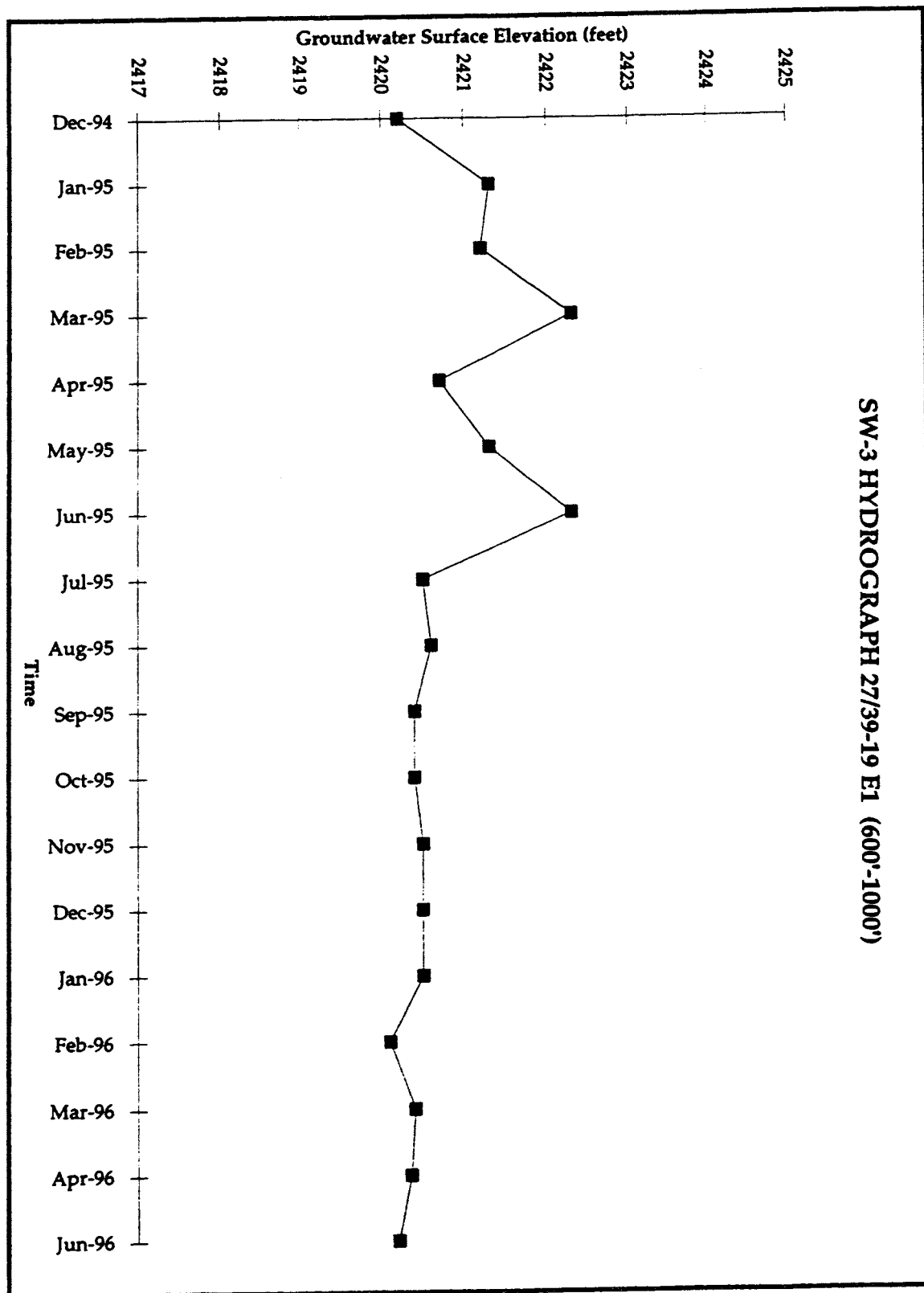
### GENESIS HYDROGRAPHS 27/38-30 K1-2

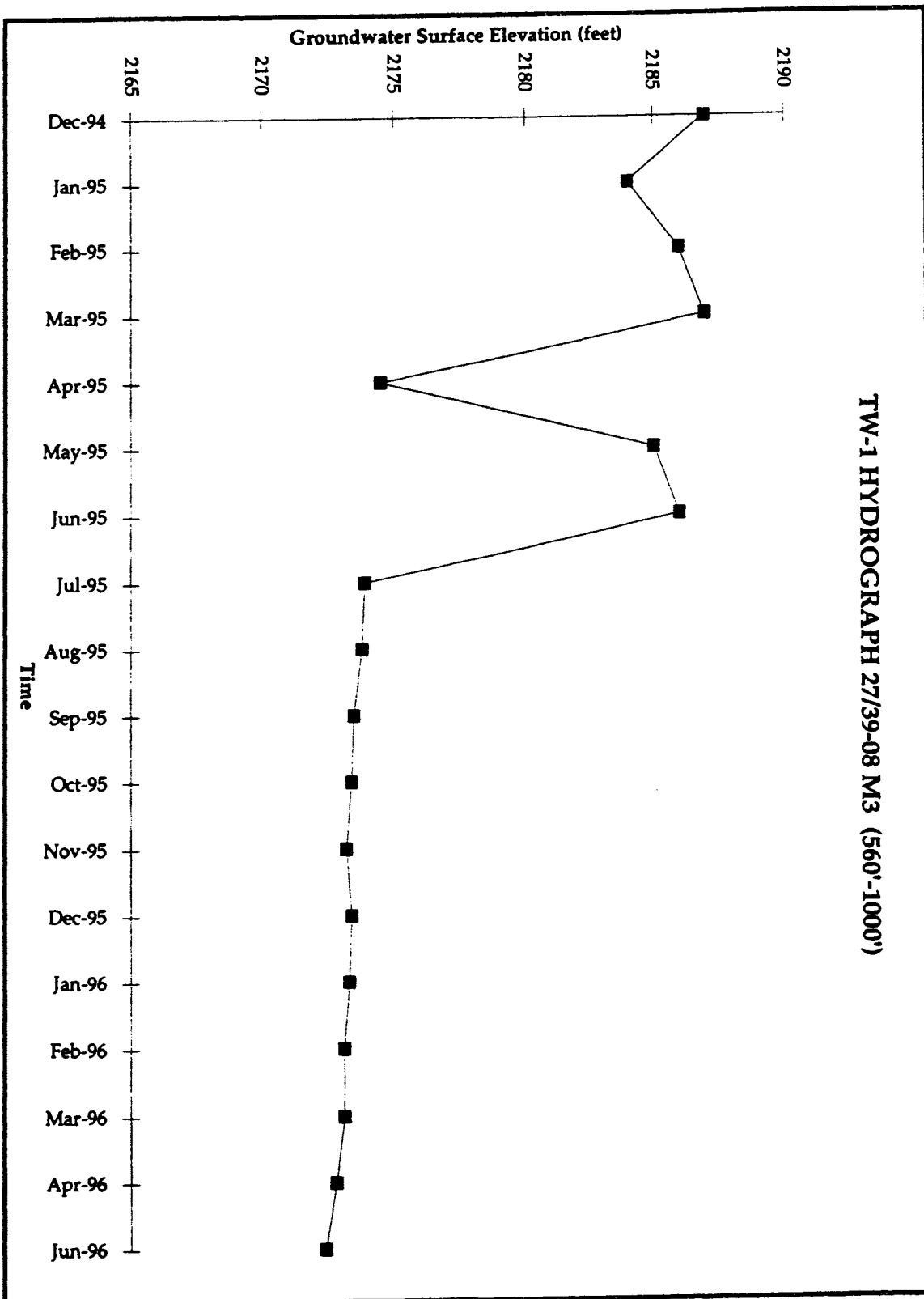






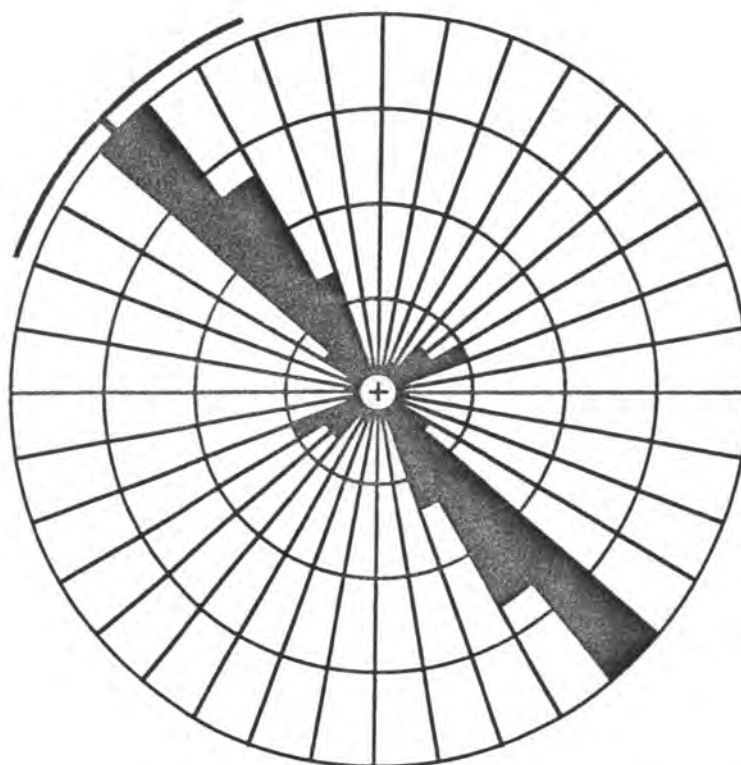




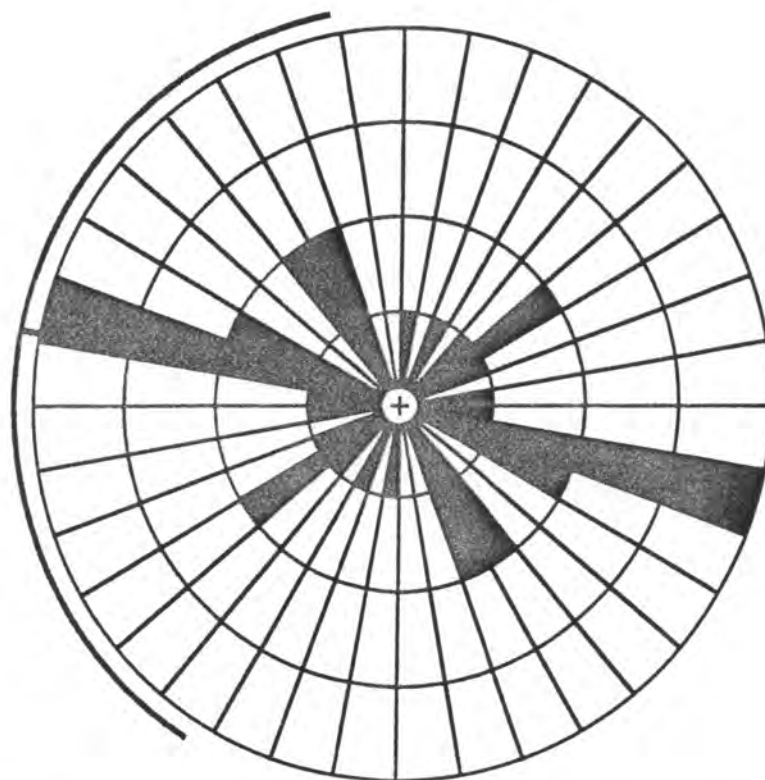


## **APPENDIX FOUR**

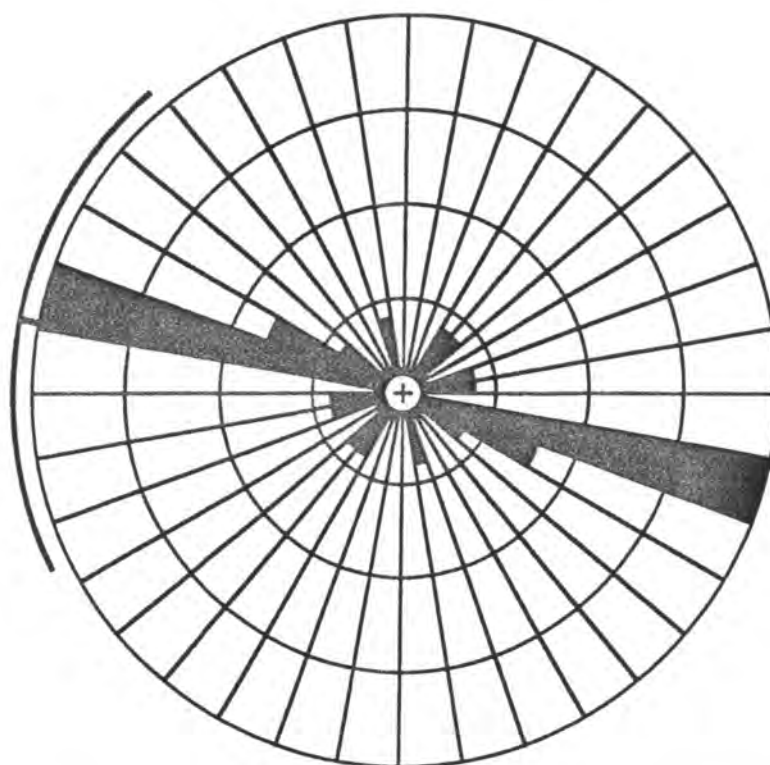
### **Fracture Data**



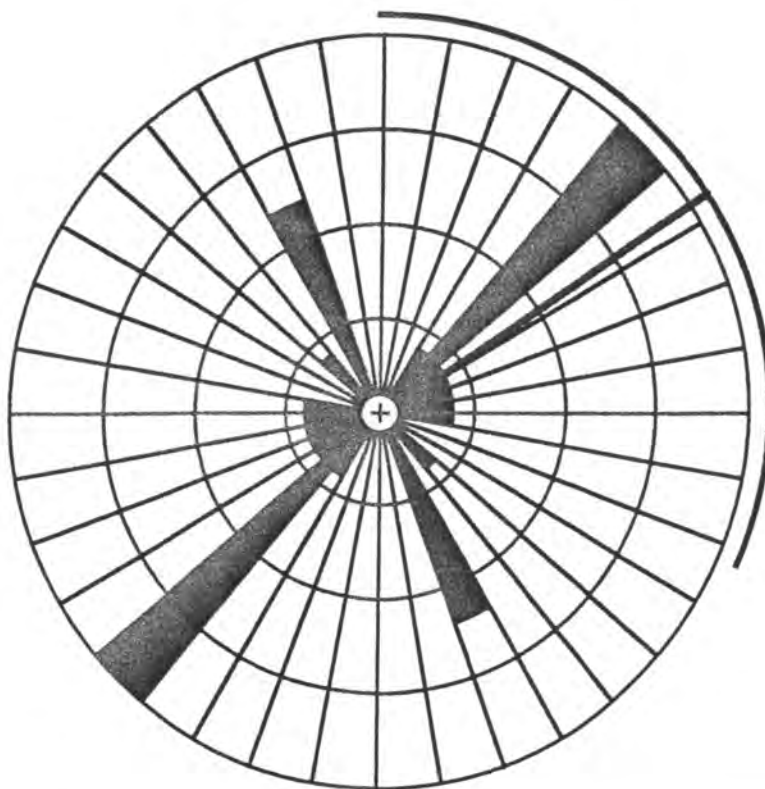
| Freeman Canyon Fracture Data Set                    | Statistics          |
|-----------------------------------------------------|---------------------|
| N = 37                                              | Vector Mean = 313.8 |
| Class Interval = 10 degrees                         | Conf. Angle = 24.27 |
| Maximum Percentage = 32.4                           | R Magnitude = 0.499 |
| Mean Percentage = 9.09    Standard Deviation = 9.31 | Rayleigh = 0.0001   |



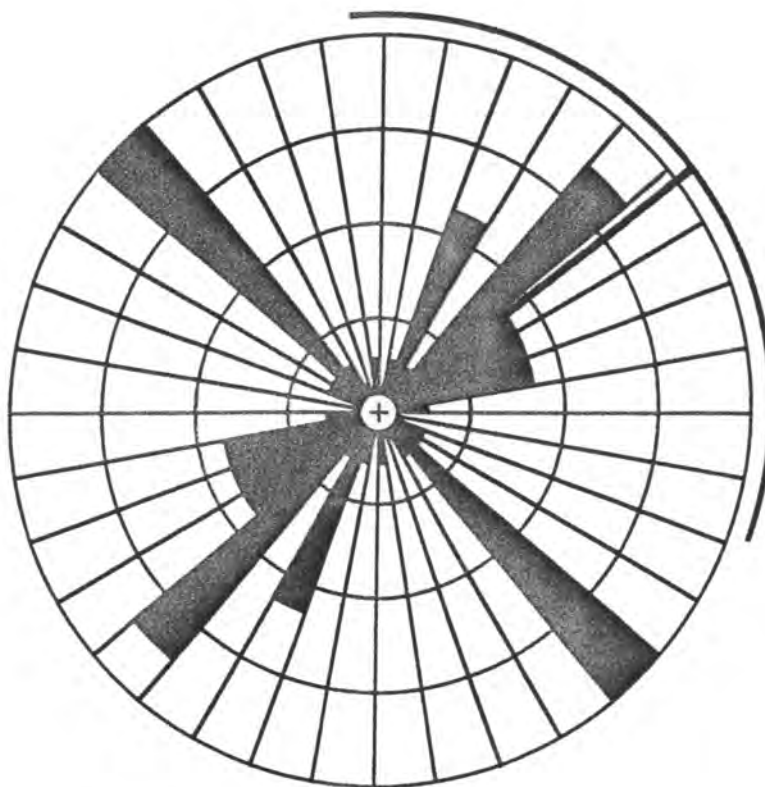
| Cow Heaven Canyon Fracture Data Set                 | Statistics          |
|-----------------------------------------------------|---------------------|
| N = 18                                              | Vector Mean = 281.4 |
| Class Interval = 10 degrees                         | Conf. Angle = 68.20 |
| Maximum Percentage = 22.2                           | R Magnitude = 0.269 |
| Mean Percentage = 9.09    Standard Deviation = 5.01 | Rayleigh = 0.2731   |



| Boulder Canyon Fracture Data Set                     | Statistics          |
|------------------------------------------------------|---------------------|
| N = 13                                               | Vector Mean = 281.1 |
| Class Interval = 10 degrees                          | Conf. Angle = 38.04 |
| Maximum Percentage = 38.5                            | R Magnitude = 0.534 |
| Mean Percentage = 12.50   Standard Deviation = 10.46 | Rayleigh = 0.0247   |



| Sage Canyon Fracture Data Set                       | Statistics          |
|-----------------------------------------------------|---------------------|
| N = 15                                              | Vector Mean = 56.4  |
| Class Interval = 10 degrees                         | Conf. Angle = 57.06 |
| Maximum Percentage = 33.3                           | R Magnitude = 0.345 |
| Mean Percentage = 11.11   Standard Deviation = 9.15 | Rayleigh = 0.1671   |



| Horse Canyon Fracture Data Set                      | Statistics          |
|-----------------------------------------------------|---------------------|
| N = 33                                              | Vector Mean = 51.9  |
| Class Interval = 10 degrees                         | Conf. Angle = 57.10 |
| Maximum Percentage = 21.2                           | R Magnitude = 0.237 |
| Mean Percentage = 7.69    Standard Deviation = 6.13 | Rayleigh = 0.1566   |

**APPENDIX FIVE**  
**TW-1 Drawdown Data**

INDIAN WELLS VALLEY WATER DISTRICT  
SOUTHWEST WELL FIELD  
AQUIFER TEST DATA

TEST NAME: MONITORING WELL 1 - 24 HOUR CONSTANT RATE - DRAWDOWN

TEST DATE: JUNE 5, 1989

| ELAPSED<br>TIME<br>(MIN) | DRAWDOWN<br>(FT) | FLOW<br>(GPM) |
|--------------------------|------------------|---------------|
| 30s                      | 0.40             | N/A           |
| 1m                       | 0.48             |               |
| 1m 30s                   | 0.58             |               |
| 2m                       | 0.70             |               |
| 2m 30s                   | 0.81             |               |
| 3m                       | 0.90             |               |
| 3m 30s                   | 1.00             |               |
| 4m                       | 1.10             |               |
| 4m 30s                   | 1.18             |               |
| 5m                       | 1.26             |               |
| 6m                       | 1.41             |               |
| 7m                       | 1.55             |               |
| 8m                       | 1.66             |               |
| 9m                       | 1.77             |               |
| 10m                      | 1.86             |               |
| 15m                      | 2.25             |               |
| 20m                      | 2.51             |               |
| 25m                      | 2.71             |               |
| 30m                      | 2.88             |               |
| 35m                      | 3.01             |               |
| 40m                      | 3.12             |               |
| 45m                      | 3.22             |               |
| 50m                      | 3.30             |               |
| 55m                      | 3.38             |               |
| 60m                      | 3.44             |               |
| 65m                      | 3.50             |               |
| 70m                      | 3.55             |               |
| 75m                      | 3.60             |               |
| 80m                      | 3.64             |               |
| 85m                      | 3.68             |               |
| 90m                      | 3.72             |               |
| 95m                      | 3.75             |               |
| 100m                     | 3.78             |               |
| 105m                     | 3.81             |               |
| 110m                     | 3.84             |               |
| 115m                     | 3.87             |               |
| 120m                     | 3.89             | N/A           |

TEST NAME: MONITORING WELL 1 - 24 HOUR CONSTANT RATE - DRAWDOWN (CONTINUED)

TEST DATE: JUNE 5, 1989

| ELAPSED<br>TIME<br>(MIN) | DRAWDOWN<br>(FT) | FLOW<br>(GPM) |
|--------------------------|------------------|---------------|
| 130m                     | 3.94             | N/A           |
| 140m                     | 3.97             |               |
| 150m                     | 4.01             |               |
| 160m                     | 4.03             |               |
| 170m                     | 4.07             |               |
| 180m                     | 4.10             |               |
| 190m                     | 4.12             |               |
| 200m                     | 4.14             |               |
| 210m                     | 4.17             |               |
| 220m                     | 4.19             |               |
| 230m                     | 4.21             |               |
| 240m                     | 4.22             |               |
| 260m                     | 4.23             |               |
| 280m                     | 4.25             |               |
| 300m                     | 4.27             |               |
| 330m                     | 4.30             |               |
| 360m                     | 4.34             |               |
| 390m                     | 4.34             |               |
| 420m                     | 4.37             |               |
| 450m                     | 4.38             |               |
| 480m                     | 4.39             |               |
| 510m                     | 4.41             |               |
| 540m                     | 4.44             |               |
| 600m                     | 4.48             |               |
| 660m                     | 4.53             |               |
| 720m                     | 4.56             |               |
| 780m                     | 4.57             |               |
| 840m                     | 4.64             |               |
| 900m                     | 4.64             |               |
| 960m                     | 4.64             |               |
| 1020m                    | 4.66             |               |
| 1080m                    | 4.69             |               |
| 1140m                    | 4.70             |               |
| 1200m                    | 4.72             |               |
| 1260m                    | 4.72             |               |
| 1320m                    | 4.73             |               |
| 1380m                    | 4.74             |               |
| 1440m                    | 4.75             | N/A           |