CNWRA 95-009

THE CNWRA REGIONAL HYDROGEOLOGY GEOGRAPHIC INFORMATION SYSTEM DATABASE

Prepared for

Nuclear Regulatory Commission
Contract NRC-02-93-005

Prepared by

Center for Nuclear Waste Regulatory Analyses
San Antonio, Texas

April 1995

CNWRA 95-009

THE CNWRA REGIONAL HYDROGEOLOGY GEOGRAPHIC INFORMATION SYSTEM DATABASE

Prepared for

Nuclear Regulatory Commission
Contract NRC-02-93-005

Prepared by

Gordon Wittmeyer
Richard Klar
George Rice
William Murphy

Center for Nuclear Waste Regulatory Analyses
San Antonio, Texas

April 1995

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

The Geographic Information System (GIS) database for the Research Project on Regional Hydrogeologic Processes of the Death Valley Region was developed to facilitate the evaluation of existing conceptual models and the construction of alternative conceptual models of the regional flow system. This GIS will also be used to assess the adequacy of the U.S. Department of Energy's (DOE) investigation of the regional hydrogeologic setting for Yucca Mountain (YM) as it relates to the regulations governing geologic disposal of HLW outlined in 10 CFR 60. This report summarizes the data collected, interpreted and entered into the ARC/INFO GIS database and describes the maps and ARC/INFO coverages specifically constructed for this research project. Data were obtained electronically from the U.S. Geological Survey (USGS), digitized directly from existing geologic maps, and manually entered from charts and tables contained in USGS and DOE reports. The regional hydrogeology GIS database is composed of seven sections: 1. physiography; 2. surface water hydrology; 3. precipitation and climate; 4. recharge and discharge; 5. wells, springs, and water level contour maps, 6. hydrogeology; and 7. hydrogeochemistry. Although these basic data categories provide a reasonably complete description of the Death Valley Region, none have yet been fully populated with data. Moreover, while most of the data that has been entered may be used to construct maps, much of the data are not yet in a format suitable for performing complex spatial queries. Once all data are placed in a format that permits queries, the GIS can be used to evaluate alternative conceptual models of the regional flow regime.

THIS PAGE INTENTIONALLY LEFT BLANK

CONTENTS

CONTENTS

FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

This report was prepared to document work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the Nuclear Regulatory Commission (NRC) under Contract No. NRC-02-93-005. The activities reported here were performed on behalf of the NRC Office of Nuclear Regulatory Research, Division of Regulatory Applications. The report is an independent product of the CNWRA and does not necessarily reflect the views or regulatory position of the NRC.

This report was greatly improved by thorough technical and programmatic reviews provided by English Pearcy and Patrick Mackin. David Turner and Sandy Nguyen assisted greatly in the development of the Stiff diagrams shown in Section 9. Finally, the careful formatting, reference checking, and preparation of tables performed by Rebecca Sanchez and Esther Cantu is greatly appreciated.

THIS PAGE INTENTIONALLY LEFT BLANK

1 INTRODUCTION

Yucca Mountain, Nevada (YM) has been proposed as a potential high-level nuclear waste (HLW) repository in part because of the favorable hydrologic environment provided by its 700-m thick unsaturated zone. Siting the repository in the unsaturated zone may significantly reduce the potential for dissolution of the waste form. Moreover, the low water flux rates that are presumed to exist in the unsaturated zone may reduce the likelihood that radionuclides that are dissolved will be rapidly transported to the accessible environment. Mechanisms that may saturate the repository horizon, and thus compromise favorable conditions provided by the YM site, include rapid infiltration of water from the surface through highly conductive fracture networks or an increase in the elevation of the regional water table. The first mechanism is a site-scale or subregional issue and is not addressed by this research project. Elevation of the water table may occur due to increased recharge to the regional carbonate aquifer along stream channels and mountain fronts in topographically closed basins 100 km to the north and northeast of YM. Even if an increase in the elevation of the regional water table does not saturate the repository block, the reduced thickness of the unsaturated zone has the potential to diminish travel times within the vadose zone. In addition, travel times in the saturated zone, and the location of potential discharge areas for dissolved radionuclides downgradient from YM are performance related issues addressed by this research project. The U.S. Department of Energy's (DOE) Waste Containment and Isolation Strategy contained in the revised Program Approach for obtaining a license to operate a HLW repository at YM places increased emphasis on the role of the saturated zone in diluting dissolved radionuclides in order to meet possible dose-based performance standards. If significant flow channeling occurs within the fractured tuff aquifer or the underlying Paleozoic carbonate aquifer, dilution of radionuclides may be greatly reduced. Therefore, this research project will examine hydraulic, mineralogic and hydrochemical data to assess the potential for radionuclides to reach the accessible environment along fast flow channels. The primary objectives of this research project are to: (i) analyze existing conceptual models and develop new conceptual models of the regional hydrogeologic flow regime in the Death Valley Region that contains YM, and (ii) construct numerical models of regional flow that may be used to assess the potential for the water table beneath YM to rise in response to wetter climatic conditions.

Predictions made with numerical models will be used by the DOE in their license application to demonstrate that the YM site meets the overall performance standards outlined in 10 CFR 60.112 and the geologic subsystem performance standard defined in 10 CFR 60.113(a)(2). In addition, the DOE may choose to use numerical models to demonstrate the absence or influence of potentially adverse conditions including: the effects of future pumping on the regional flow system [10 CFR 60.122(c)(2)]; the potential for deleterious changes to the hydrologic system [10 CFR 60.122(c)(5)]; the potential for changes to the hydrologic conditions resulting from climate change [10 CFR 60.122(c)(6)]; the potential for water table rise [10 CFR 60.122(c)(22)]; and the presence and influence of favorable conditions, including the clear absence of fully saturated pathways connecting the repository to the water table [10 CFR 60.122(b)(8)(ii)]. Understanding of the regional hydrogeologic system developed from this project will be used to guide the review of the DOE license application and to assess the adequacy of the models used by the DOE to demonstrate compliance with the regulatory requirements and environmental standards.

1.1 OUTLINE OF REPORT

This report contains a summary of data collected, interpreted, and entered into the ARC/INFO Geographic Information System (GIS) database and an overview of maps and ARC/INFO coverages constructed for the research project on Regional Hydrogeologic Processes of the Death Valley Region. Since its inception in May, 1993, considerable effort in this research project has been directed toward accomplishing the goals outlined in Task 1 on the Collection and Analysis of Data and Existing Models. The specific goals of this task are to: 1. review the existing literature; 2. conduct an inventory of hydrogeologic data in the immediate vicinity of the proposed YM repository and the Death Valley Region; and 3. compile relevant hydrogeological, hydrochemical, and mineralogical data into an integrated Geographic Information System (GIS) database. Inasmuch as DOE and its contractors are continuing to collect hydrogeologic data, and to develop conceptual and numerical models of the Death Valley regional flow system as part of the site characterization program, this report does not define the state of knowledge of the regional flow system. Moreover, much of the raw data acquired for this project were not yet been processed and synthesized into GIS coverages or into hydrostratigraphic cross-sections or 3D models.

This report is divided into seven chapters that describe the data that has been collected and the GIS coverages and databases that have subsequently been generated. A comprehensive review of literature describing the existing conceptual models of the regional flow system will be given in a forthcoming NUREG/CR. Therefore, except for brief citations from the literature describing these models and for coverages and databases developed from data contained in these reports, the literature review conducted within Task 1 will not be summarized herein. This report also describes some data and coverages that have been compiled by other research projects or NMSS task work that will be used in constructing hydrogeologic maps and hydrostratigraphic cross-sections.

1.2 REGULATORY BASIS FOR COMPILING HYDROGEOLOGIC DATABASE

Understanding of the regional hydrogeologic system gained from reviewing the existing literature and compiling relevant hydrogeologic data will be used to construct specific Compliance Determination Methods (CDMs) outlined in the License Application Review Plan (LARP) (U.S. Nuclear Regulatory Commission, 1994). Information contained in this report will provide information that may be directly used to assess the description of individual systems and characteristics of the site (LARP section 3.1) and in particular the description of the hydrologic and geochemical systems (LARP sections 3.1.2 and 3.1.3, respectively). Evidence gleaned from these data along with conceptual and numerical models of the regional flow regime developed in other tasks within this research project will be directly used to determine if the applicant has provided convincing evidence of the presence or absence of favorable hydrogeologic conditions and potentially adverse hydrogeologic conditions (LARP sections 3.2.1.1, 3.2.2.1, 3.2.2.2, 3.2.2.3, 3.2.2.6, 3.2.2.7 3.2.2.8, 3.2.2.9, 3.2.2.11, and 3.2.4.2). Flow models developed in this project will also be used to confirm that velocity fields and travel times within the saturated zone estimated by the DOE are accurate enough to demonstrate compliance with the groundwater travel time (GWTT) performance objective (LARP section 3.3).

Compliance Determination Strategies (CDSs) for the LARP sections listed previously have been developed but will not be finalized until a thorough review of the LARP has been conducted. However, the Regional Hydrogeology Research Project will be instrumental in addressing specific technical uncertainties identified during the CDS development process. Key Technical Uncertainties (KTUs) that pose a high risk of noncompliance with the total-system or subsystem performance requirements may require that the Nuclear Regulatory Commission (NRC) conduct independent research to investigate the issue. Development of a conceptual groundwater flow model that is representative of the YM site groundwater system has been identified as a KTU that must be addressed in LARP Sections 3.2.2.1, 3.2.2.9, and 3.3

1.3 PURPOSE OF THE REGIONAL HYDROGEOLOGY GIS DATABASE

A computer-based GIS database system is designed to link quantitative and qualitative data contained within a database to a common spatial reference. As such, a GIS database permits the trained user to ask questions regarding the spatial coincidence of two or more variables having values within specified ranges. For example, the regional hydrogeology GIS database may be used to construct a map showing the locations of all wells with 10 or more years of water level measurements that also lie within a zone where annual average precipitation exceeds 350 mm. Although the ability to make spatial queries is the most powerful aspect of a GIS, the primary use of this system in this research project is to construct maps consisting of one or more coverages. For example, a map consisting of water level contour from wells penetrating the Paleozoic carbonate aquifer may be overlaid on a coverage of all major faults within the Death Valley Region to assess the hydraulic control effected by these faults.

The computerized database for the regional hydrogeology of the Death Valley system was developed using the ARC/INFO GIS developed by Environmental Systems Research Institute (ESRI). ARC/INFO has been designed to facilitate the co-registration, scaling, and display of geographical data sets. The main advantage of ARC/INFO is its ability to simultaneously display and manipulate spatial information taken from sources that have different map projections and scales. Typically in GIS environments, discrete data types intrinsically tied to geographic localities are separated into coverages or layers. Coverages usually consist of a single data format: points, vectors, areas, or matrices. These data types may actually represent well locations, faults, hydrographic basins, or finite-difference grids with respect to hydrogeology.

2 PHYSIOGRAPHY

2.1 OVERVIEW

Physiographic maps, which have been traditionally sketched by hand, are constructed to highlight the landforms of primary geomorphic, geologic, hydrologic and topographic importance in a region. While excellent physiographic maps of the region of interest exist [e.g. Bedinger et al. (1989)], they do not conform to the needs of this research project since the hand-sketched features are difficult to accurately co-register with other map coverages. Moreover, their inclusion in a computer-based GIS system would require the use of an electronic image scanner with unusual accuracy. Since a map coverage is needed to convey a sense of the general topography and to establish a geographic context for other map coverages, a shaded relief map was constructed from digital elevation model (DEM) data obtained from the U.S. Geological Survey (USGS).

2.2 DATA AND GIS MAP COVERAGES

Figure 2-1 is a grayscale shaded relief map constructed from 20, 1-degree DEMs obtained for the region between 34° to 40° north latitude and 115° to 119° west longitude. Each 1×1 degree DEM consists of a 1,201 by 1,201 array of elements each of which gives the mean elevation for each 3 arc second square area. The elevation data were derived from both cartographic and photographic sources. The cartographic sources consist of map series from the 1:24,000 scale quad maps (7.5 minute series) to the 1:250,000 scale maps (1 degree). Elevation data from photographic sources were collected by using both manual and automated correlation techniques. All elevations in the DEM are given in meters relative to the North American Datum of 1929 (NGVD 29).

The shaded relief map was constructed using the software package GEOVIEW developed at the CNWRA. To construct a shaded relief map GEOVIEW first tessellates the three-dimensional (3D) topographic surface with right triangular facets. The normal vector to the triangular facet is determined by computing the cross product of the 3D vectors that coincide with the legs of the right triangle. The user of GEOVIEW then specifies the number of suns to be used for illumination as well as each sun's elevation angle, azimuth and intensity. Finally, GEOVIEW determines the albedo to be assigned to the triangular facet by summing the inner products of the normal to the facet with each sun's intensity vector. The shaded relief map constructed for this region was transferred into the ARC/INFO database as a screen raster image. A separate annotation file was constructed within ARC/INFO for this region consisting of the names of the major mountain ranges and major valleys. Figure 2-1 consists of the grayscale shaded relief screen raster image overlaid by this annotation file.

The Death Valley Region of the Great Basin has been identified as the hydrogeologic setting for YM. However, the boundaries of the Death Valley hydrogeologic system are defined differently by the various researchers who have studied the flow system. Figure 2-2 consists of the basic grayscale shaded relief map shown in Figure 2-1 overlaid by colored lines that delineate the extent of the regional flow system defined in five separate studies. The deep blue or purple lines show the region considered by Rush (1970). The outermost yellow lines define the extent of the region considered by Waddell et al. (1984). The regional flow system defined by Rice (1984) is enclosed by the cyan line. The extent of the Death Valley system of Bedinger et al. (1989) is defined by the outermost green lines. Bedinger et al. (1989) further subdivided their Death Valley Region into the eight hydrogeologic sub-basins also shown in green. Burbey and Prudic's (1991) Death Valley Region is delineated by the red line in Figure 2-2.

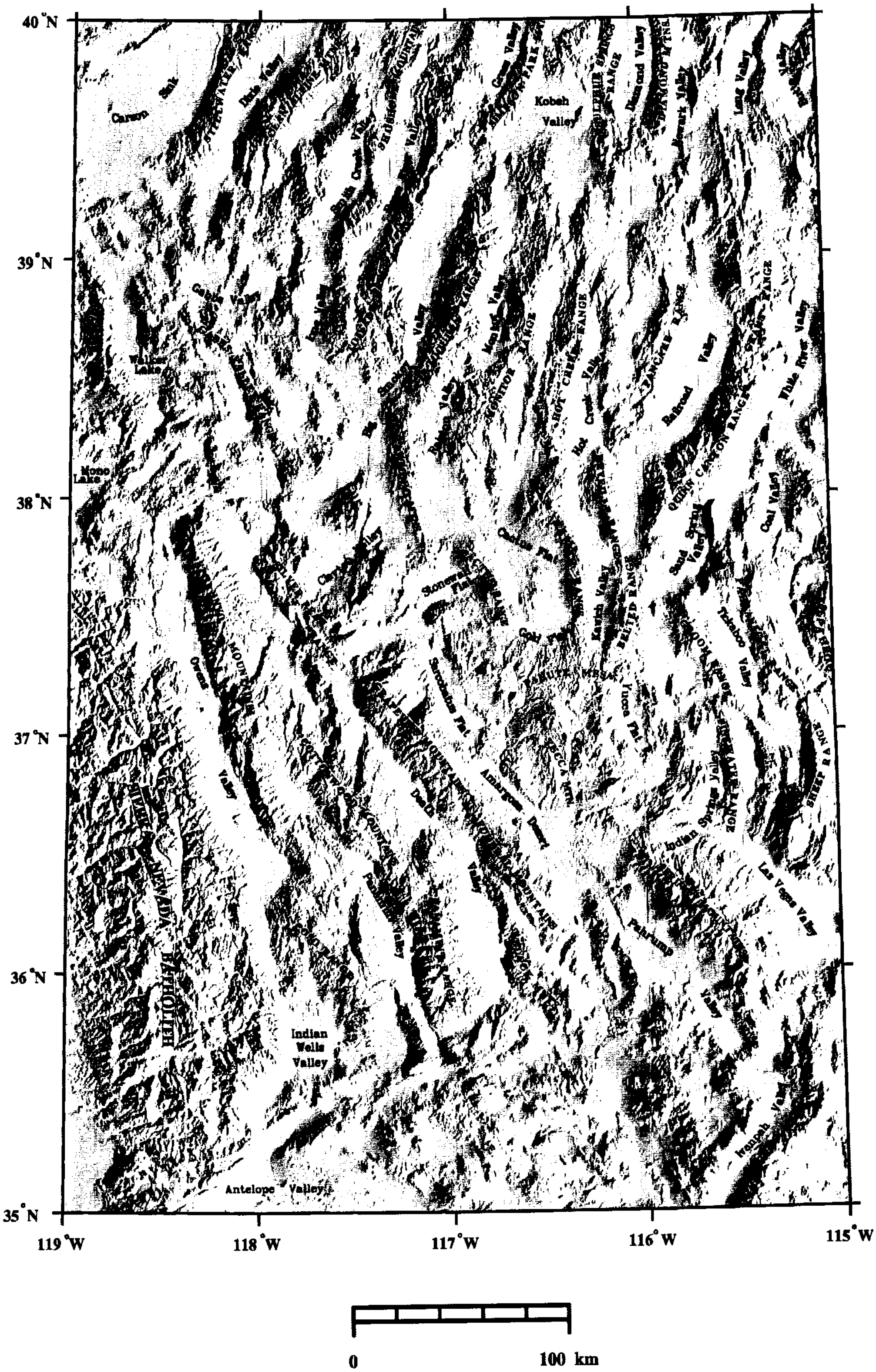

Figure 2-1. Grayscale shaded relief map showing the physiography of the Death Valley region

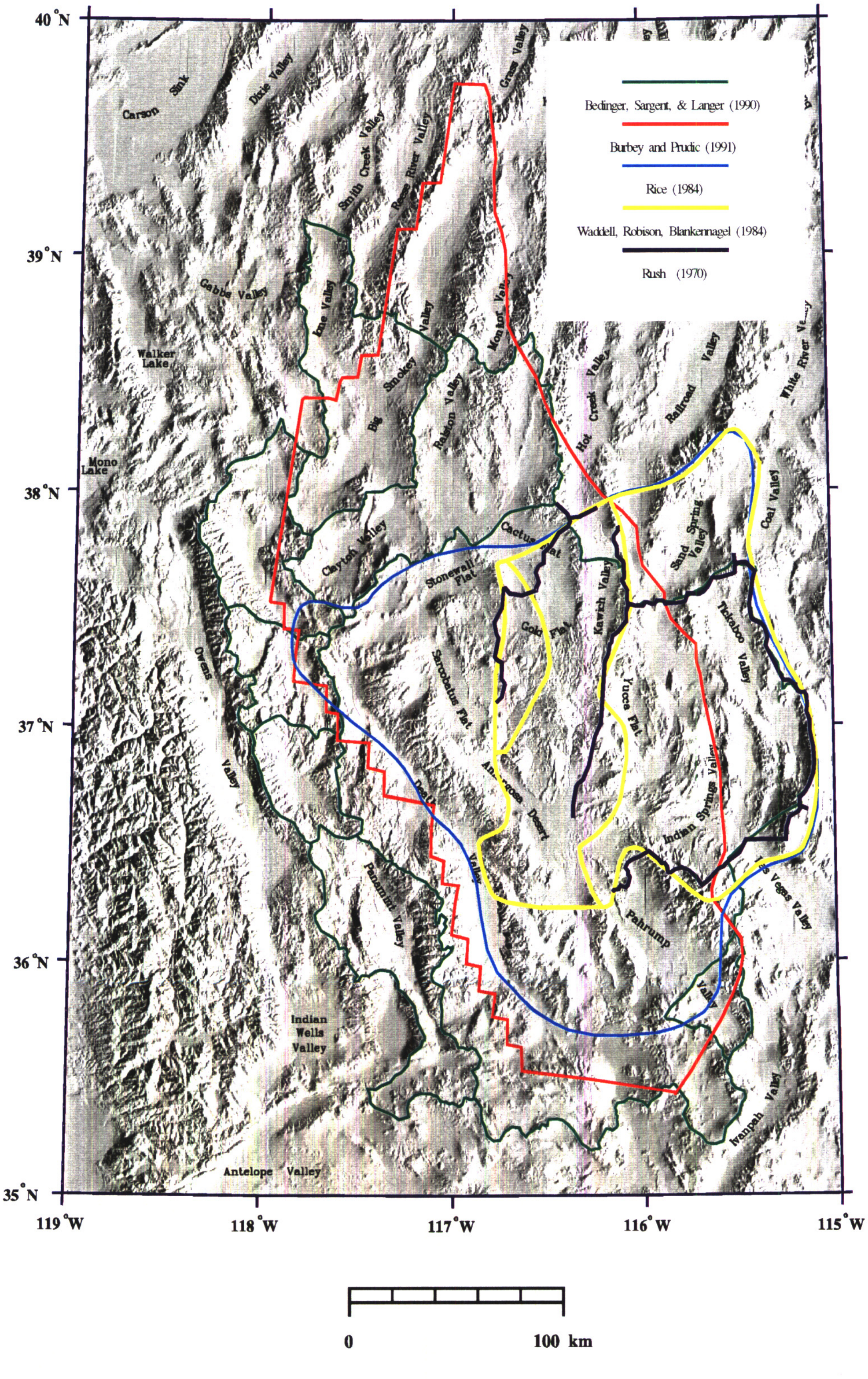

Figure 2-2. Shaded relief map with colored lines showing the boundaries of the Death Valley regional groundwater flow system as defined in five separate studies

Note that the eastern and northeastern boundaries of the region defined by Waddell et al. (1984) and Rice (1984) are roughly coincident. These system boundaries were digitized from plates or figures contained in the corresponding reports and were entered in the GIS database as arc coverages.

As can be seen in Figures 2-1 and 2-2, the area formed by the union of these hydrogeologic system boundaries is roughly bounded by latitudes 35.2 to 39.6° north, and longitudes 115.2 to 118.3° west; a area of approximately 115,000 km^2. This area includes the western portions of Clark and Lincoln Counties, most of central and southern Nye County, and Esmeralda County in Nevada, as well as the northeastern portion of San Bernardino County and the eastern portions of Inyo and Kern Counties in southeastern California. Major physiographic features of the Region include the Panamint Range, Cottonwood Range, and Inyo Mountains forming its western boundary; the Spring Mountains and Sheep, Pahranagat, Belted, Reveille and Toquima ranges forming the eastern boundary. The southern and northern boundaries of the region do not coincide with any major physiographic features.

As can be seen in Figure 2-1, the dominant features of the Death Valley Region are linear mountain ranges and intervening alluvial basins. The mountains generally trend north and northwest, reflecting the late Cenozoic structural grain. However, much of the western portion of the Region lies within the Walker Lane paralleling the southern portion of the Nevada-California border, in which the mountain ranges and valleys predominantly trend northwest. Elevations range from 86 m below sea level at Death Valley, to 3,600 m above sea level at Charleston Peak in the Spring Mountains and 4,300 m above sea level at White Mountain Peak in the Inyo Mountains. Local relief between basins and adjacent mountains is typically 1,500 m. At Death Valley, however, the difference in elevation between the highest point in the Panamint Range and the valley floor is nearly 3,500 m and occurs over a distance of less than 20 km.

The largest mountain ranges in the region are the White and Inyo mountain (combined length 190 km, elevation 4300 m),which form its extreme northwestern boundary. Other large mountain ranges in the Region include the Panamint Range west of Death Valley (140 km in length, 3400 m maximum elevation), and the Spring Mountains in the southeastern portion of the Region (75 km, 3,600 m). In general, the mountains in the northern portion of the Region are generally higher than those in the south. Elevations in the north commonly range from 2,500 m to 3,000 m, while elevations in the south tend to range from 1,800 m to 2,500 m.

3 SURFACE WATER HYDROLOGY

3.1 OVERVIEW

The Death Valley Region lies within the southern portion of the Great Basin hydrographic province, which is defined exclusively on the basis of internal drainage of surface and subsurface water. It should be noted that there are other definitions of the Great Basin that are not coincident with the hydrographically-based definition. Trimble (1989) identifies two physically-based definitions of the Great Basin defined by physiography and biology. The physiographic Great Basin, defined on the basis of distinct landforms and features, constitutes the northern half of the larger Basin and Range physiographic province. Unlike the hydrographic Great Basin, which includes the inland draining portion of the Mojave Desert in California and southern Nevada, the physiographic Great Basin's southern boundary is defined by a line extending from the southern terminus of the Sierra Nevada to the western extent of the Colorado Plateau near Lake Mead. The biologic Great Basin, includes the area within the Sierra Nevada rain shadow lying west of the Wasatch Range, south of the Snake River Plain, and north of the creosote bushes and Joshua trees, which typify the flora of the Mojave Desert.

The majority of the individual intermontane valleys that comprise the hydrographic Great Basin and the Death Valley Region are topographically closed and form smaller, internally drained sub-basins. Streams arise in the adjacent mountain ranges and may be perennial at higher elevations. However, where they cross alluvial fans as they enter a basin, streamflow becomes ephemeral and most streams are influent along lower elevation reaches. Streams in the Great Basin terminate in either deep-water lakes such as Walker Lake and Pyramid lake, or dry lake beds referred to as playas. According to Mifflin (1988), the character of the terminal sinks in these closed basins depend on "...[the] paleohydrologic history of the basin, rate of tectonic movement,, terminal-basin size and configuration, history of stream capture and sedimentation rates."

Unlike the northwestern portion of Nevada, there are no deep-water terminal lakes within the Death Valley Region. Without exception wet or dry playas form the terminal points for surface water in the Death Valley Region. Wet or phreatic playas occur in basins that have very shallow water tables. Dry or vadose playas occur in basins where the depth to water is too great for the capillary fringe to reach the surface. Mifflin (1988) notes that "[p]hreatic playas commonly have areas of puffy or salty surfaces [while] vadose playas are normally composed entirely of smooth pans of clay and silt." Mifflin (1988) also points out that a single playa may grade from vadose to phreatic. Salts are commonly produced by the evaporation of discharging groundwater and indicate that a basin is closed with respect to the flow of shallow groundwater, as well as being closed with respect to the flow of surface water. The salts are chiefly composed of chloride, sulfate, carbonate, and borate minerals such as halite, gypsum, calcite, and borax. Massive surficial deposits more than a meter thick are not uncommon. The largest salt deposit in the Region is the Death Valley saltpan. This feature is approximately 80 km long and covers over 500 km^2.

As described in Section 2, Bedinger et al. (1989) divided the Death Valley Region into nine hydrogeologic sub-basins or groundwater units (Figure 2-2). The presence of wet, phreatic playas indicate that three of these units, DV-02, which contains the Mesquite Valley at the southern end of Pahrump Valley, DV-04, which contains Panamint Valley, and DV-09, which contains the southern end of Big Smoky Valley, are closed groundwater basins coincident with topographically closed basins. The presence of regional springs, absence of discharging playas and great depths to water indicate that the remaining six groundwater units are composed of two or more hydraulically connected, closed topographic basins. The largest of these six units is DV-03 which lies in the central portion of the Death Valley Region containing YM.

Rush (1968) divided Nevada into 14 hydrographic regions and 253 hydrographic areas. Hydrographic regions were defined on the basis of three large-scale unifying hydrographic features: 1. drainage basins of large regional streams; 2. basins that have no large regional streams, and 3. groups of mostly topographically closed valleys. The Death Valley Region lies within the area covered by the Death Valley hydrographic region and Central hydrographic region as defined by Rush (1968). The Death Valley hydrographic region has no major regional streams whereas the Central hydrographic region consists of mostly topographically closed basins.

3.2 DATA AND GIS MAP COVERAGES

Although the hydrographic basins delineated by Rush (1968) within the Death Valley and Central hydrographic regions could have been digitized and entered as an ARC/INFO arc coverage, the location of the surface water divides may not conform with topographic and physiographic maps constructed from DEM data because the sources of topographic and hydrographic data are not necessarily the same. In addition, detailed digital line coverages of the surface drainage obtained from the USGS may not conform with these hydrographic basins. For these reasons new hydrographic basin boundaries were constructed using a shaded relief topographic map constructed from DEM overlaid by the USGS digital line coverage for surface drainage. An example of how these basin boundaries were constructed is shown in Figure 3-1 for Yucca Flat. For topographically closed basins such as Yucca Flat, the drainage divides were delineated by manually tracing the ridgelines that separate the initiation points of first order streams in adjacent watersheds. For basins that have surface water outlets, the location of the boundary crossing the stream is arbitrary. Hence, these boundaries chosen to conform to Rush's (1968) definitions except for those areas outside of Nevada.

Figure 3-2 shows the boundaries of hydrographic basins that lie within the general area of the Death Valley Region. Overlaid on this figure are the major streams within the Death Valley Region defined by Bedinger et al. (1989). Since the stream coverage depicted in the figure was digitized from Bedinger et al. (1989) it does not conform to the detailed surface drainage digital data used to delineate the basins. The detailed drainage network, retained as a line coverage in the ARC/INFO GIS database, is far too dense to be displayed in a small scale map (e.g., 1:3,000,000). The boundaries of each basin have been entered into the GIS database as individual line coverages. In Figure 3-3 the stream coverage has been removed and the name of each hydrographic basin added. Table 3-1 lists the names and the surface areas of the hydrographic basins that comprise the Death Valley Region defined by Bedinger et al. (1989). The boundaries of each hydrographic basin are stored as ARC/INFO line coverages.

The primary drainage system within the Death Valley Region is the Amargosa River (delineated by the heavy green line in Figure 3-2) whose headwaters lie on the western uplands of Pahute Mesa. The headwaters for the Amargosa River lie wholly within the Oasis Valley hydrographic basin. The primary tributary to the Amargosa River within the Oasis Valley hydrographic basin is Beatty Wash, which drains the southern flanks of Timber Mountain. Fortymile Wash (delineated by the heavy dark blue line in Figure 3-2) drains the southern flanks of Pahute and Buckboard Mesas, and eastern Timber Mountain, which lie within the Buckboard Mesa hydrographic basin. After Fortymile Wash enters the Jackass Flats hydrographic basin it receives some inflow from Yucca Wash, Busted Butte Wash and other washes

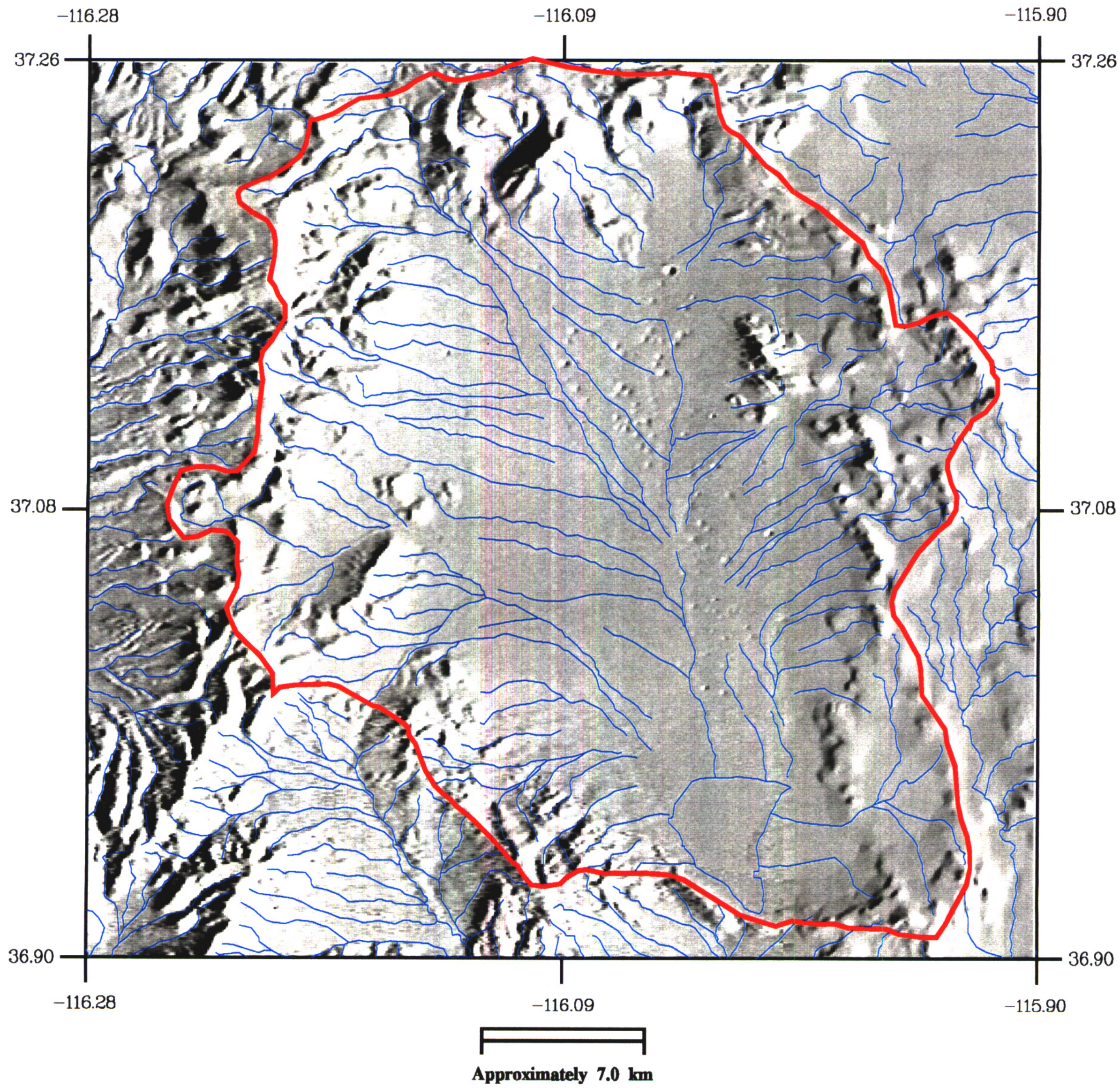

Figure 3-1. Shaded relief map of Yucca Flat overlaid by USGS stream drainage network vector file. The dark line indicates the boundary of the Yucca Flat hydrographic basin.

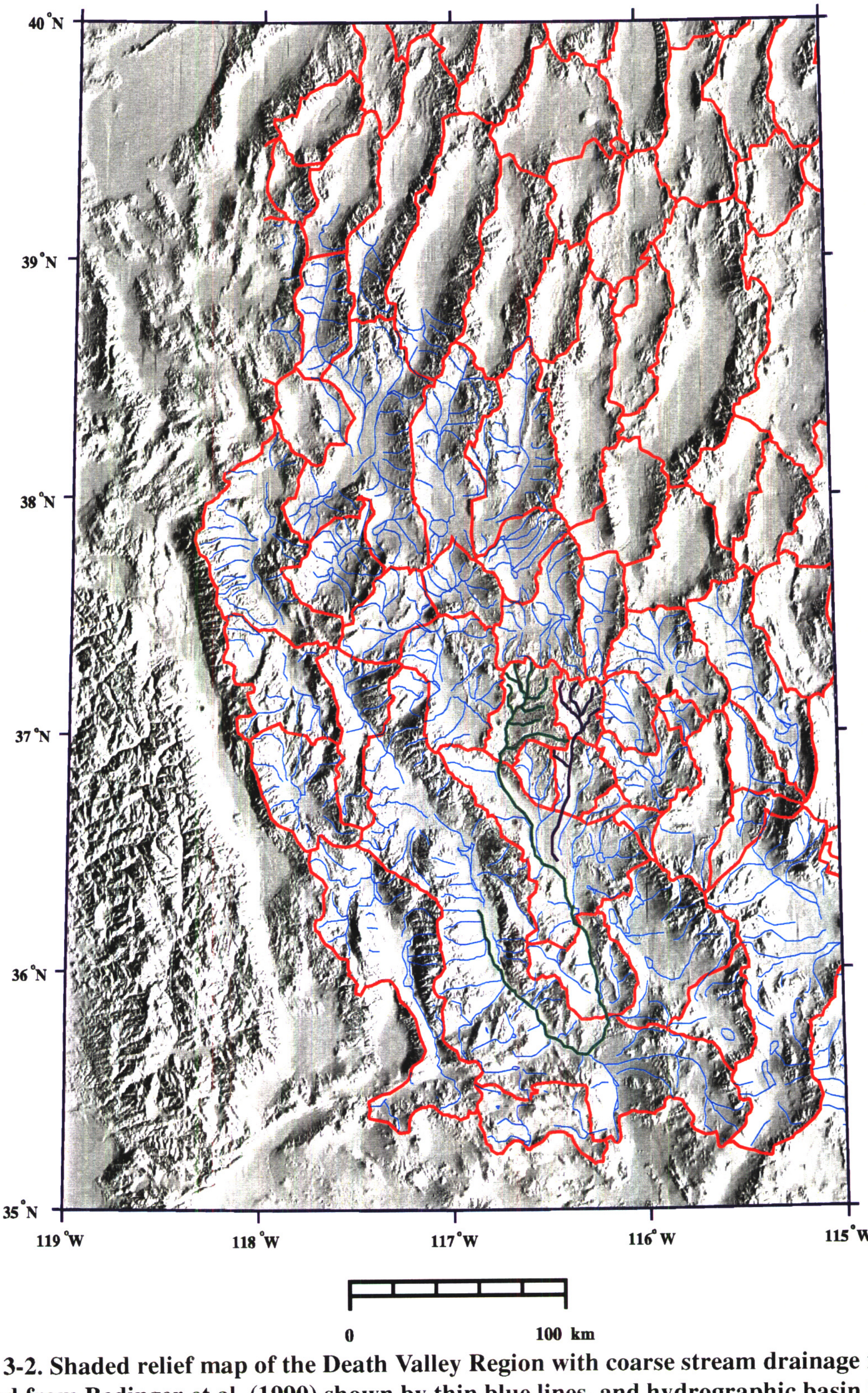

Figure 3-2. Shaded relief map of the Death Valley Region with coarse stream drainage network digitized from Bedinger et al. (1990) shown by thin blue lines, and hydrographic basin boundaries shown by thick red lines

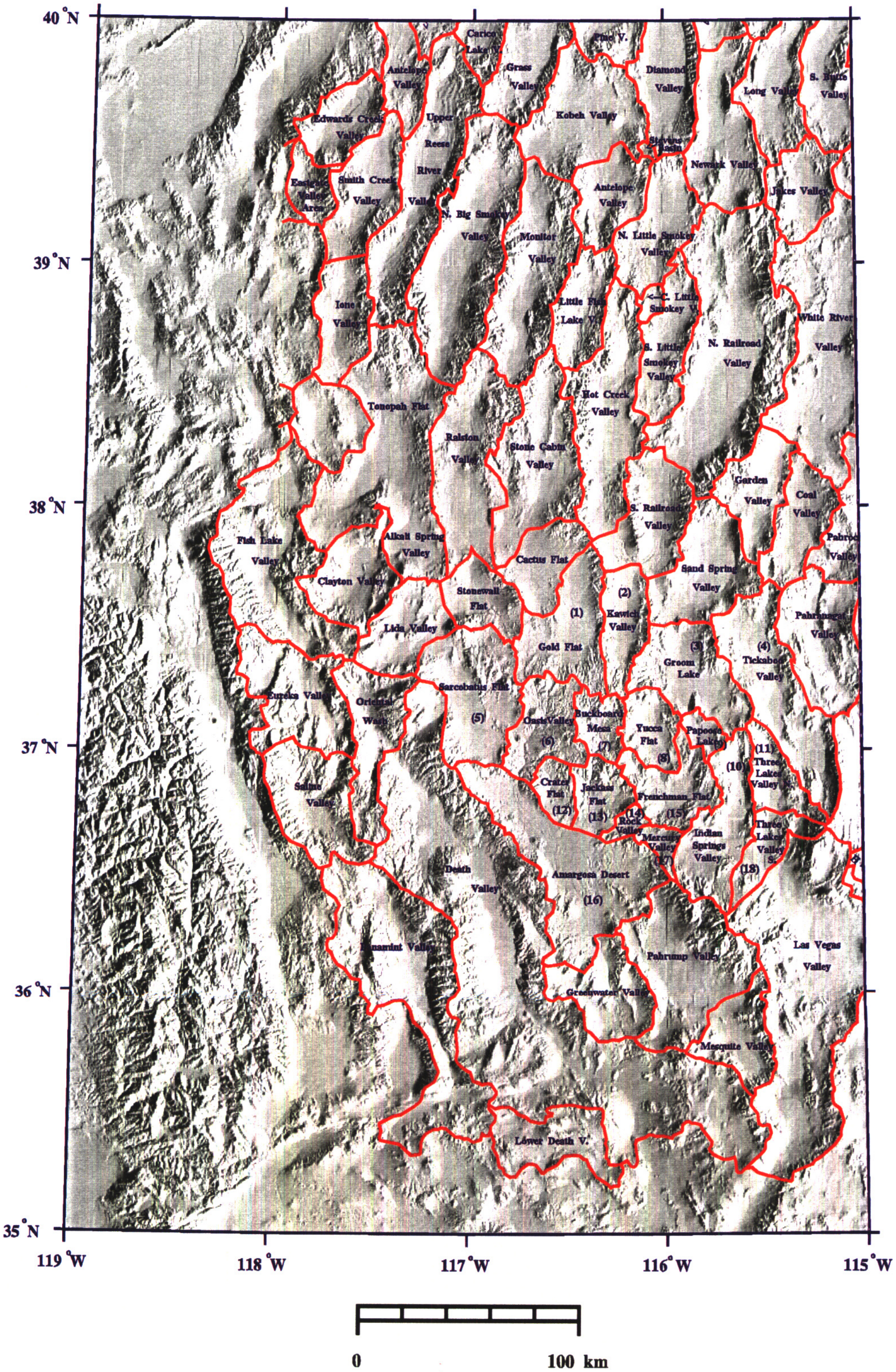

Figure 3-3. Shaded relief map of the Death Valley Region with hydrographic basin boundaries shown by thick red lines

Table 3-1. Names and surface areas of hydrographic basins within the Death Valley Region defined by Bedinger et al. (1990)

Hydrographic Basin	Surface Area (km^2)
Death Valley	12,068
Amargosa Desert	3,440
Pahrump Valley	2,935
Tickaboo Valley	2,537
Sarcobatus Flat	2,180
Gold Flat	1,760
Groom Lake	1,734
Indian Springs Valley	1,724
Oriental Wash	1,561
Greenwater Valley	1,486
Lower Death Valley	1,379
Lida Valley	1,248
Oasis Valley	1,222
Frenchman Flat	1,176
Cactus Flat	1,019
Kawich Valley	1,018
Stonewall Flat	953
Three Lakes Valley North	797
Yucca Flat	781
Jackass Flat	764
Three Lakes Valley South	761
Buckboard Mesa	596
Papoose Lake	270
Mercury Valley	268
Rock Valley	186

draining the eastern side of YM, before entering the Amargosa Desert hydrographic basin. It is unclear whether Fortymile Wash is tributary to the Amargosa River. The Amargosa River flows south through the Amargosa Desert hydrographic basin crossing through the Greenwater Valley hydrographic basin before entering the Death Valley hydrographic basin where it turns north and terminates near Badwater. All of the remaining hydrographic basins listed in Table 3-1 are internally draining except for Mercury Valley and Rock Valley, which drain to Amargosa Lake in the eastern portion of the Amargosa Desert hydrographic basin.

4 PRECIPITATION AND CLIMATE

4.1 OVERVIEW

The climate of the Death Valley Region ranges from arid on the valley floors to subhumid on the highest mountain ranges. The amount of annual precipitation received in the region is highly variable. Death Valley itself is one of the most arid places in the world; the average annual precipitation is approximately 50 mm and summer temperatures often reach 50° C (Hunt et al., 1966). In contrast, the highest elevations of the Spring and Panamint Mountains average more than 500 mm of precipitation annually (Mifflin, 1988), with as much as one third of this precipitation occurring as snow (Winograd and Thordarson, 1975).

Two distinct North American deserts converge within the Death Valley Region. The Great Basin Desert, which lies to the north, is a cold desert and receives most of its annual precipitation as snow during the winter. The Mojave Desert, which lies to the south, is a hot desert receiving most of its annual precipitation as rain during both winter and summer. Prevailing winds at these latitudes are the westerlies, which steer winter storms generated by low-pressure centers located in the eastern Pacific Ocean across the Great Basin. Of five primary winter weather types that affect the Pacific coast, only the San Diego Low and the Tonopah Low produce significant winter precipitation in southern Nevada.

San Diego Low systems are produced when a zone of high pressure develops over the Pacific northwest, displacing the storm track southward and driving low pressure centers onshore along the United States-Mexico border (U.S. Department of Energy, 1991). San Diego Low frontal systems generally move slowly through southern California, southern Nevada, and western Arizona, increasing the duration of precipitation (U.S. Department of Energy, 1991). Tonopah Lows develop in the lee of the Sierra Nevada from storms that are spawned in the Gulf of Alaska and driven south by the Canadian High before moving onshore (U.S. Department of Energy, 1991). Tonopah Lows may produce precipitation in southern Nevada if sufficient atmospheric moisture is available from the Pacific or from snowmelt (U.S. Department of Energy, 1991; Trimble, 1989).

During July and August, moisture from the Gulf of Mexico, the Gulf of California, and the Pacific Ocean west of Baja California is driven northward into southern Nevada by a westward expansion of the Bermuda High. This so-called Southwest Monsoon sometimes generates mesoscale convective complexes in Arizona and New Mexico that may very occasionally intrude into southern Nevada (U.S. Department of Energy, 1991). These mesoscale convective complexes produce southern Nevada's heaviest summertime rainfall and provide the greatest chances of flash flooding, hail, and high winds (U.S. Department of Energy, 1991). However, summer precipitation more often comes from isolated convective thunderstorm cells of limited areal extent and limited duration.

The spatial distribution of average annual precipitation within the Death Valley Region can be estimated well taking only synoptic and mesoscale effects into consideration. The predominant mesoscale effect is orographic precipitation resulting from the extreme relief of Basin and Range topography. Only after the orographic effect is subtracted from the measured average annual precipitation do the secondary, synoptic effects become apparent. According to French (1983), average annual precipitation in the western and northwestern portion of the Death Valley Region is depleted relative to that in the southern and southeastern portions primarily due to the rain shadow produced by the Sierra Nevada during the winter. However, because the southern and southeastern areas lie within the Mojave Desert where summer convective storms are more prevalent, the rain shadow may reflect more than one synoptic effect.

4.2 DATA AND GIS MAP COVERAGES

Hevesi et al. (1992) reanalyzed the work of French and chose to exclude data from precipitation stations with less than 8 years of record leaving 42 stations. The 42 precipitation stations having records with 8 or more years of record that were selected by Hevesi et al. (1992) are shown in Table 4-1. The location of these precipitation stations are shown in Figure 4-1 overlaid on a grayscale shaded relief map. The dark blue line shown in Figure 4-1 is the boundary of the DV-03 sub-region defined by Bedinger et al. (1989). Note that the data listed in Table 4-1 were transcribed by hand from Hevesi et al. (1992) and entered into the GIS database.

Wittmeyer and Klar (1995) developed a hybrid, nonintrinsic co-estimation procedure for estimating average annual precipitation in the Death Valley Region. This co-estimation procedure, takes advantage of the relative abundance of elevation data from DEMs, and combines residual kriging in the presence of an external drift function with polynomial trend surface fitting. The external drift model is used to account for orographic effects while the polynomial trend surface accounts for the Sierra Nevada leeward rain shadow effect. Orographic effects were estimated from a 301×401 grid of elevation measurements extracted from DEMs for the region between 35° and 39° north, and 115° and 118° west. However, to avoid extrapolation with the trend surface polynomial used to describe the Sierra Nevada rain shadow, estimates of average annual precipitation were only determined within the region covered by the precipitation stations.

Figure 4-2 is a color contour plot of estimated average annual precipitation determined using the method of Wittmeyer and Klar (1995) within the irregularly shaped area covered by the precipitation stations that has been clipped on the east and west by the 115° and 118° west meridians, respectively. The map of colored contours, which are stored in the GIS as a screen raster image, have been overlaid on topographic contours constructed from DEMs. Estimated average annual precipitation ranges from over 440 mm at the highest elevations of the Spring Mountains to less than 60 mm within Death Valley.

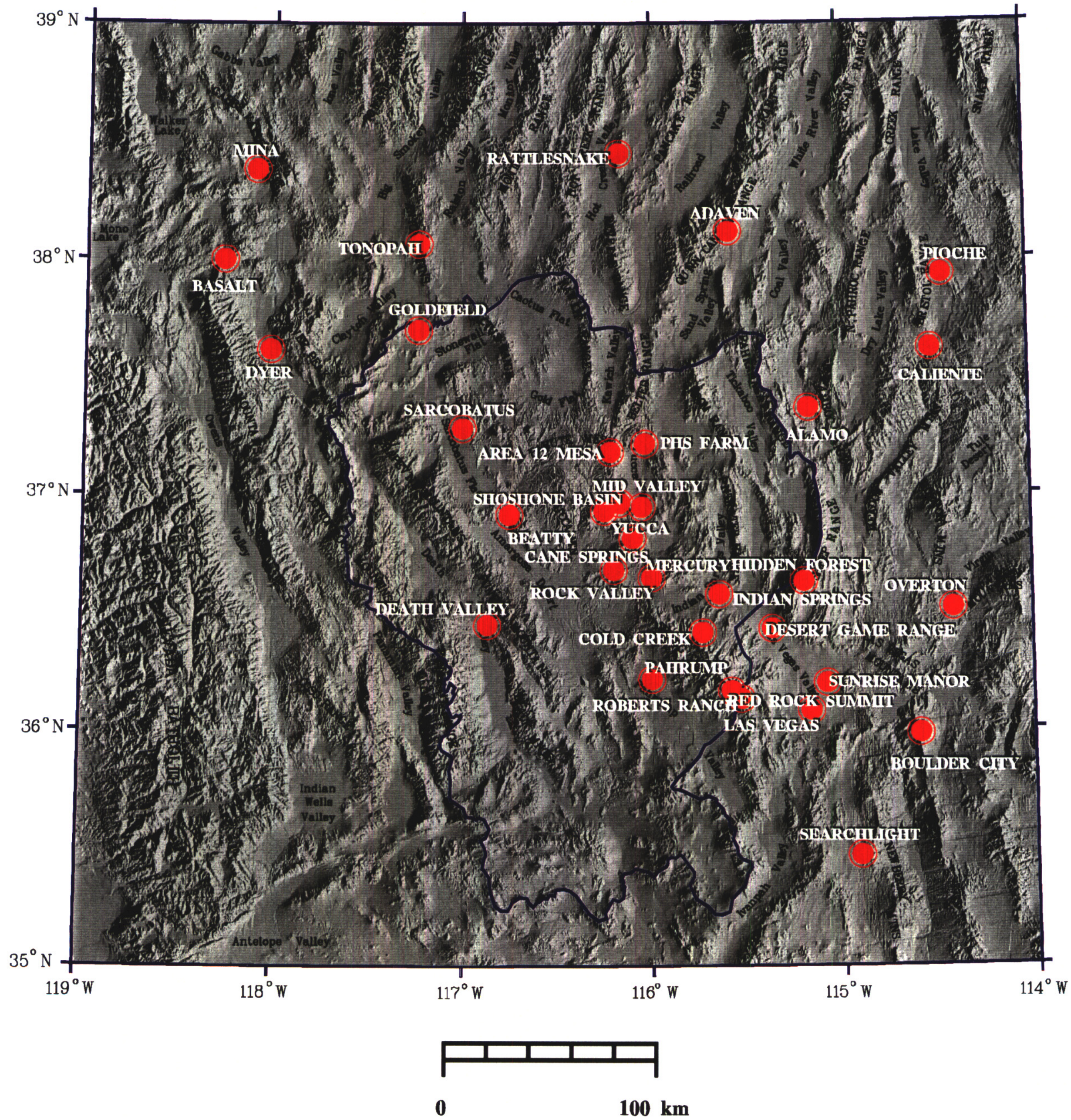

Figure 4-1. Shaded relief map of the Death Valley Region with locations of precipitation stations indicated by large red dots, and boundary of DV-03 sub-basin of Bedinger et al. (1990) shown by the dark blue line

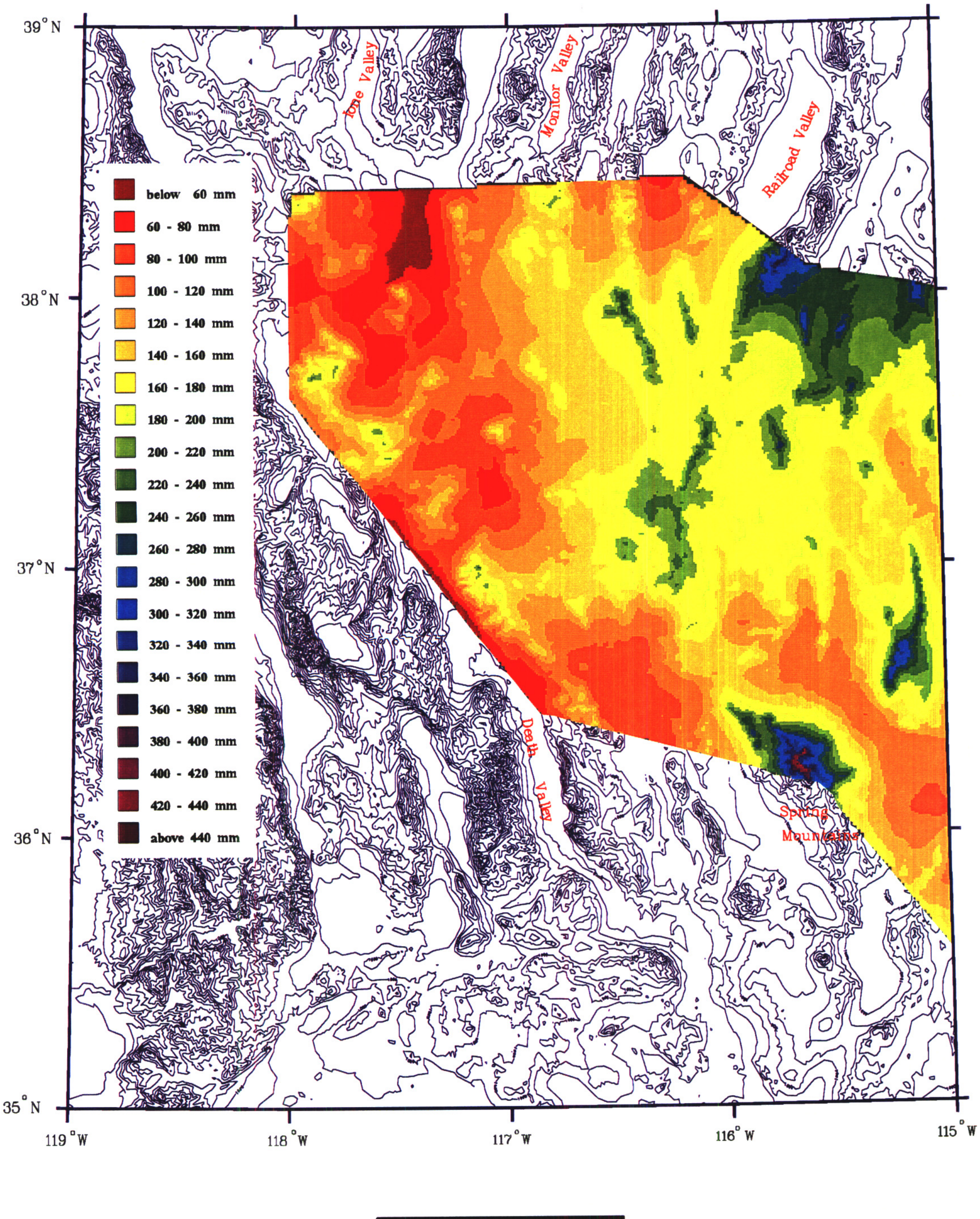

Figure 4-2. Color-filled contours of estimated average annual precipitation in Death Valley

Table 4-1. Precipitation stations in southern Nevada (after Hevesi et al., 1992)

Precipitation Station	X (m)	Y (m)	Elevation (m)	Record Length (yr)	AAP (mm)	σ_{AAP}
Rock Valley	571477	4059803	1036	8	157	23
Desert Rock Airport	587903	4052634	1005	15	157	17
Mercury	589385	4056310	1149	13	159	18
4JA	563978	4070837	1043	16	119	15
Cane Springs	580272	4074747	1219	21	208	21
Well 5B	592156	4072981	938	19	128	12
Shoshone Basin	566792	4087499	1725	12	225	25
Mid Valley	574151	4091332	1420	13	226	23
Yucca	584585	4089544	1194	25	177	17
40 MN	563756	4100456	1469	18	202	18
Tippipah Springs 2	572648	4100527	1517	20	245	23
BJY	584456	4102523	1241	22	177	17
Area 12 Mesa	569503	4115256	2282	17	295	31
PHS Farm	585797	4119179	1391	8	193	22
Little Feller 2	562189	4107877	1572	8	229	36
Adaven	624217	4219539	1905	47	321	16
Alamo	662317	4136958	1048	26	128	10
Boulder City	716377	3984526	769	50	139	9
Caliente	719152	4166016	1343	51	231	11
Cold Creek	613593	4030745	1828	8	230	33
Hidden Forest	660934	4055467	2301	9	320	27
Las Vegas Airport	665043	3994509	658	33	104	8
Sunrise Manor	672351	4007634	554	32	106	8
Overton	731299	4044195	371	26	91	13
Pioche	724110	4201242	1865	44	313	16
Red Rock Summit	632002	3999496	1981	8	270	36
Roberts Ranch	627448	4003200	1859	8	354	47
Searchlight	689009	3926628	1078	50	185	14
Basalt	388755	4206366	1935	15	142	17
Beatty	522268	4085491	1082	47	159	12
Death Valley	511918	4033668	−51	18	69	7
Desert Game Range	646379	4033013	890	42	106	8
Dyer	410244	4163603	1516	31	125	9
Goldfield	479459	4712350	1734	39	136	12
Indian Springs	619255	4049239	955	25	116	16
Lathrop Wells	553630	4056012	663	21	85	11
Mina	403923	4248677	1387	53	115	7
Pahrump	589883	4008279	822	20	126	16
Rattlesnake	572688	4255867	1802	20	121	13
Sarcobatus	500000	4126063	1225	14	90	13
Tonopah Airport	492719	4213046	1654	29	163	10
Tonopah City	479561	4213068	1857	22	126	11

5 RECHARGE AND DISCHARGE

5.1 OVERVIEW

In order to construct a regional scale flow model of the Death Valley Region's hydrogeologic regime, the locations of the natural system boundaries and areas of recharge and discharge must be identified. Since the groundwater system within the Death Valley Region is composed of a number of topographically closed basins that are hydraulically connected at depth by the highly transmissive Paleozoic carbonate aquifer, the extent of the region may be fixed if a boundary across which no groundwater is transported can be delineated. If these zero-flux boundaries can be identified, the nature of the hydrogeologic regime is largely determined by the location and magnitude of the internal recharge and discharge zones.

5.2 RECHARGE DATA AND GIS MAP COVERAGES

Recharge to the regional system is presumed to occur primarily along the upper reaches of stream channels that drain the higher mountain ranges. Unlike discharge, which can at least be roughly estimated by measuring spring discharge and calculating the area and water use of native vegetation and agricultural crops dependent on spring discharge, estimating the location and magnitude of natural recharge is extremely difficult. Direct measurement of recharge to shallow aquifers can be made using lysimeters; however, this method is probably not practical for estimating recharge to the extremely deep Paleozoic carbonate aquifer. Straightforward application of the water budget method is also impractical since estimates of evapotranspiration must be obtained for the entire region. Empirical techniques are often the only methods that can be easily used to obtain rough predictions of recharge, although their derivation is often not carefully documented and their reliability is often in question.

Watson et al. (1976) conducted a statistical evaluation of the empirical formula developed by Maxey and Eakin (1949) to estimate groundwater recharge for basins in Nevada. In the Maxey-Eakin method, recharge is estimated from specific percentages of the mean annual precipitation. According to Watson et al. (1976), Maxey and Eakin defined five mean annual precipitation zones (> 20 in., 15–20 in., 12–15 in., 8–12 in., and < 8 in.), based on Hardman's (1936) precipitation map of Nevada. The fixed percentage from each precipitation zone that is recharged to a basin, which is shown in Table 5-1, was determined by assuming that each hydrologic basin is in equilibrium so that total basin recharge could be equated to the estimated basin discharge. As pointed out by Watson et al. (1976), "[t]he predictive equations derived relate discharge to precipitation in each zone and, therefore, only give values of discharge." However, the assumption of equilibrium makes estimated recharge equivalent to estimated discharge. Watson et al. (1976) conclude that the Maxey-Eakin formula, is not highly reliable. The authors assert "...that...[the] predictive equation [cannot] be used for anything more than a first approximation to recharge." Regardless of the accuracy of these equations, Watson et al. (1976) recognize that in the absence of other data, this simple approach may be the only practical method to estimate recharge in Nevada.

For future numerical modeling work that will be conducted in this research project, estimates of recharge must be obtained by some procedure. Even though statistically based inversion methods will be used to calibrate the numerical flow model, prior estimates of all parameters, including the location and magnitude of recharge, are required both to regularize the inverse problem, and to provide initial guesses for the optimization routine. Because there are currently few alternative procedures for obtaining

Table 5-1. Maxey-Eakin recharge (from Watson et al., 1976)

Hardman Zones	Maxey-Eakin Recharge (%)
> 20 in. (490 mm)	25
15-20 in. (381-490 mm)	15
12-15 in. (305-381 mm)	7
8-12 in. (203-305 mm)	3
< 8 in. (203 mm)	0

prior estimates of recharge within the Death Valley Region, the Maxey-Eakin formula will be used; final estimates of recharge being obtained from the model calibration results. Prior estimates of mean annual recharge based on the isohyetal map in Figure 4-1, and the Maxey-Eakin formula are shown in Figure 5-1. The coverage of the Maxey-Eakin recharge estimates presented in Figure 5-1 is included as a screen raster image in the ARC/INFO database. As shown in Figure 5-1, estimated average annual areal recharge within most of the Death Valley Region is less than 5 mm. Areal recharge increases to between 5 and 20 mm per year in the Spring Mountains, Sheep Range, Timber Mountain, Pahute Mesa, Kawich Range, Groom Range, and the highlands near the Delamar Mountains in the northeastern portion of the region. Only at the highest elevations within the Spring Mountains, Sheep Range, and Delamar Mountains does the Maxey-Eakin formula estimate areal recharge in excess of 20 mm per year.

5.3 DISCHARGE DATA AND GIS COVERAGES

Water exits the Death Valley regional groundwater system primarily by evapotranspiration of spring discharge. Some water is also lost through transpiration by phreatophytes or evaporation directly through the vadose zone in those areas where the depth to water is shallow. Shallow water tables are characteristic of the phreatic, or wet, playas that are typically located at the topographic low within closed basins. Phreatophyte growth along short reaches of the Amargosa River may also act as sink for the regional system. The springs of primary interest for this study are those whose source is the Paleozoic carbonate aquifer. There are many springs within the Death Valley Region. However, many of these springs are ephemeral, discharging only after periods of prolonged, heavy precipitation, and may be the outflow point of a perched water body that is hydraulically unconnected to the local alluvial aquifers or the regional carbonate aquifer.

In the Death Valley Region, groundwater from the carbonate aquifer emerges at 13 major discharge areas. These areas, along with estimated discharge rates, are listed in Table 5-2 and shown in red on the topographic map shown in Figure 5-2. Discharge area locations and estimates of flow are based on the references listed in Table 5-2. The geometry of each discharge zone shown in Figure 5-2 was defined by first hand sketching its location on a base map and then digitizing the zone's boundary. Locations and shapes of the discharge areas were extracted from plates, maps, and figures contained in the reports referenced in Table 5-2. Not all of the discharge zones in Table 5-2 are located in Figure 5-2.

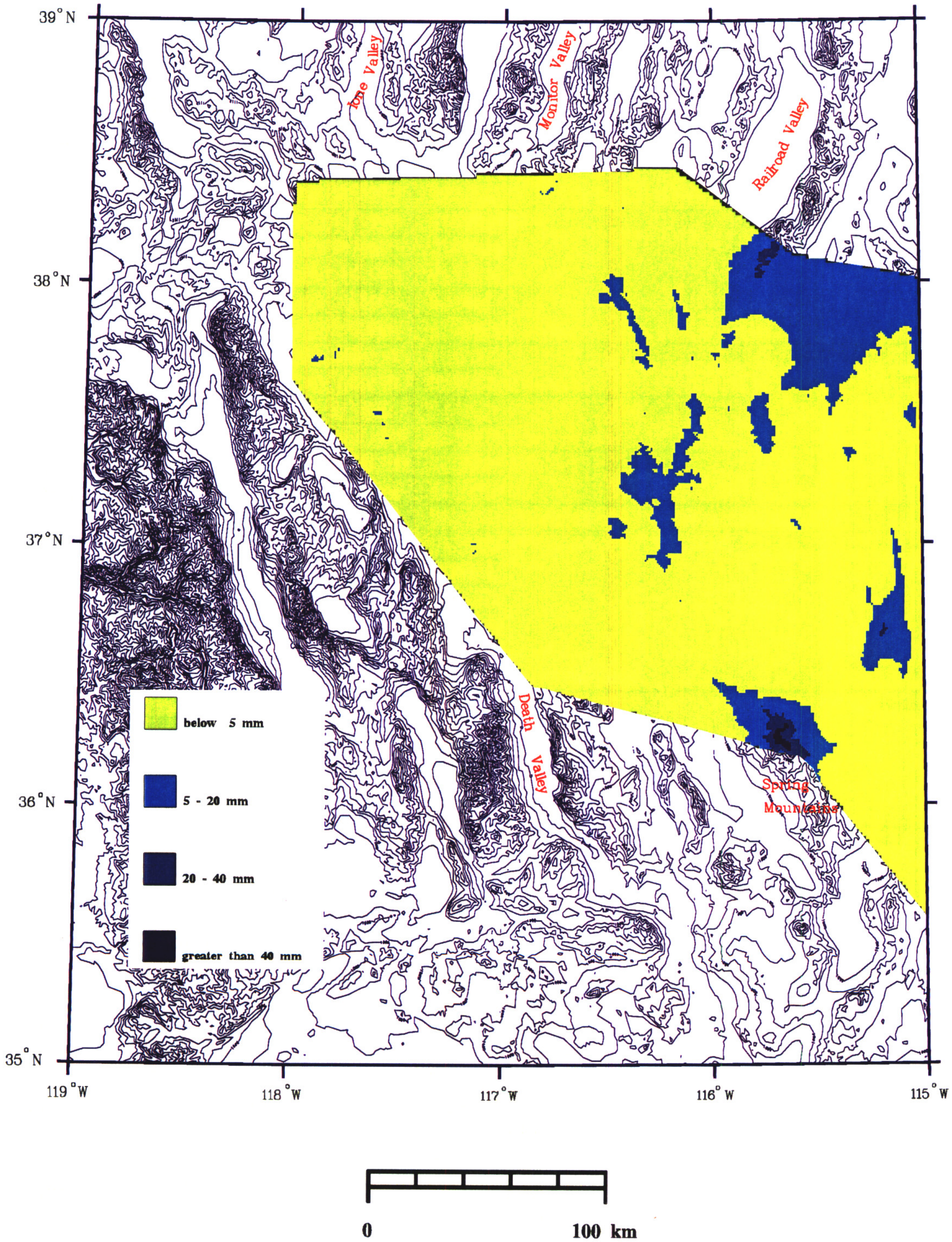

Figure 5-1. Color-filled contours of estimated average annual areal recharge based on the Maxey-Eakin method and precipitation map shown in Figure 4-2

Table 5-2. Major discharge areas within the Death Valley Region

Discharge Area		Discharge Rate (l/s)	Source of Data[a]
Death Valley		340	Rice (1984)
		900	Burbey and Prudic (1993)
		340	Hunt et al. (1966)
Furnace Creek Ranch Area (Includes Major Springs Near Furnace Creek Ranch)		200	Rice (1984)
		200	Winograd and Thordarson (1975)
		220	Czarnecki and Waddell (1984)
		160	Waddell et al. (1984)
		160	Hunt et al (1966)
Major Springs Near Furnace Creek Ranch	Nevares Springs	17	Winograd and Thordarson (1975)
		21	Hunt et al. (1966)
	Texas Spring	14	Winograd and Thordarson (1975)
		14	Hunt et al. (1966)
	Travertine Spring	54	Winograd and Thordarson (1975)
		120	Hunt et al. (1966)
Shoshone Springs		230	Burbey and Prudic (1991)
Alkali Flat (Franklin Lake Playa)		390	Rice (1984)
		390	Winograd and Thordarson (1975)
		260	Czarnecki (1990)
		410	Czarnecki and Waddell (1984)
		200	Burbey and Prudic (1991)
		390	Waddell et al. (1984)
Ash Meadows		2200[b]	Rice (1984)
		670	Winograd and Thordarson (1975)
		260[c]	Dudley and Larson (1976)
		780	Burbey and Prudic (1991)
		660	Waddell et al. (1984)
Amargosa Lake (Peter's Playa)		75	Rice (1984)
		40	Winograd and Thordarson (1975)
Three Lakes Valley/Corn Creek Springs		23	Rice (1984)
		7.9	Winograd and Thordarson (1975)
Indian Springs Valley		49	Rice (1984)
		27	Winograd and Thordarson (1984)
Oasis Valley		160	Rice (1984)
		120	Burbey and Prudic (1991)
		78	Waddell et al. (1984)
Sarcobatus Flat		210	Rice (1984)
		120	Rush (1971)
		270	Burbey and Prudic (1991)
Clayton Valley		1300	Burbey and Prudic (1991)
Grapevine/Straininger Springs		6.2	Rice (1984)

[a] Refers to document where information cited, not original document.
[b] Includes estimated pumpage rate. Except as noted, other estimates are of spring discharge only.
[c] Estimated pumpage, 1971.

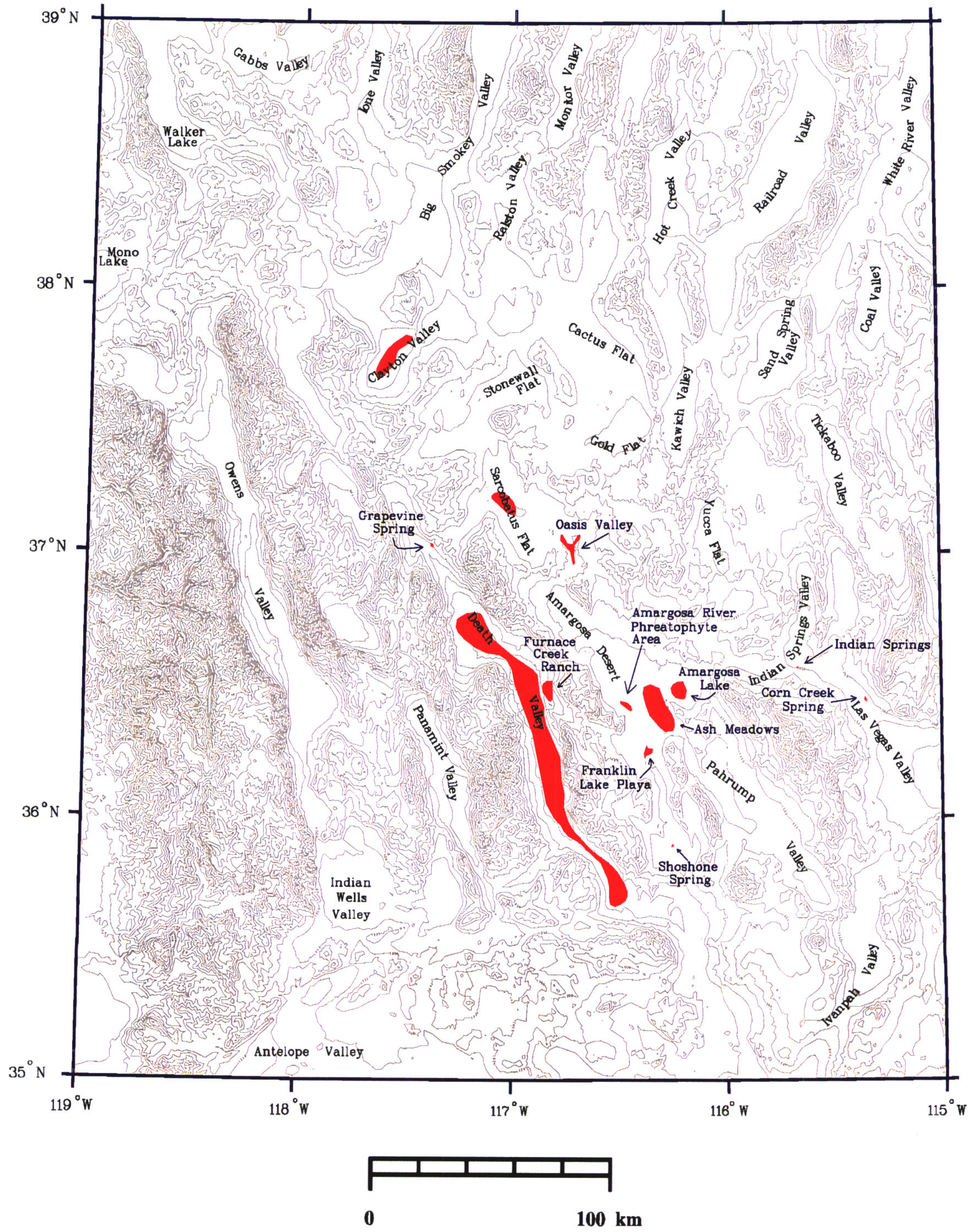

Figure 5-2. Locations of major discharge zones in the Death Valley Region overlain on topographic contour lines

Three of the largest discharge areas are in the southern Amargosa Desert, along the Nevada - California border. These are: Ash Meadows, Franklin Lake Playa (Alkali Flat), and an unnamed valley to the northeast of Ash Meadows (referred to here as Amargosa Lake). Ash Meadows is the largest discharge area in the Death Valley Region. Discharge occurs as springflow, evapotranspiration, and pumpage. Natural discharge occurs primarily along a line of thirty springs. This line trends northwest and is about 16 km long. Although the water that feeds the springs comes from the lower carbonate aquifer, most of the springs emerge from low permeability lake bed deposits or travertine deposits. Flow is forced to the surface by a hydraulic barrier, probably a fault that places the lake beds across the lower carbonate aquifer (Dudley and Larson, 1976). Estimates of total spring discharge range from 660 *l*/s to 780 *l*/s (Table 5-2). Two of the largest springs, Fairbanks and Crystal Pool, each flow at more than 100 *l*/s. According to Winograd and Thordarson (1975), total spring discharge at Ash Meadows has not changed significantly since the turn of the century. However, Dudley and Larson (1976) state that irrigation pumpage has reduced springflow and water levels in Devils Hole. According to Rice (1984), the amount of water discharged by pumpage is approximately twice that discharged by natural flow from the springs. Discharges from Franklin Lake Playa and the Amargosa Lake are due to the presence of shallow water tables. In both areas, moist sediments are found within a foot or two of land surface and water is discharged by phreatophytes and by bare-soil evaporation (Winograd and Thordarson, 1975; Czarnecki, 1990).

Death Valley and the Furnace Creek area are presumed to be the ultimate discharge area of the lower carbonate aquifer. Moreover, Death Valley is the hydrologic and topographic low point of the Death Valley Region (86 m below sea level). Groundwater discharges at many small springs and seeps along the length of the valley, and some springs support perennial marshes. Groundwater is also discharged by phreatophytes and by bare-soil evaporation. Much of the groundwater that discharges along Death Valley is highly saline, with total dissolved solids contents greater than 10,000 ppm. At Furnace Creek, the primary discharge points are three large groups of springs: Nevares, Texas, and Travertine. Travertine Springs is the largest, with a flow of approximately 125 *l*/s. The water discharged from all three springs is fresh, with total dissolved solids contents of about 600 ppm (Hunt et al., 1966).

Groundwater discharge from Sarcobatus Flat occurs primarily as evapotranspiration from shallow water tables. At Oasis Valley, water is forced to the surface by low conductivity rocks that form a subsurface "dam" near Beatty, Nevada (Waddell, 1982). The discharge occurs both as spring flow and as evapotranspiration. Subsurface hydraulic barriers that force water to leak upward from the lower carbonate aquifer are also thought to cause the discharges at Indian Springs and the Three Lakes Valley area (Winograd and Thordarson, 1975).

The groundwater discharge zones associated with Sarcobatus Flat, and the extensive phreatic playa within Death Valley are readily identified in Figure 5-2. The discharge area at Oasis Valley near Beatty, Nevada is depicted by the wishbone-shaped region 25 km southeast of Sarcobatus Flat. The large, kidney-shaped discharge area in southern Amargosa Desert represents the Ash Meadows springline, while the nearly circular discharge zone immediately to the east is Amargosa Lake (Peter's Playa). Immediately to the west of the Ash Meadows area is a short reach of the Amargosa River along which water is transpired by phreatophytes. South-southwest of Ash Meadows is Franklin Lake Playa. The smaller discharge zone to the east of the elongate Death Valley playa represents the Furnace Creek Ranch area. Barely visible as small red specks on this map are Grapevine/Straininger Springs at the north end of Death Valley, Shoshone Spring midway between Pahrump Valley and the southern end of Death Valley, Corn Creek Spring located at the north end of Las Vegas Valley and Indian Springs.

6 WELLS, SPRINGS, AND WATER LEVEL CONTOUR MAPS

6.1 OVERVIEW

Water levels measured in flowing springs and seeps, and in wells, shafts, and exploratory boreholes completed in unconfined units, as well as hydraulic head measurements obtained from wells, shafts, and exploratory boreholes tapping confined units are essential for constructing a basic conceptual model of the Death Valley Regional groundwater flow regime. Therefore, considerable emphasis has been placed in this research project on obtaining water level data that can be used to delineate the flow regime within the Paleozoic carbonate aquifer as well as within the basin-scale alluvial and fractured tuff aquifers. The spatial density of water level measurements varies greatly across the region; measurement locations are primarily concentrated on the Nevada Test Site (NTS), and in areas where wells have been drilled for domestic and agricultural water supply.

6.2 SOURCE OF DATA

Most of the data used to construct the water level maps and databases contained in the ARC/INFO GIS were obtained from the USGS's Ground-Water Site Inventory (GWSI) System. The GWSI System is a collection of groundwater data storage and retrieval systems that constitutes one part of the National Water Information System (NWIS) developed by the USGS. Other portions of the NWIS distributed water database include the Automated Data Processing System, the Quality of Water System (QW), and the Water-Use Data System (WUSE).

The GWSI System database contains descriptive and quantitative information wherever groundwater is accessed from wells, test holes, springs, tunnels, drains, ponds, or other excavations (Lenfest, 1989). The approximately 300 components that provide general descriptive information about a measurement site are stored in a single data file called the Site File, which is shared by all elements of the NWIS. Descriptive and quantitative information that is primarily related to groundwater is stored in eight GWSI data files containing well-construction, groundwater level, groundwater discharge, miscellaneous, geohydrologic, observation-well heading, hydraulic, and state water-use data (Lenfest, 1989).

Initial requests for groundwater-related data were submitted to the Water Resources Division (WRD) of the USGS state office in Reno, Nevada. In accordance with the request from the CNWRA, USGS personnel retrieved data for the portion of the state of Nevada bounded on the east and west by meridians at 115° and 119° west longitude, respectively, and on the north and south by parallels at 39° and 35° north latitude. The data, which included all records from the Site File and the eight GWSI-specific data files, were written to two ASCII files which were transferred to the CNWRA by anonymous FTP via the INTERNET. After their receipt, each file was duplicated and secured by setting its UNIX file protection codes so as to preclude intentional or accidental writing to the file. Copies of each file are also stored on diskette in a fireproof vault.

Maps of the spatial locations of the groundwater site data provided by the Reno, Nevada office of the USGS indicated that groundwater measurement sites located on the NTS were not included. The GWSI database for the NTS is maintained by the Las Vegas, Nevada office of the USGS, so a second request for data was submitted to this office. These data were transmitted to the CNWRA using the procedure described above, and similar procedures were followed to secure a clean copy of the data file.

Locations of the more than 5,000 groundwater measurement sites included in the GIS database are shown in Figure 6-1.

The transmittal letter that accompanied the bill for the data retrievals performed by the Las Vegas, Nevada USGS office contained the following caveat regarding the quality of the data.

> "This database, identified as the GROUND WATER SITE INVENTORY, has been approved for release and publication by the Director of the USGS. Although this database has been subjected to rigorous review and is substantially complete, the USGS reserves the right to revise the data pursuant to further analysis and review. Furthermore, it is released on condition that neither the USGS nor the United States Government may be held liable for any damages resulting from its authorized or unauthorized use."

Although a similar caveat did not accompany the GWSI data obtained from the Reno, Nevada USGS office, it is assumed that the above quote applies.

6.3 GROUNDWATER MEASUREMENT SITE IDENTIFICATION

Each groundwater measurement site included in the GWSI System database is identified by a fifteen digit site identification number (Site ID). The first six digits and second seven digits of the Site ID are the "best known" latitude and longitude of the site in degrees-minutes-seconds, respectively, while the last two digits allow for the unique identification of up 100 measurement locations within a specific one second squared area. It should be noted that a given measurement location may have as many as three Site ID numbers that were created for: 1. well construction and water-level data, 2. water-quality analysis, and 3. continuous water-level data from digital recorders. Each water well, borehole, and exploratory hole on the NTS is identified by an ID number beginning with UE (U for underground, E for exploratory), followed by the NTS area number (e.g. UE-25, for NTS wells in area 25). This ID is usually followed by one or more letters that indicate the purpose of the borehole (e.g. UZ-drilled to collect data on the unsaturated zone, WT-drilled to determine the position of the water table, G-drilled primarily to collect information on geology, H-drilled primarily to collect information on hydrology, V-drilled primarily to collect data on volcanism) and an accession number. Boreholes drilled outside of the NTS for the purpose of site characterization at YM begin with the letters USW (U-underground, S-southern Nevada, W-waste) and use designations similar to those of the NTS to indicate the wells purpose. Water wells outside of NTS and the YM area are typically identified by their owner's name, or by the well's location in terms of township, range, section, quarter-section, and possibly quarter-sections of each quarter-section, when the well can be more accurately located.

Because the GWSI System ID numbers are cumbersome and because both the NTS ID numbers, and station names for wells off the NTS, do not always convey a sense of location, an alternative well-numbering scheme was developed. As described in Section 3, the Death Valley Region has been divided into a number of individual hydrographic basins. The primary purpose of defining these hydrographic basins was to facilitate the development of a general water budget for the region. However, these basins also provide a convenient geographic and hydrologic basis for identifying the many groundwater measurement sites in the region. ARC/INFO was used to determine in which hydrographic basin each water well was located. After the well's hydrographic basin was determined, each well was assigned an accession number according to position. Wells are numbered from west to east starting at the

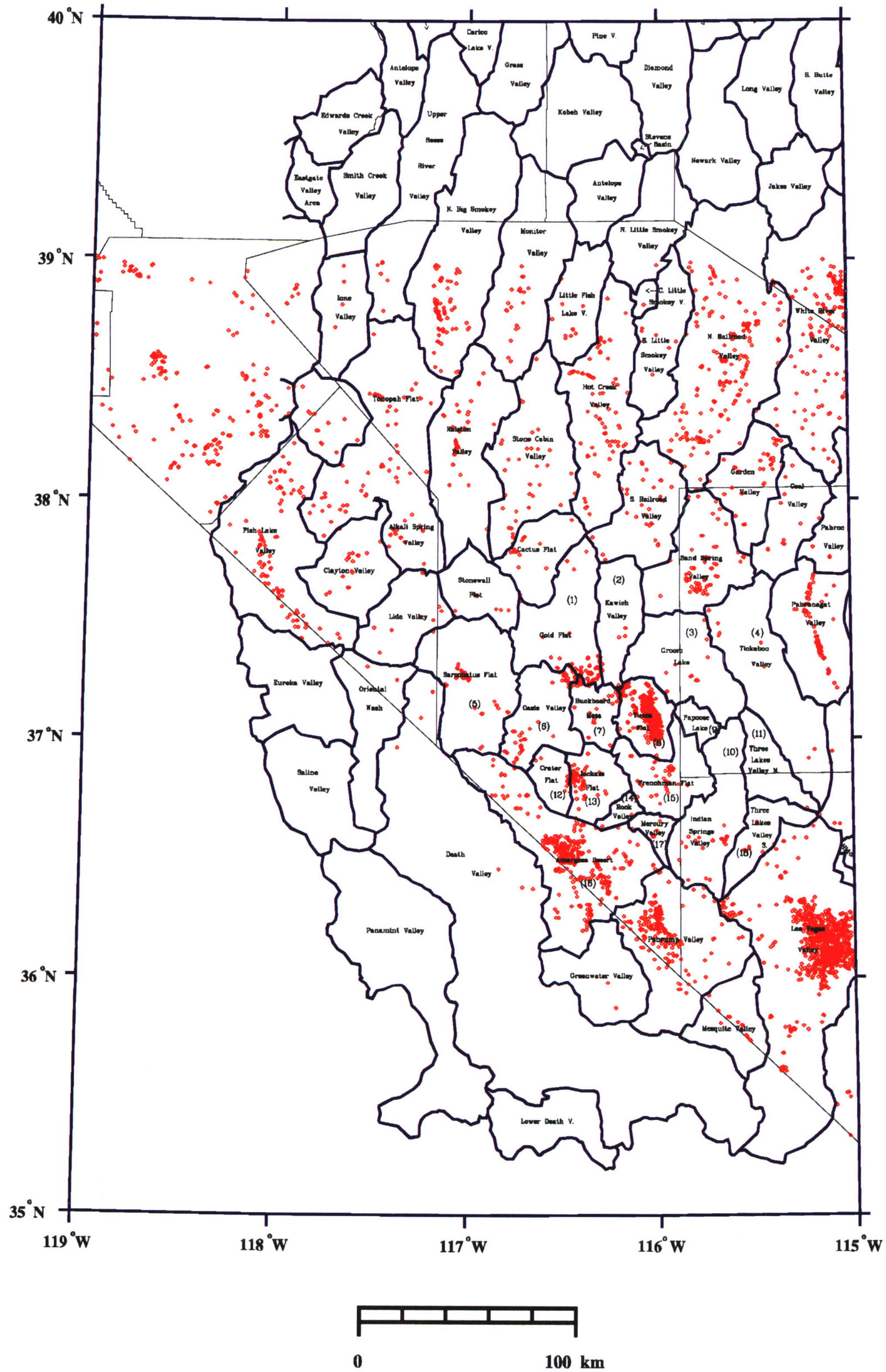

Figure [illegible]-1. Groundwater site locations obtained from USGS GWSI database shown by red circles overl[illegible] on background coverage showing the boundaries of hydrographic basins in dark blue

northernmost point within the basin. An example of this local well numbering system is shown in Figure 6-2 for the Mercury Valley hydrographic basin.

6.4 INTERPRETATION AND MEASUREMENT ERRORS IN CONSTRUCTING WATER LEVEL MAPS

Caution should be exercised when interpreting water level measurements obtained from water wells and other boreholes that were not drilled and instrumented for the express purpose of measuring subsurface hydraulic heads. Piezometers, which consist of a sealed tube that is open to the atmosphere at its top and open to water flow at its base, are specifically designed for obtaining point values of hydraulic head. Piezometers typically have a short (0.3 to 1 m) slotted section of pipe or a short well point at their base. The water level in the piezometer represents the mean hydraulic head over a vertical slice of the water bearing formation equal to the height of the screened section. However, water wells are usually screened within all water bearing units penetrated by the borehole in order to maximize the yield of the well. Where flow in a water bearing unit is horizontal and the well casing within that unit is screened, the water level represents the hydraulic head along any vertical transect. In this case the direction of flow within the water bearing unit can be determined directly from a water level contour map. If there is significant vertical flow within the water bearing unit, the water in the well may represent some composite measure of the hydraulic head. When a borehole is screened in several water bearing units separated by confining units, measured water levels are difficult to interpret. Thus, potentiometric surface maps constructed with these data may be very misleading.

For some of the groundwater sites in the GWSI database, information on well construction, such as the location and length of screened, slotted or open sections of the well casing, can be used in conjunction with well logs to determine the nature of the hydraulic regime implied by the measured water levels. However, at this point in the study these data have not been extracted from the GWSI database and entered into ARC/INFO. Moreover, the spareness of well construction data and the paucity of good borehole lithology data for sites outside of the NTS preclude conducting a systematic analysis of all sites that have water level measurements.

Water level measurements in the GWSI database are given as measured depth below the well head. Water surface elevations were computed by subtracting the depth to water from the well head elevation. The depth to water can be measured quite accurately except where a borehole deviates significantly from vertical. The single greatest source of error in determining water surface elevations is the elevation of the well head. While surveyed well head elevations can be accurate to within 0.3 cm, elevations determined by altimeter will typically be accurate only to within $\pm$3-6 m, and elevations estimated from topographic maps are accurate to one-half the contour interval if the horizontal location of the well can be accurately determined.

Hydrographs of hydraulic head versus time were constructed for each well. Hydrographs could not be plotted for all locations since many boreholes had either a single water level measurement or no measurement at all. For locations with two or more measurements, the mean, median, and standard deviation of the potentiometric surface elevations were computed to aid the estimation of the approximate steady-state potentiometric surface. Where the overall trend of potentiometric level measurements suggests that steady-state conditions exists except for a few significant departures, the median provides a reasonably robust estimate of the steady-state head. In many cases the hydrographs clearly indicate that steady-state conditions do not exist. This is most apparent in the Amargosa Desert where there are wells

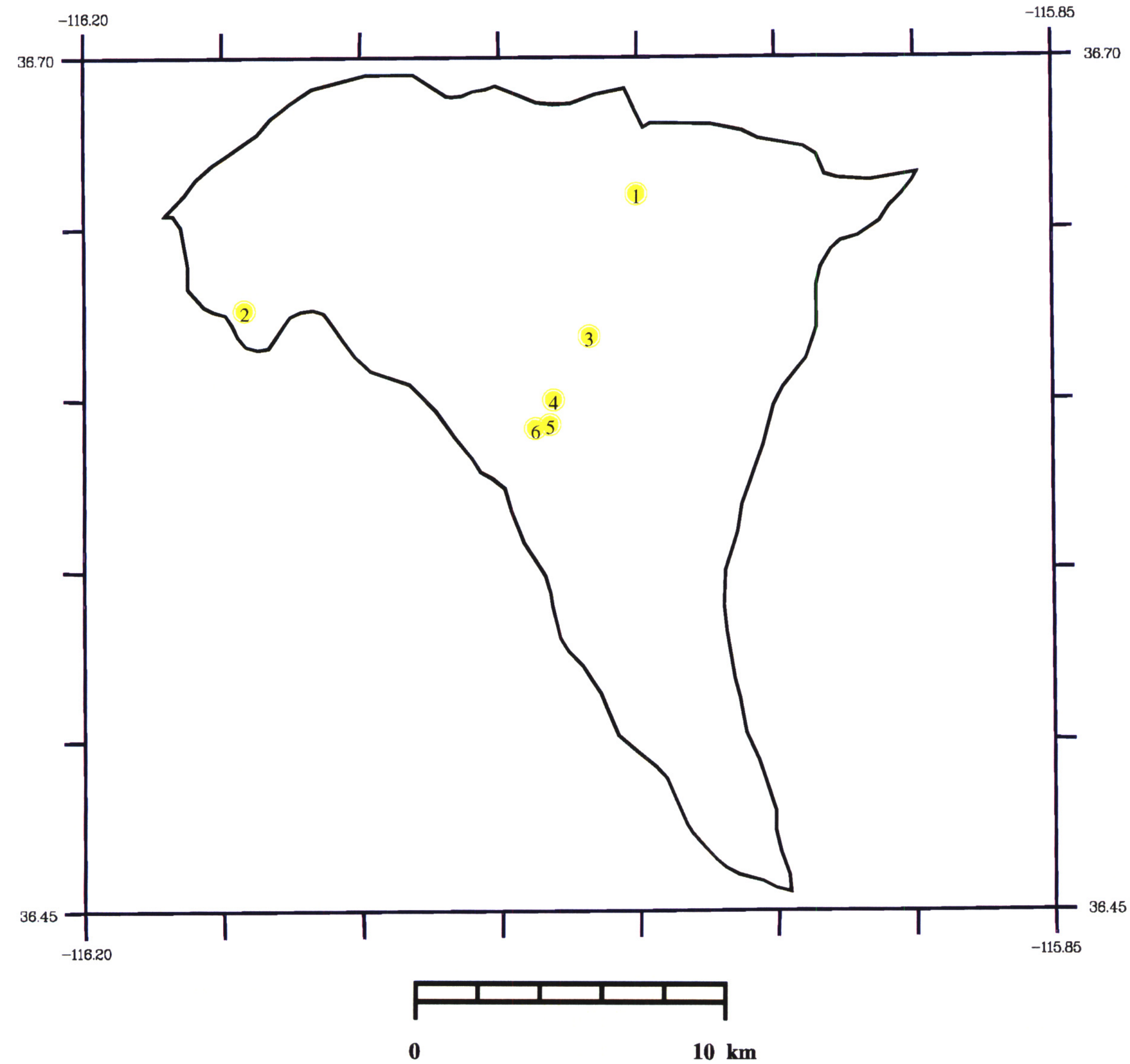

Figure 6-2. Hydrographic basin boundary for Mercury Valley showing local well numbering scheme

whose hydrographs indicate that the alluvial aquifer is being "mined" for water, and in the Ash Meadows spring area, where pumping restrictions imposed in the late 1970's to protect the endangered Devils Hole pupfish have lead to a gradual increase in water levels. For these and other areas where steady-state conditions clearly do not exist, approximate, long-term conditions were estimated by either the mean hydraulic head over either the entire period of record or over that period of record corresponding to the flattest portion of the hydrograph. Locations of the 658 pseudo steady-state water levels extracted from wells and springs in the GWSI database and from McKinley et al. (1991) as of the publication date of this report are shown in Figure 6-3.

6.5 GIS MAP COVERAGES

To date, steady-state water levels have only been determined for the area roughly coincident with the DV-03 sub-region defined by Bedinger et al. (1989). However, steady-state water levels have not yet been determined for the four northwestern hydrographic basins: 1. Oriental Wash; 2. Lida Valley; 3. Stonewall Flat; and 4. Cactus Flat. These steady-state water levels have been used to construct a pseudo steady-state water level map, which will primarily be used to develop a rough understanding of the regional hydraulic regime. As noted in Section 6.4, water level maps constructed from wells that tap different water bearing units can be very misleading. The reader is thereby cautioned when interpreting the steady-state water level map shown in Figure 6-4.

The pseudo steady-state water level contours shown in Figure 6-4 were constructed using the EarthVision geologic modeling program. EarthVision uses a minimum tension gridding procedure to construct a regular grid of water level interpolants. This grid is then contoured using a standard linear interpolation procedure. These contour lines were then transferred to the GIS database as an arc or line file. The water level contour map shown in Figure 6-4 has been overlaid on a color-filled topographic map constructed from DEMs to show the coincidence of major hydraulic and physiographic features. In Figure 6-4 the hotter colors (oranges to reds) indicate lower elevations while the cooler colors (greens to violets) indicate the higher elevations. The reader is referred to Figure 2-1 for the names of the mountain ranges and valleys depicted in Figure 6-4.

From Figure 6-4 it appears that the steep hydraulic gradient located at the north end of YM is part of a larger regional steep gradient that extends east-northeast near Timber Mountain, Shoshone Mountain, the Eleana Range, and eastward across the north end of Yucca Flat towards the Halfpint Range. Steep gradients also exist between the Amargosa Desert and Death Valley. A region of very low hydraulic gradients appears to exist within the Amargosa Desert eastward into Frenchman Flat, southern Three Lakes Valley, and Indian Springs Valley. Concentric contour lines north of Bare Mountain and in the eastern part of the Greenwater Range near Death Valley may be due to inclusion of water levels from perched systems. In general, water levels were removed if the borehole lithology or anecdotal remarks in the GWSI database indicated the tapped water body was perched. Except within Yucca Flat few boreholes penetrate the lower Paleozoic aquifer that is believed to hydraulically connect many of the closed hydrographic basins. Within areas such as the southern Amargosa Desert, where the Paleozoic carbonate aquifer and the Cenozoic alluvial aquifer are assumed to be well-connected, water levels in the alluvium may be reasonable surrogates for the lower carbonate system. In most areas the degree of connection between the alluvial aquifers, tuff aquifers, and lower carbonate aquifer is unknown, thus the use of alluvial aquifer water level measurements to infer the regional hydraulic regime must be viewed cautiously.

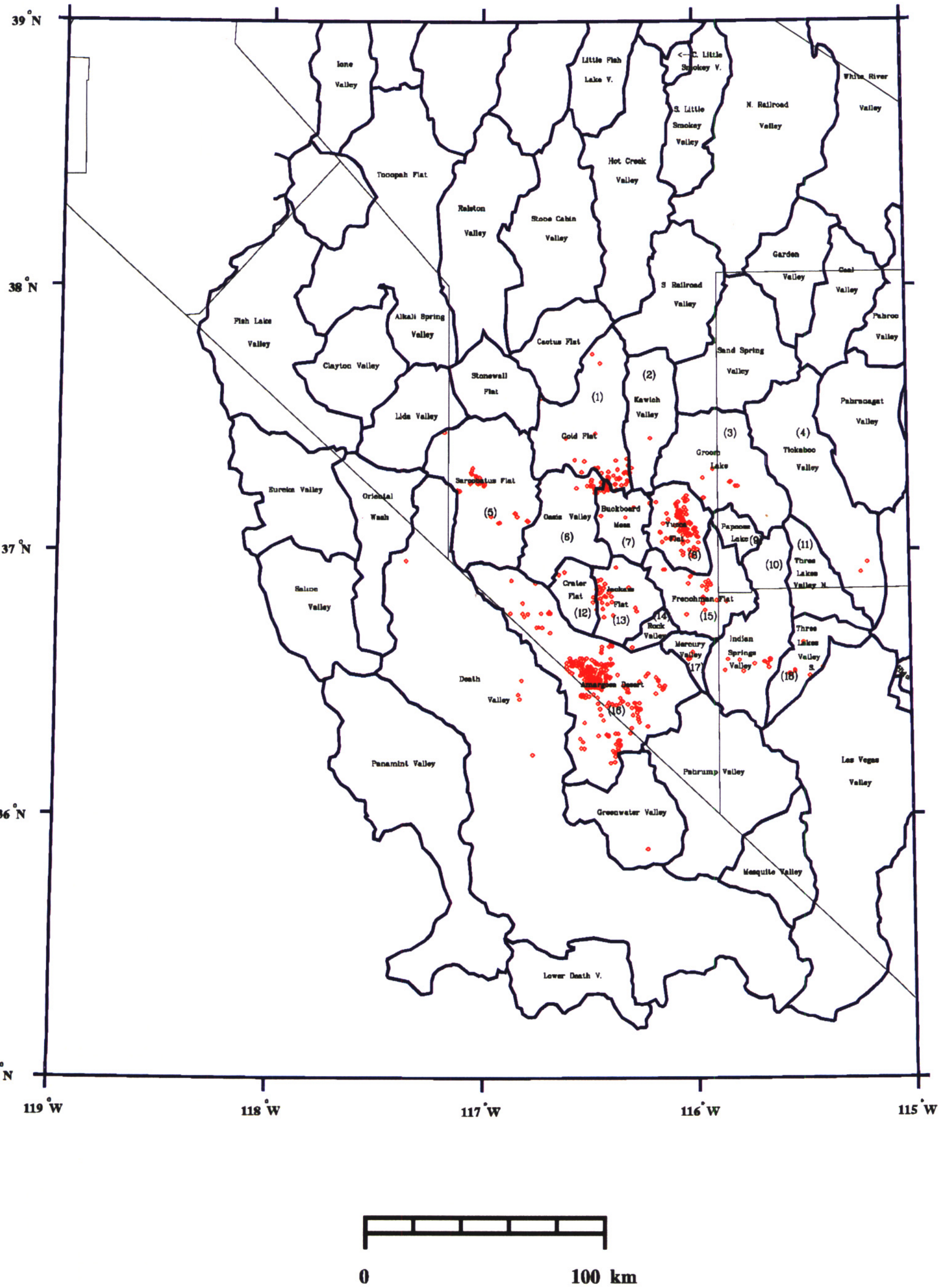

Figure 6-3. Locations of wells, boreholes, and springs used to construct pseudo steady-state water level map shown by red circles overlaid on background coverage showing the boundaries of hydrographic basins in dark blue

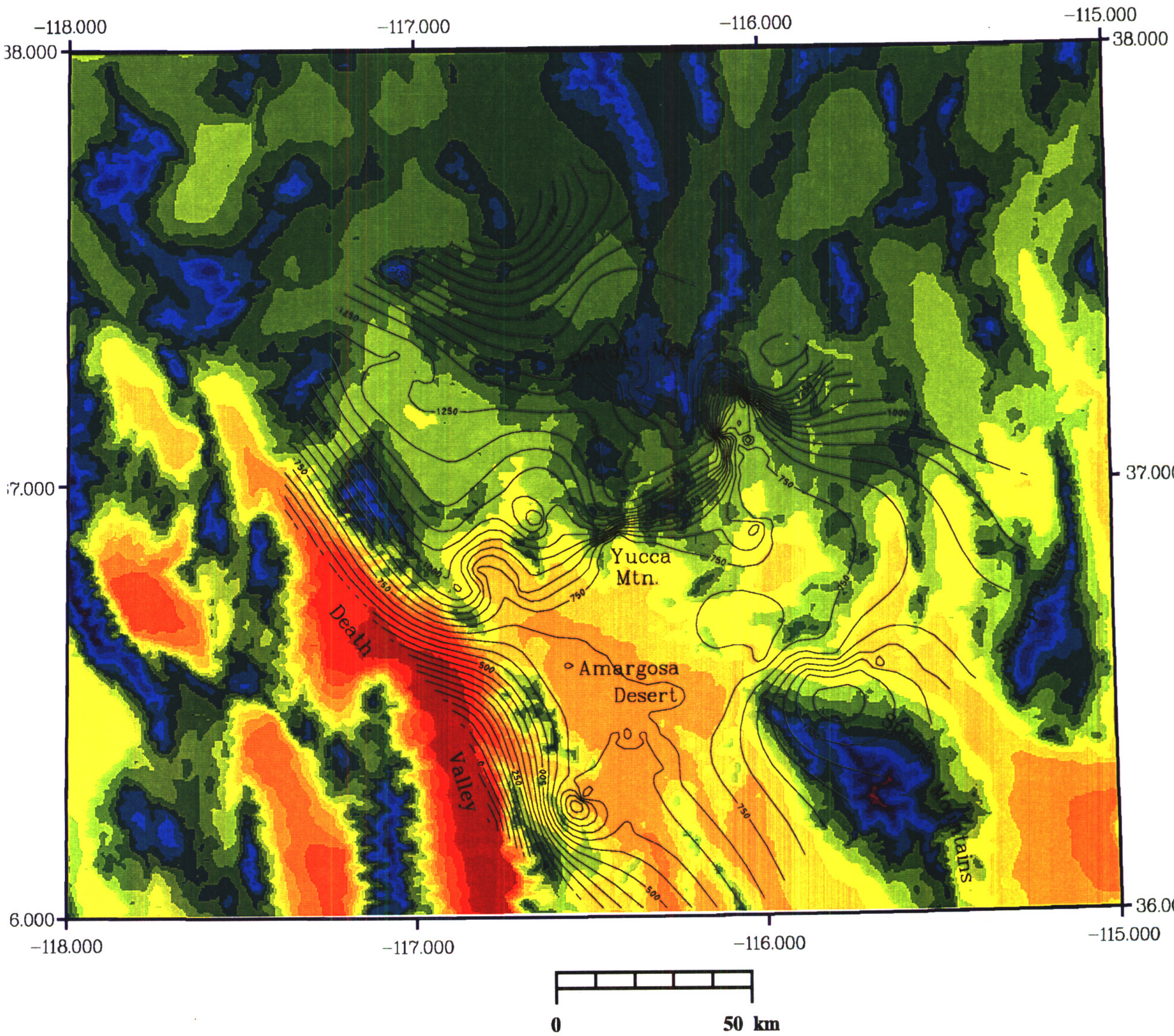

Figure 6-4. Steady-state water level contours overlaid on background coverage of color-filled elevation contours. Lower elevations are shown by hotter colors (yellow - red) and higher elevations are shown by cooler colors (green - violet).

7 HYDROGEOLOGY

7.1 OVERVIEW

Winograd and Thordarson (1975) developed a comprehensive picture of the hydrogeology of the Death Valley Region starting from detailed descriptions of the principal aquifers and aquitards found within the NTS area. Within the NTS Winograd and Thordarson (1975) identified 6 aquifers and 5 aquitards. From the bottom of the hydrostratigraphic section these hydrogeologic units are: 1. the lower clastic aquitard consisting of Precambrian to Lower Cambrian quartzites, shales and siltstones, 2. the lower carbonate aquifer consisting of middle Cambrian to Devonian limestones and dolomites, 3. the upper clastic aquitard consisting of Devonian to Mississippian argillite and quartzite, 4. the upper carbonate aquifer consisting of Pennsylvanian to Permian limestone, 5. local aquitards composed of Cretaceous granitic stocks, dikes and sills, 6. the tuff aquitard composed of Oligocene to middle Miocene interbedded, non-welded to welded ash-flow and ash-fall tuffs, 7. the lava-flow aquitard composed of upper Miocene lava flow and interflow breccia, 8. the bedded tuff aquifer consisting of upper Miocene ash-fall and fluvially rework tuff, 9. the welded tuff aquifer consisting of upper Miocene to middle Pliocene non-welded to densely welded ash-fall, and ash-flow tuffs, 10. the lava flow aquifer composed of upper Pliocene basaltic and rhyolitic flows, and 11. the valley fill aquifer consisting of upper Pliocene to Holocene alluvial, fluvial and lacustrine deposits.

Winograd and Thordarson (1975) note that the surface and subsurface extent of the principal hydrogeologic units vary from basin to basin due to the complex structural and erosional history of the rocks. However, some generalizations were drawn by Winograd and Thordarson (1975) regarding the distribution and saturation of the principal hydrogeologic units. The lower clastic aquitard and lower carbonate aquifer are present throughout the eastern two-thirds of the NTS, and are saturated except in outcrops and buried structural highs. The tuff aquitard generally separates the welded-tuff aquifer from the lower carbonate aquifer, however in areas where the Tertiary volcanics do not occur (primarily east of Pahute Mesa, Timber Mountain, and YM) Cenozoic alluvial deposits are hydraulically connected directly to the lower carbonate aquifer.

7.2 DATA AND GIS MAP COVERAGES

Surface outcrops of the regional aquifer system were identified on various geologic maps within the regional area of interest, digitized, and entered into a GIS database. Geologic data sets were spatially co-registered within the Universal Transverse Mercator (UTM) coordinate framework and can be displayed simultaneously at variable scales. Available information pertaining to the nature and location of the regional carbonate aquifer system, both in outcrops and in the subsurface, will ultimately be used in conjunction with this data set to construct regional hydrogeologic cross-sections which may better define groundwater flow paths within the regional system.

The regional area of interest encompasses the general area defined by Bedinger et al. (1989) as the Death Valley system with an extension to the north to include the region defined as the Death Valley deep-flow region of the carbonate-rock province by Burbey and Prudic (1991).

Division of lithologies within the regional area of interest into hydrostratigraphic units associated with a regional carbonate aquifer was based upon a hydrogeologic characterization of the NTS by Winograd and Thordarson (1975). On the basis of lithologic characterization and geologic age, respective formations found within the study area were grouped as follows:

- Lower Clastic Aquitard: Upper Precambrian to Lower Paleozoic clastics, predominantly quartzites and siltstones

- Lower Carbonate Aquifer: Upper Paleozoic to Late Devonian carbonates, predominantly limestones and dolomites

- Upper Clastic Aquitard: Middle to Late (Devonian - Mississippian) clastics, predominantly quartzites and argillites

- Upper Carbonate Aquifer: Late Paleozoic (Pennsylvanian - Permian) carbonates, predominantly limestones

- Minor Aquitard: Late Paleozoic to Early Mesozoic igneous rocks, predominantly granitic stocks, granodiorite, and quartz monzonite

These groupings are also listed in the hydrostratigraphic column for pre-Cenozoic units of the Death Valley Region shown in Figure 7-1. The areal extent of the surface exposure of the five hydrostratigraphic units is shown in Figure 7-2. Although formations that were added to the upper carbonate aquifer and upper clastic aquitard hydrogeologic units are stratigraphically equivalent to those defined by Winograd and Thordarson (1975), the hydraulic character of these formations may vary greatly from the southern portion of the region near the NTS to the areas near Stonewall Flat, and the Toquima and Toiyabe Ranges.

Carbonate lithologies and associated sedimentary and volcanic deposits interpreted to belong to the Regional Aquifer System were identified on large-scale quadrangle (1:24,000) and smaller scale county (~ 1:250,000) geologic maps obtained primarily from the Nevada Bureau of Mines and Geology. Surface outcrops of respective lithologies were digitized and co-registered within the UTM Coordinate System using ARC/INFO. Individual maps were assimilated into one large polygon coverage utilizing coordinate transformation capabilities of the GIS software. Polygon coverages (using ARC/INFO nomenclature) are used to capture real-world data sets associated with areal extent. Lithologies belonging to the regional system represented in this coverage, in addition to intrinsic values of areal extent, have been assigned respective hydrostratigraphic unit codes which facilitate interactive query using appropriate GIS modules (ARCPLOT and ARCEDIT).

It should be noted that the resolution of this regional aquifer system coverage is ultimately limited to that of constituent geologic base maps. Highest resolution in terms of lithologic (hydrostratigraphic) contacts and areal extent will be limited to those areas which were digitized from large-scale (1:24,000) quadrangle maps. Geologic maps of this scale were preferred to larger county maps and used extensively where available. Hydrostratigraphy for most of the southern region was gleaned from this source. Smaller-scale county maps (~ 1:250,000) were used to "fill in" gaps within the developing coverage for remaining areas within the state of Nevada. Although coarser in resolution, these smaller-scale base maps maintained the degree of stratigraphic division necessary for defining the hydrogeologic units set forth by Winograd and Thordarson (1975). Where maps of varying scale came into contact, good agreement was generally found in terms of stratigraphic definition and areal extent. Uniform geologic coverage for California could not be obtained at an appropriate scale for hydrostratigraphic division. As a result, isolated relatively large-scale maps (~ 1:100,000) were used as base maps. All geologic maps used to construct Figure 7-2 are listed in Appendix A.

HYDRO-GEOLOGIC UNIT	SYSTEM	SERIES	STRATIGRAPHIC UNIT	MAJOR LITHOLOGY	MAX THICK (M)
Minor Aquitard	Cretaceous to Permian		Granitic stocks	Granodiorite and quartz monzonite	
Upper Carbonate Aquifer	Permian and Pennsylvanian		Tippipah Limestone	Limestone	1,100
			Bird Spring Formation	Limestone and silty-limestone	
Upper Clastic Aquitard	Mississippian and Devonian		Chainman Shale	Shale and argillite	>55
			Limestone of Timpi Canyon	Clayey-limestone	120
			Mercury Limestone	Limestone	67
			Bristol Pass Limestone	Limestone	
			Joana Limestone	Limestone	
			Narrow Canyon Limestone	Clayey- to silty-limestone	66
			Pilot Shale	Silty limestone	50-300
			Eleana Formation	Argillite, quartzite, conglomerate, limestone	2,400
Lower Carbonate Aquifer	Mississippian		Monte Cristo Limestone	Limestone	
	Devonian	Upper	Devil Gate Limestone	Limestone, dolomite, minor quartzite	>420
		Middle	Guilmette Formation	Various	1070
			Sultan Limestone	Limestone	
			Nevada Formation	Dolomite	>460
	Devonian and Silurian		Undifferentiated (Simonson, Sevy, Hidden Valley, Spotted Range, Laketown, Lone Mountain and others)	Dolomite	430
	Ordovician	Upper	Ely Springs Dolomite	Dolomite	95
		Middle	Eureka Quartzite	Quartzite, minor limestone	105
		Lower	Pogonip Group	Limestone and claystone	>840
	Cambrian	Upper	Nopah Formation	Dolomite, limestone	325
		Middle	Highland Peak Formation	Limestone and dolomite	~1370
			Emigrant Formation	Limestone	>186
			Bonanza King Formation	Limestone, dolomite, minor siltstone	745
			Upper Carrara Formation	Primarily limestone	320
Lower Clastic Aquitard		Lower	Lower Carrara Formation	Primarily siltstone	290
			Chisholm Shale	Fissile shale	<52
			Lyndon Limestone	Limestone	122
			Pioche Shale	Shale	<295
			Prospect Mountain Quartzite	Quartzite	122-2395
			Zabriskie Quartzite	Quartzite	70
			Wood Canyon Formation	Quartzite, siltstone, shale, minor dolomite	665
	Precambrian		Stirling Quartzite	Quartzite, siltstone	1,040
			Johnnie Formation	Quartzite, sandstone, siltstone, minor limestone and dolomite	>975
			Ibex Formation	Dolomite, sandstone, shale, siltstone	
			Noonday Dolomite	Dolomite	

Figure 7-1. Hydrostratigraphic column for pre-Cenozoic units in the Death Valley Region

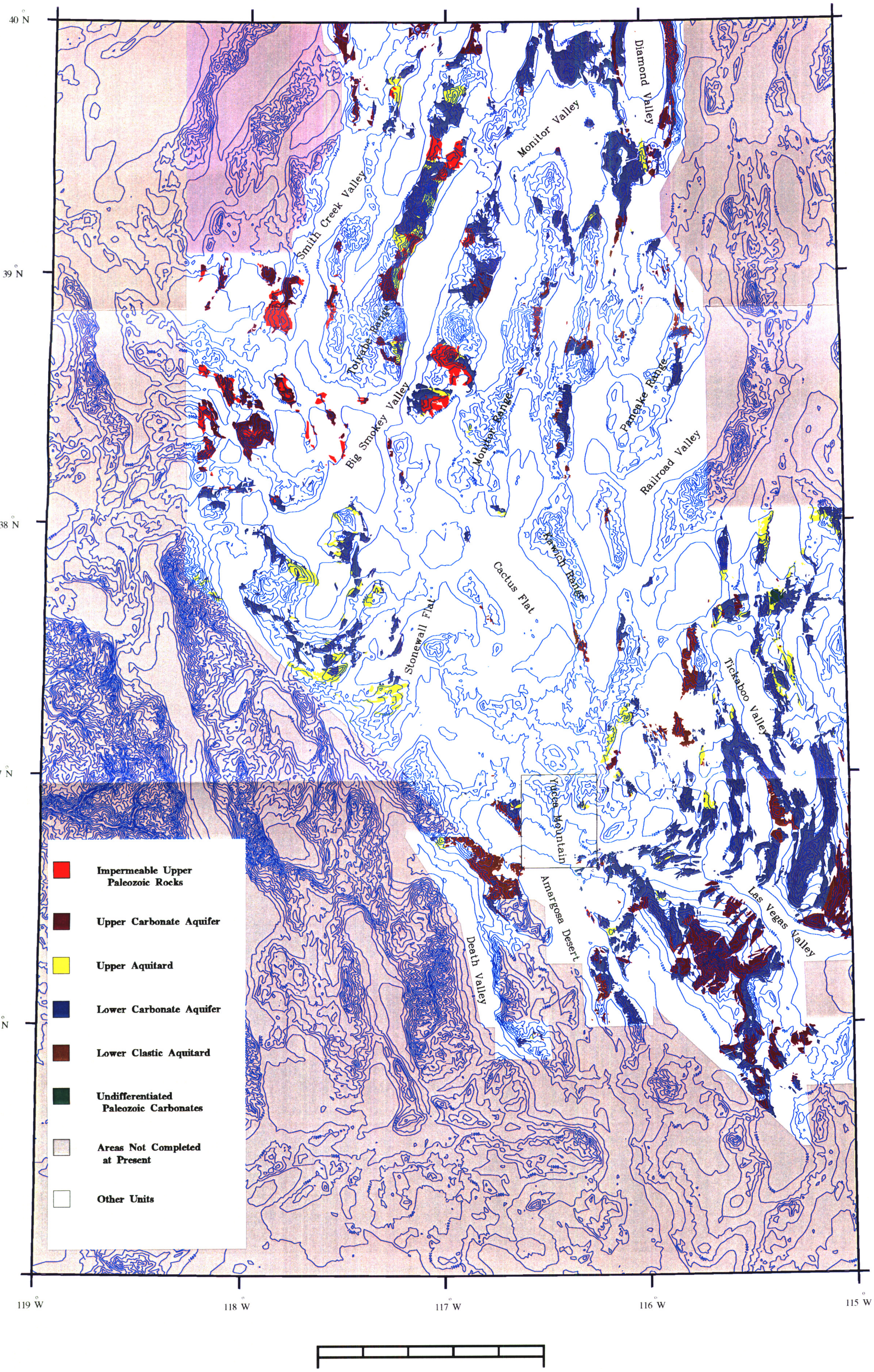

Figure 7-2. Map of surface exposure of pre-Cenozoic hydrostratigraphic units in the Death Valley Region overlaid on topographic contours

8 HYDROGEOCHEMISTRY

8.1 OVERVIEW

Chemical analyses of 279 groundwater samples from wells and springs in the Death Valley Region have been entered into ARC/INFO. In addition to chemical analyses, the ARC/INFO record for each sample includes where available: 1. sample location expressed as Nevada Central Coordinates and latitude and longitude; 2. date sample collected; 3. elevation of well or spring; 4. depth to water; 5. well depth; 6. lithology and geologic unit from which the sample obtained. These data were entered into the ARC/INFO database by Turner and Pickett (1994) from a compilation by McKinley et al. (1991).

Groundwater chemistry in the Death Valley Region is highly variable. Some waters, such as those found around the Spring Mountains and Rainier Mesa are quite fresh, with total dissolved solids (TDS) contents often less than 200 ppm. On the other hand, some waters are highly saline, with TDS exceeding 50,000 ppm. Highly saline waters are often associated with playas and salt pans and are found at Death Valley (TDS as high as 23,600 ppm) and Franklin Lake Playa (TDS as high as 79,700 ppm). The high salinities are usually caused by evaporation leading to high concentrations of sodium, chloride, bicarbonate, and sulfate. Some of the saline waters also contain unusually high concentrations of fluoride (as high as 30 ppm) and nitrate (as high as 200 ppm). Surface water samples collected from playas and salt pans are often more saline than the groundwater that discharges to them. Brines sampled from the salt pan at Death Valley contained more than 300,000 ppm TDS (Hunt et al., 1966).

Most groundwater in the region is neutral to slightly alkaline, with the great majority of pHs ranging between 7 and 9. The highest measured pHs (maximum = 9.8) tend to be associated with highly saline waters, such as those found at Franklin Lake Playa. The lowest pHs (minimum = 6.2) tend to be associated with fresh waters having TDS values less than 500 ppm.

Groundwater temperatures typically range between 20° and 30° C. The warmest groundwater (temperatures greater than 50° C) are found at YM, and nearby Jackass and Yucca Flats. Temperatures of 57° and 64° C were measured in samples taken from Paleozoic carbonate rocks at depths greater than 1,000 m. However, the warmest sample (74° C) was taken from a well completed in alluvium to a depth of only 383 m. The coldest groundwater in the Death Valley Region emanates from springs on the higher mountain ranges. The lowest temperature (3° C) was measured at Mazie Spring (elevation 2,783 m) in the Spring Mountains.

8.1.1 Hydrochemical Facies

Winograd and Thordarson (1975) define five hydrochemical facies in the south-central Great Basin, and present a summary of their major component chemistry. The facies are listed in Table 8-1.

The water quality of the calcium-magnesium bicarbonate facies of the lower carbonate aquifer varies little with depth or geographic location. Excess sodium and sulfate in the calcium-magnesium-sodium bicarbonate facies is derived from Tertiary tuff aquifers and aquitards. Sodium within the lower carbonate aquifer water beneath the NTS is a consequence of cross flow through tuffaceous rocks, or importation from the northeast, e.g., Pahranagat Valley. The chemistry of water in the carbonate aquifer beneath eastern Frenchman Flat is almost identical to that of water discharging at Ash Meadows. Therefore, the source of the sodium and sulfate components may be to the north or east of Frenchman

Table 8-1. Hydrochemical facies in the Death Valley Region (after Winograd and Thordarson, 1975)

Hydrochemical Facies	Main Occurrences	Associated Rock Types
Calcium-Magnesium-Bicarbonate	Southern Indian Springs Valley	Lower Carbonate Aquifer Carbonate-Rock Valley Fill Carbonate-Rock Springs
	Southern Three Lakes Valley	
	Northwestern Las Vegas Valley	
	Pahrump Valley	
	Spring Mountains	
	Pahranagat Valley Springs	
Sodium-Potassium-Bicarbonate	Western Emigrant Valley (Groom and Papoose Lakes)	Tuff Rhyolite Volcanic-Rock Valley Fill
	Frenchman Flat	
	Jackass Flats	
	Pahute Mesa	
	Oasis Valley	
Calcium-Magnesium and Sodium-Bicarbonate	Ash Meadows	Mixed Carbonates-Volcanics
	Eastern NTS	
Playa Type	Phreatic Playas	
Sodium-Sulfate-Bicarbonate	Furnace Creek Wash	
	Nevares Springs	

Flat. Sodium and sulfate contents of carbonate aquifer waters in the southeastern NTS are higher than in water taken from the upper zone of saturation of overlying tuffaceous aquifer waters. Sodium and sulfate increase with depth in the tuffaceous rocks, which contain gypsum in basal strata of the tuff aquitard.

Waters from Pahrump Valley are typical of the calcium-magnesium bicarbonate facies and contain less sodium and sulfate than waters discharging at Ash Meadows. It is unlikely that there is significant flow from Pahrump Valley to Ash Meadows springs. Lower sodium, potassium, sulfate, and chloride in Indian Springs Valley, Three Lakes Valley, and northwest Las Vegas Valley waters than in water from the NTS and Ash Meadows indicates that water does not flow eastward from the NTS.

Relations for mixing of a hypothetical water from the tuff aquitard with the carbonate aquifer water indicate that leakage from the tuff accounts for only a few percent to perhaps 20 percent of the discharge at Ash Meadows.

Diverse water types in the valley fill of the Amargosa Desert indicate diverse sources. Calcium-magnesium-sodium bicarbonate water probably leaks through the barrier responsible for the Ash Meadows springs. Sodium-potassium bicarbonate facies waters probably are derived from western Jackass Flats. Low dissolved salt contents of waters in Fortymile Wash may reflect local infiltration along the arroyo bed and little westward flow in the vicinity of Lathrop Wells. Water in a 530 foot deep well three miles east of the Ash Meadows springs is 8° C cooler and contains high sodium potassium bicarbonate concentrations similar to playa water. It must be isolated from the discharging waters in Ash Meadows. Water discharging at Furnace Creek Wash-Nevares Springs may be a mixture of water from Ash Meadows and Oasis Valley with addition of sulfate and chloride. Although unnoted by Winograd and Thordarson (1975), the data they report show that the Furnace Creek Wash-Nevares Springs waters resemble closely those of wells in the valley fill of the north central Amargosa Desert.

8.2 DATA AND GIS MAP COVERAGES

The groundwater chemistry data in the ARC/INFO GIS were used to construct the Stiff diagrams shown in Figure 8-1. A Stiff diagram is a graphical method of displaying analytical data that facilitates rapid comparison of the chemical characteristics of samples. The diagrams shown in Figure 8-1 consist of three parallel horizontal axes extending across a vertical axis. The vertical axis represents a concentration of zero. The concentrations of major cations (sodium plus potassium, calcium, magnesium), expressed as meq/l, are plotted on the horizontal axes to the left of zero. The concentrations of major anions (chloride, bicarbonate, sulfate) are plotted to the right of zero. When the resulting points are connected, the analytical data appear as an irregular polygons. The polygons take on distinctive shapes that are due to differences in chemical compositions and concentrations. For example, the Stiff diagrams in Figure 8-1 clearly display the differences between the sodium poor waters found around the Spring Mountains and Pahrump Valley, and the relatively sodium rich waters at Ash Meadows and Death Valley. The Stiff diagrams in Figure 8-1 have been overlaid on a coverage consisting of the southern half of the hydrostratigraphic map shown in Figure 7-2. Figure 8-1 clearly shows the association of the calcium-magnesium-bicarbonate facies with the occurrence of the Paleozoic carbonate aquifer. Since the hydrogeologic map does not yet include the surface exposure of the Tertiary tuff units their strong correlation with the sodium-potassium-bicarbonate facies cannot be seen.

Identification of hydrochemical facies has been and will continue to be one of the primary tools used to infer the hydraulic regime of the Death Valley Region. The current data entered into the GIS database generally support the conclusions of Winograd and Thordarson (1975) as well as that of Schoff and Moore (1964). Water chemistry data will be needed from areas north of the NTS in order to assess the validity of Burbey and Prudic's (1991) regional conceptual model, which suggests that recharge to the regional system may be derived from as far north as the Monitor, Toquima, and Toiyabe Ranges.

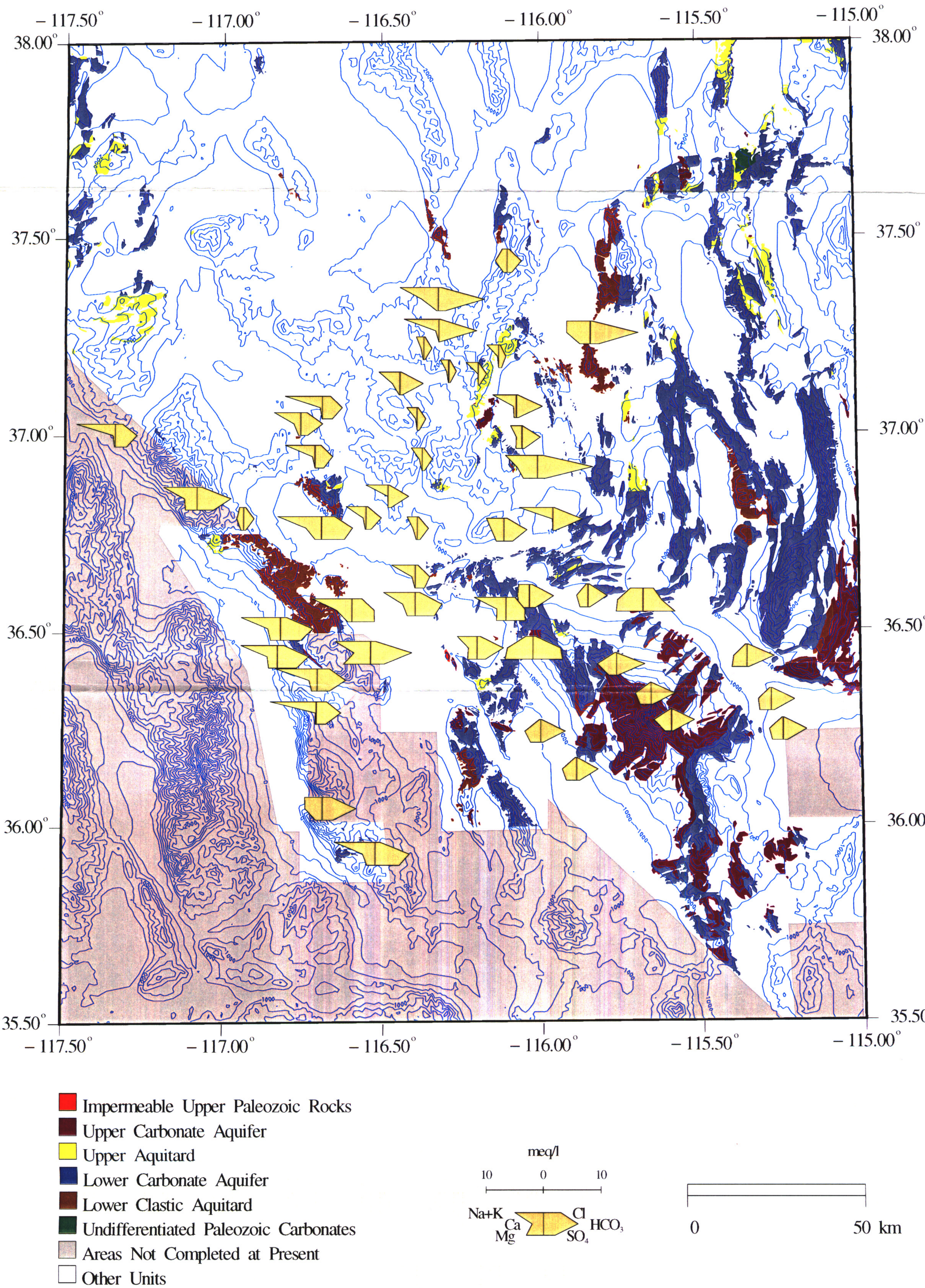

Figure 8-1. Map showing Stiff diagrams for water chemistry analyses from McKinley et al. (1991) and pre-Tertiary surface hydrostratigraphy.

9 SUMMARY AND PROSPECTIVE

This report provides detailed descriptions of the data and coverages that have been entered into the Regional Hydrogeology GIS database to define the physiography, surface water hydrology, precipitation and climate, recharge and discharge regimes, groundwater levels, hydrogeology, and hydrogeochemistry of the Death Valley Region. Although these basic data categories are reasonably complete, none have yet been fully populated with data. Moreover, while most of the data that has been entered may be readily used to construct maps, much of the data are not yet in a format that is convenient for performing complex spatial queries.

To date, hydrogeologic data has been entered in three basic formats: 1. point data; 2. arc coverages, which may in turn be used to form lines and polygons; and 3. screen raster images. Point data include: 1. precipitation station locations with associated measurements of average annual precipitation, length of record, etc.; 2. groundwater measurement locations with associated information such as water levels, well construction, borehole lithology, spring discharge, etc.; and 3. water chemistry measurement locations with data chemical analyses. Line or polygon coverages include: 1. boundaries defined by various researchers that delineate the extent of the Death Valley Region; 2. boundaries of each hydrographic basin within the Death Valley Region; 3. lines defining the surface water drainage network; 4. steady-state water level contours extracted from EarthVision; 5. polygons defining the surface hydrostratigraphy; 6. topographic contour lines; 7. polygons defining major discharge zones. Screen raster images include: 1. the grayscale shaded relief map of the topography within the Death Valley Region; 2. color-filled contours of average annual precipitation; 3. color-filled contours of average annual areal recharge estimated using the Maxey-Eakin method. Screen raster images are primarily useful for constructing maps, while point, line, and polygon data can be used for performing spatial queries of the GIS database. While screen raster images can be relatively easily constructed by taking computer snapshots of screen images produced by other software packages, lines and polygons must be digitized from other maps or entered as spatial data in order to define the topology of the coverage.

The screen raster images presented in this report will be converted in the future to a format that will allow spatial queries to made of the GIS database. Digitizing detailed maps, such as Figure 4-2 showing estimated average annual precipitation, is very time consuming and may be prohibitively expensive. Figure 4-2 can be directly converted to an ARC/INFO grid file, which can be queried about the spatial location of all grid points having a value of "red", however, the resolution of the grid will be limited. Alternatively, those screen images, such as Figure 4-2, which are obtained from color-filled contour maps, may be converted to polygon coverages by first extracting the contour lines that separate the colors, saving these contour lines as line files, and finally connecting the endpoints of those lines which enclose a region of constant color.

Those sections of the GIS that will continue to be refined during the remainder of this project include:

- Precipitation and Climate: extend the average annual precipitation coverage to include all of Death Valley proper and the areas to the north included in the conceptual model of Burbey and Prudic (1991)

- Recharge and Discharge: extend the coverage of estimated average annual areal recharge based on the extended precipitation coverage, and refine the shape and location of the discharge zone polygons

- Wells, Springs, and Water Level Contour Maps: continue to refine the steady-state water level map, and develop separate water level maps for the basin-scale alluvial and tuff aquifers, and the regional carbonate aquifer

- Hydrogeology: incorporate the surface geology for the Tertiary tuffs and Cenozoic alluvial deposits

- Hydrogeochemistry: obtain water chemistry data for areas located to the north of NTS

In the future the Regional Hydrogeology GIS database will be extensively used to: 1. construct additional maps needed for evaluation of alternative conceptual models; and 2. prepare base maps to be used for preparing finite element or finite grids used in 2D and 3D groundwater flow modeling. In addition, this GIS database will be used to evaluate portions of DOE's site suitability evaluation on geohydrology and transport currently scheduled for completion in late 1997. In addition, the GIS will be used to support the development of methods for assessing the adequacy of conceptual and mathematical flow models constructed by DOE. The measurement methods will form the technical basis for CDM related to regional groundwater flow.

10 REFERENCES

Bedinger, M.S., K.A. Sargent, and W.H. Langer. 1989. *Studies of Geology and Hydrology in the Basin and Range Province, Southwestern United States, for Isolation of High-Level Radioactive Waste—Characterization of the Death Valley Region.* United States Geological Survey Professional Paper 1370-F. Washington, DC: U.S. Geological Survey.

Burbey, T.J., and D.E. Prudic. 1991. *Conceptual Evaluation of Regional Ground-Water Flow in the Carbonate-Rock Province of the Great Basin, Nevada, Utah, and Adjacent States.* United States Geological Survey Professional Paper 1409-D. Washington, DC: U.S. Geological Survey.

Czarnecki, J.B. 1990. *Geohydrology and Evapotranspiration at Franklin Lake Playa, Inyo County, California,* United States Geological Survey Open-File Report 90-356. Washington, DC: U.S. Geological Survey.

Czarnecki, J.B., and R.K. Waddel. 1984. *Finite-Element Simulation of Ground-Water Flow in the Vicinity of Yucca Mountain, Nevada-California,* United States Geological Survey Water-Resources Investigations Report 84-4349. Washington, DC: U.S. Geological Survey.

Dudley, W.W., Jr., and J.D. Larson. 1976. *Effect of Irrigation Pumping on Desert Pupfish Habitats in Ash Meadows, Nye County, Nevada.* United States Geological Survey Professional Paper 927. Washington, DC: U.S. Geological Survey.

French, R.H. 1983. Precipitation in southern Nevada. *American Society of Civil Engineers Journal of Hydraulic Engineering* 109(7): 1.023-1,036.

Hardman, G. 1936. *Nevada Precipitation and Acreages of Land by Rainfall Zones.* University of Nevada Experimental Station Mimeograph Paper. Reno, NV: University of Nevada.

Hevesi, J.A., J.D. Istok, and A.L. Flint. 1992. Precipitation estimation in mountainous terrain using multivariate statistics. Part I: Structural analysis. *Journal of Applied Meteorology* 31(7): 661–676.

Hunt, C.B., T.W. Robinson, W.A. Bowles, and A.L. Washburn. 1966. *Hydrologic Basin, Death Valley, California.* United States Geological Survey Professional Paper 494-B. Washington, DC: U.S. Geological Survey.

Lenfest, L.W. 1989. Introduction. *National Water Information System User's Manual 2(4) — Ground-Water Site Inventory System.* S.B. Mathey, ed. U.S. Geological Survey Open-File Report 89-587. Washington, DC: U.S. Geological Survey. 1-1–1-6.

Maxey, G.B., and T.E. Eakin. 1949. Groundwater in White Pine, Nye, and Lincoln Counties, Nevada. *Water Resource Bulletin.* No. 8. Carson City, NV: State of Nevada Office of the Stage Engineer.

Mifflin, M.D. 1988. Region 5, Great Basin, in the geology of North America, Volume 0-2. Geological Society of America. W. Back, J.S. Rosenshein, and P.R. Seaber, editors. *Hydrology*: 69–78

McKinley, P.W., M.P. Long, and L.V. Benson. 1991. *Chemical Analyses of Water from Selected Wells and Springs in the Yucca Mountain Area, Nevada and Southeastern California*. United States Geological Survey Open-File Report 90-355. Washington, DC: U.S. Geological Survey.

Rice, W.A. 1984. *Preliminary Two-Dimensional Regional Hydrologic Model of the Nevada Test Site and Vicinity*. SAND83-7466. Albuquerque, NM: Sandia National Laboratories.

Rush, F.E., 1971. *Regional Ground-Water Systems in the Nevada Test Site Area, Nye, Lincoln, and Clark Counties, Nevada*. United States Geological Survey Water Resources - Reconnaissance Series Report 54. Washington, DC: U.S. Geological Survey.

Rush, F.E. 1970. *Index of Hydrographic Areas in Nevada*. U.S. Geological Survey Water Resources Information Series, Report 6. Washington, DC: U.S. Geological Survey.

Schoff, S.L., and J.E. Moore. 1964. *Chemistry and Movement of Ground Water, Nevada Test Site*. U.S. Geological Survey Open-File Report TEI-787. Washington, DC: U.S. Geological Survey.

Trimble, S. 1989. *The Sagebrush Ocean, a Natural History of the Great Basin*. Reno, NV: University of Nevada Press: 248.

Turner, D., and D. Pickett. 1994. *Report on Geographic Database Development and Investigations to Support CDM Development - Geochemistry FY94*. San Antonio, TX: Center for Nuclear Regulatory Analyses.

U.S. Department of Energy. 1991. *Study Plan for Study 8.3.1.2.1.1—Characterization of the Meteorology for Regional Hydrology: Revision 0*. Las Vegas, NV: U.S. Department of Energy, Yucca Mountain Site Characterization Project Office.

U.S. Nuclear Regulatory Commission. 1994. *License Application Review Plan for the Review of a License Application for a Geological Repository for Spent Fuel and High-Level Radioactive Waste*. NUREG-1323. Washington, DC: Nuclear Regulatory Commission.

Waddell, R.K. 1982. *Two-Dimensional, Steady-State Model of Ground-Water Flow, Nevada Test Site and Vicinity, Nevada-California*. U.S. Geological Survey Water Resources Investigations Report 82-4085. Washington, DC: U.S. Geological Survey.

Waddell, R.K., J.H. Robison, R.K. Blankennagel. 1984. *Hydrology of Yucca Mountain and Vicinity, Nevada-California—Investigative Results Through Mid-1983*, United States Geological Survey Water-Resources Investigations Report 84-4267. Washington, DC: U.S. Geological Survey.

Watson, P., P. Sinclair, and R. Waggoner. 1976. Quantitative evaluation of a method for estimating recharge to desert basins of Nevada. *Journal of Hydrology* 31: 335–357.

Winograd, I.J., and W. Thordarson. 1975. *Hydrogeologic and Hydrochemical Framework, South-Central Great Basin, Nevada-California, with Special Reference to the Nevada Test Site*. United States Geological Survey Professional Paper 712-C. Washington, DC: U.S. Geological Survey.

Wittmeyer, G.W., and R.V. Klar. 1995. *Regional Hydrogeologic Processes of the Death Valley Region. NRC High-Level Radioactive Waste Research at CNWRA, July-December 1994*. CNWRA 94-02S. B. Sagar, ed. San Antonio, TX: Center for Nuclear Waste Regulatory Analyses: 155–175.

APPENDIX A

Bibliography

Albers, J.P., and J.H. Stewart. 1972. Geology and Mineral Deposits of Esmeralda County, Nevada. Nevada Bureau of Mines & Geology Bulletin 78: Reno, NV: University of Nevada.

Barnes, H., R.L. Christiansen, and F.M. Byers, Jr. 1965. Geologic Map: Jangle Ridge Quadrangle, Nye and Lincoln Counties, Nevada. U.S. Geological Survey Geologic Quadrangle Map GQ-363. 1:24,000.

Barnes, H., Ekren, E.B., Rodgers, C.L., and D.C. Hedlund. 1982. Geologic and Tectonic Maps of the Mercury Quadrangle, Nye and Clark Counties, Nevada. U.S. Geological Survey Miscellaneous Investigations Series Map I-1197. 1:24,000.

Barnes, H., F.N. Houser, and F.G. Poole. 1963. Geologic Map: Oak Spring Quadrangle, Nye County, NV. U.S. Geological Survey Geologic Quadrangle Map GQ-214. 1:24,000.

Burchfiel, B.C., G.S. Hamill, IV, and D.E. Wilhelms. 1982. Stratigraphy of the Montgomery Mountains and the Northern Half of the Nopah and Resting Springs Ranges, Nevada and California. Geological Society of America Map & Chart Series MC-44.

Byers, F.M., Jr., and H. Barnes. 1967. Geologic Map: Paiute Ridge Quadrangle, Nye & Lincoln Counties, NV. U.S. Geological Survey Geologic Quadrangle Map GQ-577. 1: 24,000.

Colton, R.B., and E.J. McKay. 1966. Geologic Map: Yucca Flat Quadrangle, Nye and Lincoln Counties, Nevada. U.S. Geological Survey Geologic Quadrangle Map GQ-582. 1: 24,000.

Cornwall, H.R. 1967. Geologic Map of Southern Nye County, Nevada. Nevada Bureau of Mines Bulletin 77 1:250,000.

Denny, C.S., and H. Drewes. 1952. Topo Map Ash Meadows 15 Minute Quadrangle, Nevada-California. U.S. Geological Survey 1:62,500.

Ekren, E.B., C.L. Rogers, R.E. Anderson, and T. Botinelly. 1967. Geologic Map: Belted Peak Quadrangle, Nye County, Nevada. U.S. Geological Survey Geologic Quadrangle Map GQ-606. 1:62,500.

Frizzell, V.A., Jr., and J. Shulters. 1990. Geologic Map: Nevada Test Site, Southern Nevada. U.S. Geological Survey Miscellaneous Investigations Series Map I-2046. 1:100, 000.

Gibbons, A.B., E.N. Hinrichs, W.R. Hansen, and R.W. Lemke. 1963. Geologic Map: Ranier Mesa Quadrangle, Nye County, Nevada. U.S. Geological Survey Geologic Quadrangle Map GQ-215. 1:24,000.

Hinrichs, E.N., and E.J. McKay. 1965. Geologic Map: Plutonium Valley Quadrangle, Nye & Lincoln Counties, NV. U.S. Geological Survey Geologic Quadrangle Map GQ-384. 1: 24,000.

Hinrichs, E.N. 1968. Geologic Map: Camp Desert Rock Quadrangle, Nye County, NV. U.S. Geological Survey Geologic Quadrangle Map GQ-726. 1:24,000.

Hunt, C.B., and D.R. Mabey. 1966. Stratigraphy and Structure Death Valley, California. U.S. Geological Survey Professional Paper 494-A: Washington, D.C.: U.S. Government Printing Office: 162 pages.

Kleinhampl, F.J., and J.I. Ziony. 1985. Geology of Northern Nye County, Nevada. Nevada Bureau of Mines & Geology Bulletin 99-A: Reno, NV: University of Nevada: 172 pages & 2 plates

Longwell, C.R., E.H. Pampeyan, B. Bowyer, and R.J. Roberts. 1965. Geology and Mineral Deposits of Clark County, Nevada. Nevada Bureau of Mines & Geology Bulletin 62: Reno, NV: Mackay School of Mines: 218 pages & 16 plates.

Maldonado, F. 1990. Geologic Map: Northwest Quarter of the Bullfrog 15-Minute Quadrangle, Nye County, Nevada. U.S. Geological Survey Miscellaneous Investigations Series Map I-1985. 1:24,000.

Maldonado, F. 1990. Geologic Map: Northeast Quarter of the Bullfrog 15-Minute Quadrangle, Nye County, Nevada. U.S. Geological Survey Miscellaneous Investigations Series Map I-2049. 1:24,000.

McAllister, J.F. 1970. Geology of the Furnace Creek Borate Area, Death Valley, Inyo County, California. California Department of Conservation Division of Mines and Geology Map Sheet 14. 1:24,000.

McKay, E.J., and W.P. Williams. 1964. Geologic Map: Jackass Flats Quadrangle, Nye County, Nevada. U.S. Geological Survey Geologic Quadrangle Map GQ-368. 1:24,000.

McKeown, F.A., D.L. Healey, and C.H. Miller. 1976. Geologic Map: Yucca Lake Quadrangle, Nye County, Nevada. U.S. Geological Survey Geologic Quadrangle Map GQ-1327. 1: 24,000.

Monsen, S.A., M.D. Carr, M.C. Reheis, and P.P. Orkild. 1992. Geologic Map: Bare Mountain Quadrangle, Nye County, Nevada. U.S. Geological Survey Miscellaneous Investigations Series Map I-2201. 1:24,000.

Noble, D.C., and R.L. Christiansen. 1968. Geologic Map: Southwest Quarter of the Black Mountain Quadrangle, Nye County, Nevada. U.S. Geological Survey Miscellaneous Investigations Series Map I-562. 1:24,000.

Orkild, P.P. 1968. Geologic Map: Mine Mountain Quadrangle, Nye County, Nevada. U.S. Geological Survey Geologic Quadrangle Map GQ-746. 1:24,000.

Orkild, P.P. 1963. Geologic Map: Tippipah Spring Quadrangle, Nye County, Nevada. U.S. Geological Survey Geologic Quadrangle Map GQ-213. 1:24,000.

Poole, F.G. 1965. Geologic Map: Frenchman Flat Quadrangle, Nye, Lincoln, and Clark Counties, Nevada. U.S. Geological Survey Geologic Quadrangle Map GQ-456. 1:24,000.

Roberts, R.J., K.M. Montgomery, and R.E. Lehner. 1967. Geology and Mineral Resources of Eureka County, Nevada. Nevada Bureau of Mines & Geology Bulletin 64: Reno, NV: Mackay School of Mines: University of Nevada–Reno: 152.

Rogers, C.L., and D.C. Noble. 1969. Geologic Map: Oak Spring Butte Quadrangle, Nye County, Nevada. U.S. Geological Survey Geologic Quadrangle Map GQ-822. 1:24,000.

Rogers, C.L., R.E. Anderson, E.B. Ekren, and J.T. O'Connor. 1967. Geologic Map: Quartzite Mountain Quadrangle, Nye County, Nevada. U.S. Geological Survey Geologic Quadrangle Map GQ-672. 1:62,500.

Ross, D.C. 1961. Geology and Mineral Deposits of Mineral County, Nevada. Nevada Bureau of Mines & Geology Bulletin 58: Reno, NV: University of Nevada:

Sargent, K.A., S.J. Luft, A.B. Gibbons, and D.L. Hoover. 1966. Geologic Map: Quartet Dome Quadrangle, Nye County, Nevada. U.S. Geological Survey Geologic Quadrangle Map GQ-496. 1:24,000.

Sargent, K.A., and P.P. Orkild. 1973. Geologic Map: Wheelbarrow Peak-Rainier Mesa Area, Nye County, Nevada. U.S. Geological Survey Miscellaneous Investigations Series Map I-754. 1:48,000.

Sargent, K.A., E.J. McKay, and B.C. Burchfiel. 1970. Geologic Map: Striped Hills Quadrangle, Nye County, Nevada. U.S. Geological Survey Geologic Quadrangle Map GQ-882. 1:24,000.

Sargent, K.A., and J.H. Stewart. 1971. Geologic Map: Specter Range NW Quadrangle, Nye County, Nevada. U.S. Geological Survey Geologic Quadrangle Map GQ-884. 1:24,000.

Snyder, R.P., E.B. Ekren, and G.L. Dixon. 1972. Geologic Map: Lunar Crater Quadrangle, Nye County, Nevada. U.S. Geological Survey Miscellaneous Investigations Series Map I-700. 1:48,000.

Stager, H.K. 1977. Geology and Mineral Deposits of Lander County, Nevada. Part II, Mineral Deposits. Nevada Bureau of Mines & Geology Bulletin 88: Reno, NV: Mackay School of Mines, University of Nevada-Reno: 60-99.106pp.

Stewart, J.H., and E.H. McKee. 1977. Geology and Mineral Deposits of Lander County, Nevada. Part I, Geology. Nevada Bureau of Mines & Geology Bulletin 88: Reno, NV: Mackay School of Mines, University of Nevada-Reno: 1-59.106pp.

Tschanz, C.M., and E.H. Pampeyan. 1970. Geology and Mineral Deposits of Lincoln County, Nevada. Nevada Bureau of Mines & Geology Bulletin 73: Reno, NV: University of Nevada: 188.

Wright, L.A., and B.W. Troxel. 1993. Geologic Map: Central and Northern Funeral Mountains and Adjacent Areas, Death Valley Region, Southern California. U.S. Geological Survey Miscellaneous Investigations Series Map I-2305. 1:48,000.

Wright, L.A., and B.W. Troxel. 1984. Geology of the North 1/2 Confidence Hills 15 Minute Quadrangle, Inyo County, California. California Department of Conservation, Division of Mines and Geology California Division of Mines & Geology Map Sheet 34. 1:24,000.