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DEATH VALLEY LOWER CARBONATE AQUIFER MONITORING PROGRAM- WELLS DOWN GRADIENT OF THE PROPOSED YUCCA MOUNTIAN NUCLEAR WASTE REPOSITORY

U.S. DEPARTMENT OF ENERGY COOPERATIVE AGREEMENT DE-FC28-06RW12368 YEAR ONE PROJECT REPORT

PREPARED BY INYO COUNTY YUCCA MOUNTAIN REPOSITORY ASSESSMENT OFFICE

Inyo County completed Year One of U.S. Department of Energy Cooperative Agreement No. DE-FC28-06RW12368. This report presents the results of research conducted within this cooperative agreement in the context of Inyo County's Yucca Mountain oversight program goals and objectives. The Hydrodynamics Group, LLC prepared this report for Inyo County Yucca Mountain repository Assessment Office. The overall goal of Inyo County's Yucca Mountain research program is the evaluation of far-field issues related to potential transport, by ground water, of radionuclide into Inyo County, including Death Valley, and the evaluation of a connection between the Lower Carbonate Aquifer (LCA) and the biosphere. Data collected within the cooperative agreement is included in interpretive illustrations and discussions of the results of our analysis. The central element's of this Cooperative Agreement program was the drilling of exploratory wells, analysis of geochemical data, geophysical surveys, and geological mapping of the Southern Funeral Mountain Range. The culmination of this research was two numerical ground water models of the Southern Funeral Mountain Range and Yucca Mountain region demonstrating the potential of a hydraulic connection between the LCA and the major springs in the Furnace Creek area of Death Valley.

1.0 Introduction

The focus of the investigations by the Hydrodynamics Group for Inyo County is to assemble the best possible data on the Paleozoic Carbonate Aquifer, and then to use that data to assess the likelihood of contaminant transport from the planned Yucca Mountain high-level nuclear waste repository to the biosphere in Inyo County. The work plan in pursuit of this goal includes:

1) Drilling and construction of exploratory monitoring wells to located and characterize the LCA in the Death Valley study area,
2) Geological mapping by the U.S. Geological Survey
3) Conduct geophysical studies in an effort to better understand the subsurface, especially in Amagosa Valley,
4) Compilation of a comprehensive geochemical data base of groundwater in the region, and
5) Conduct model analyses of potential rates of transport through the carbonate Aquifer from the area of the Repository to the springs in Death Valley.

Results of year one studies presented in this report are:

1. Well completion records and borehole logs for BLM #1 and 1A, and the deepening of BLM #2.
2. Completion of U.S. Survey mapping of the Southern Funeral Mountains.
3. Conduct and analyze geophysical surveys in the southern Funeral Mountains, the Amargosa Valley area, and the Devil's Hole area.
4. Tabulation and analysis of a comprehensive Death Valley National Park geochemical database.
5. Numerical model analysis of groundwater flow in the LCA through the Southern Funeral mountain range and from Yucca Mountain through the Amargosa Valley.

2.0 Statement of Problem

The U.S. Department of Energy (DOE) is preparing a license application for a high-level nuclear repository for construction at Yucca Mountain, Nevada—just to the west of the Nevada Test Site and forty miles northeast of Death Valley, California (Figure 1). The repository is to be a mine in unsaturated volcanic tuffs beneath the mountain.

Underlying the Tertiary tuffs that make up the upper parts of the mountain at the site is a sequence of much older Paleozoic carbonate rock that is a good aquifer. Winograd and Thordarson (1975) working at the Nevada Test Site in the 1950s indicated that this large Paleozoic Carbonate Aquifer underlies a large area of southern and eastern Nevada and integrates the groundwater hydrology of a number of valleys in the region. Groundwater that flows beneath Yucca Mountain and the Nevada Test Site and discharges in large spring complexes to the south—Ash Meadows in Nevada, and the Furnace Creek springs in Death Valley, California. Flowing groundwater in the Paleozoic Carbonate Aquifer is one potential pathway by which contaminants from the proposed repository could reach the biosphere.

Working on behalf of Inyo County, California, the Hydrodynamics Group is concerned with the potential for contaminants from the Yucca Mountain Repository to reach the Paleozoic Carbonate Aquifer. A number of groundwater models of the hydrology of the area were created. Key models include Yucca Mountain Repository site model by DOE, several regional models by the USGS, and several models by our Group. The models show that should contaminants reach the Carbonate Aquifer they will almost certainly be quickly transported to the springs in Death Valley.

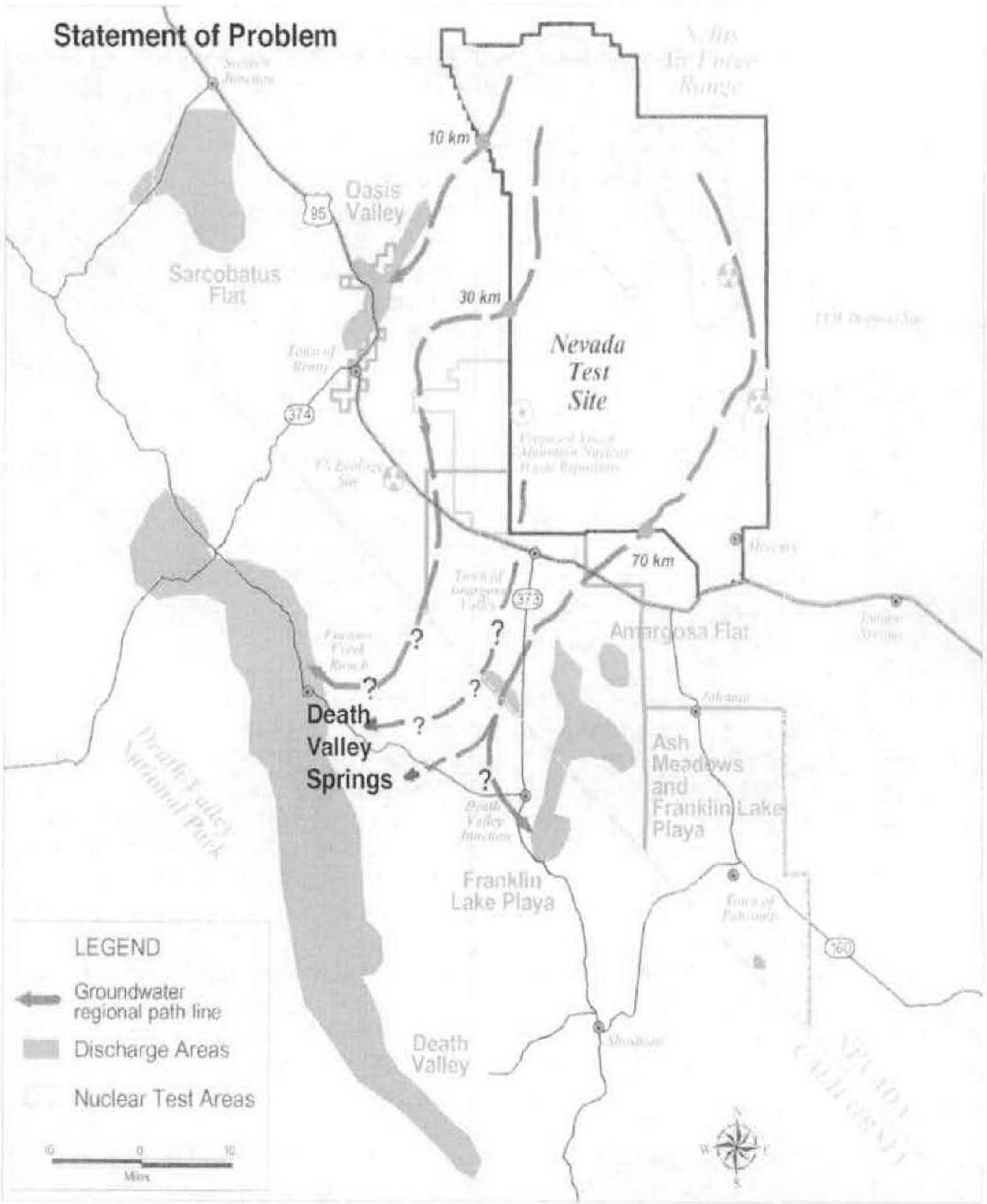


Figure 1. Regional Groundwater Flow Path Line from Yucca Mt. And Nevada Test Site.

2.1 What Protects the Carbonate Aquifer at Yucca Mountain?

Only one borehole, UE 25p1, reached the Paleozoic Carbonate Aquifer in the vicinity of Yucca Mountain; it penetrated the aquifer at a depth of approximately 1200 m (3900 ft). The aquifer was quite permeable with a low porosity—less than 1% porosity. It also had a hydraulic head in the Paleozoic Carbonate Aquifer that was 15 m higher than the hydraulic head in the overlying Tertiary volcanic rocks. This higher head has the potential to move groundwater upward from the carbonate into the overlying volcanic sequence of rocks. As long as the head relationship remains as presently observed, the carbonate is protected from contamination moving downward from the repository to the Carbonate Aquifer. Our group drilled a second deep Paleozoic Carbonate Aquifer observation well just to the northeast of the Funeral Mountains in California, adjacent to Death Valley National Park.

2.2 A Potential Problem

Hydraulic head is one of the more ephemeral of hydrologic conditions. Head is subject to change by development of groundwater for water supply in the Amargosa Valley south of the Repository site. The population of southern Nevada is growing rapidly. Local groundwater is looked to for a large portion of the water supply. Both the valley fill deposits and the Paleozoic Carbonate Aquifer are targets for development. Groundwater pumping, lowering the hydraulic head, could eliminate the upward hydraulic head gradient that serves as the barrier to contaminate movement into the Carbonate Aquifer at Yucca Mountain.

For example, recently the Southern Nevada Water Authority (SNWA) proposed to pump groundwater from the Paleozoic Carbonate Aquifer in the vicinity of Ely, Nevada and pipe it to Las Vegas. In a recent request they received approval to pump from the Nevada State Engineer pump 74 million cubic meters (60,000 acre-feet) annually from Spring Valley. Nye County has recently made a request to pump 87,680 acre-feet per year, from the Carbonate Aquifer in the vicinity of the southern boundary of the Nevada Test Site.

2.3 The Bottom Line

Ground water development could destroy the upward head gradient in the Paleozoic Carbonate Aquifer that currently serves as a barrier to downward contaminant movement at Yucca Mountain. Should contaminants reach the Paleozoic Carbonate Aquifer, they will be transported quickly to the springs in Death Valley.

3.0 Southern Funeral Mountain Monitoring Well Data

BLM #1 was successfully completed this year as the only known Lower Carbonate Aquifer monitoring well south of Yucca Mountain. BLM #1A was successfully complete as an upper Tertiary aquifer monitoring well. BLM #2 was deepened to a depth of 3,309 feet below ground surface (bgs) with available Cooperative Agreement funding. A summary of drilling activities is provided in Table 1. The location of exploratory monitoring wells is provided in Figure 2. The GPS location, elevation, and static water level of wells are provided in Tables 2.and 3. A geological profile of these three wells is provided in Figure 3. A detailed geological log of the boreholes is provided in Appendix A.

Table 1. Summary of Drilling Program Work Activities.

1. Inyo County prepared to initiate monitoring well drilling operations.
2. Well drill operations began on 2 February 2007 at BLM #1. Specific work activities by well is as follows:

BLM #1
- 2/2/07 Drill site set-up
- 2/3/07 to 2/5/07 Cleaned borehole out to 2470' depth
- 2/6/07 to 2/8/07 Attempted to cement casing in-place using basket
- 2/9/07 to 2/14/07 Set and cement well casing to 2450' depth
- 2/15/07 to 2/20/07 Clean open borehole to 2570' using airlift
- 2/21/07 Cut off and remove casing from 2000' depth

BLM #1A
- 2/22/07 Drill site set-up and drilling

2/22/07 to 2/25/07 Drilled borehole to 640' Depth-Logged well
2/25/07 to 2/27/07 Cased well- Screened well 610' to 640' Depth
2/27/07 Developed well

BLM #2
2/27/07 to 3/2/07 Set-up and start drilling
3/2/07 to 3/9/07 Repair rig and drill to 3309' Depth
3/10/07 Pull drill pipe and mobilize off site

3. Borehole cutting sample bags were transferred to DOE for BLM #1A and #2

Table 2. GPS Location and Elevation of Monitoring Wells.

Location	Northing	Easting	Elevation (feet)
BLM #1 Ground Surface	36.40047326	116.4691703	2281.577
BLM #1 Top of Steel Well Cap	36.40047311	116.4691695	2283.919
BLM #1A Ground Surface	36.40052236	116.4691802	2281.868
BLM #1A Top of Steel Well Cap	36.400524	116.4691797	2284.716
BLM #2 Ground Surface	36.41705424	116.4946533	2318.911
BLM #2 Top of Steel Well Cap	36.41705485	116.4946518	2323.158
Amargosa River A	36.42538373	116.4659718	2186.315
Amargosa River B	36.39288656	116.4310277	2111.009

Datum is WGS 84 (functionally equivalent [within 1 or 2 meters horizontally] to NAD 83)

Figure 2. Inyo County LCA Monitoring Program Well Locations

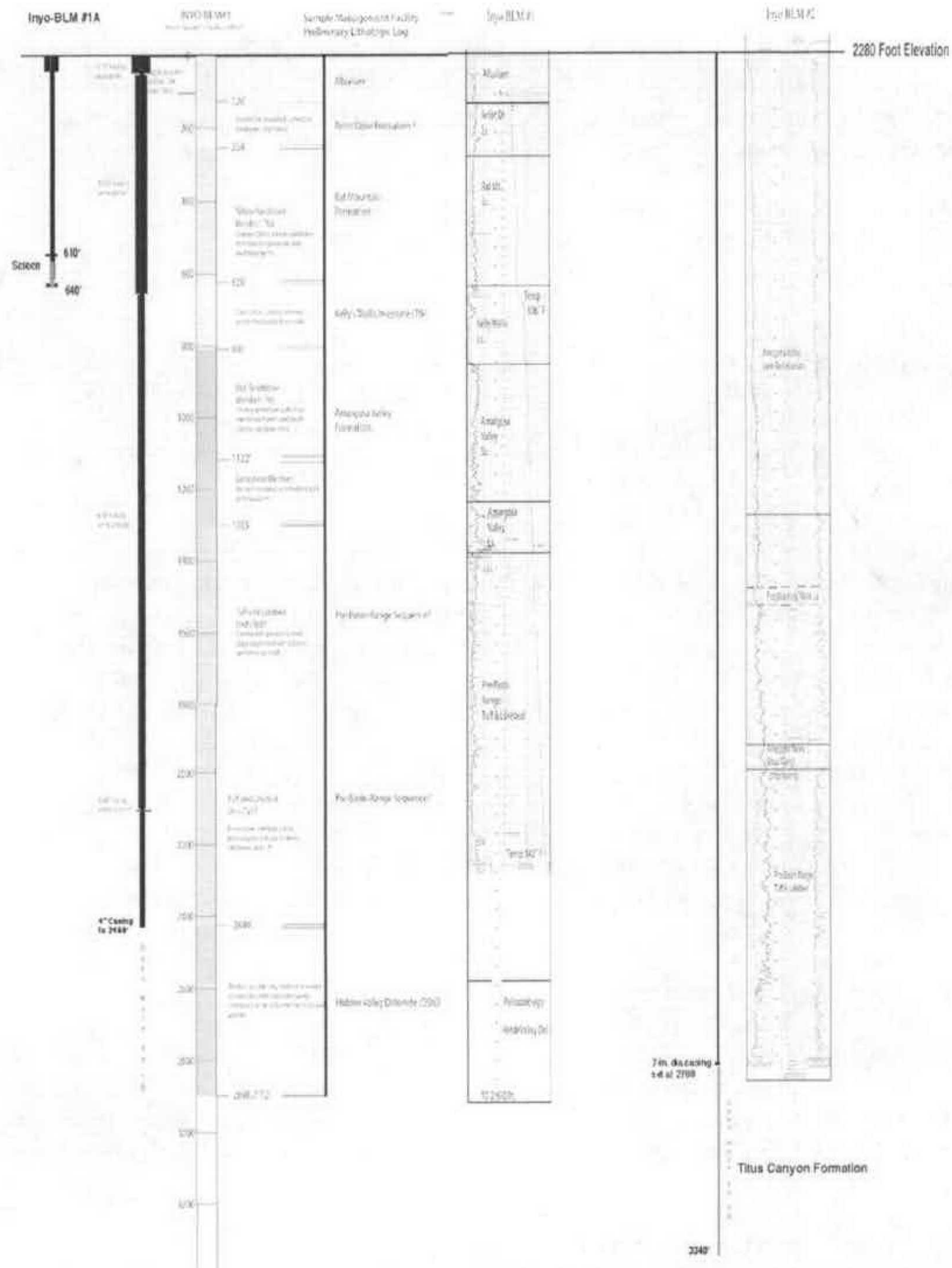


Figure 3. Geological Profile of Southern Funeral Mountain Monitoring Wells.

Table 3. Measured Static Water Levels.

Well Identification	Aquifer	Well Cap Elevation (feet)	Depth to Water (ft)	Correction (ft)	Water Elevation (ft)
BLM #1 Top of Well Cap	Carbonate	2283.92	95.62	0.04	2188.26
BLM #1A Top of Well Cap	Basin Fill	2284.72	107.35	0.04	2177.33
BLM #2 Top of Well Cap	Titus Canyon Fm	2323.16	248.57	0.04	2074.55

Note: Correction for Top of Well Casing. BLM #2 Undeveloped Open-Hole.

3.1 BLM #1

BLM #1 and #2 were originally drilled on October 4, 2004 and was completed on November 15, 2004 under Cooperative Agreement No. DE-FC08-02RW12162. During this period BLM #1 was drilled to a depth of 2,900 feet bgs in the Lower Carbonate Aquifer. The well was cased to a depth of 2240 feet bgs with an open hole to the remaining depth of the well.

The well was completed in this project year of Cooperative Agreement DE-FC28-06RW12368. The completion of the well was complicated by borehole washout zone in a basal conglomerate at the contact of the LCA and with a zone at an approximate depth of 2,550 feet bgs in the LCA. These drilling conditioned dictated that the well be cased with a 4-inch diameter steel casing to a depth of 2460 feet bgs, and was completed as an open-hole in the LCA aquifer. This completion isolated the LCA.

3.2 BLM #1A

BLM #1A is located approximately 20 feet north of BLM #1 (Table 2, Figure 2). The well was completed as a Tertiary aquifer monitoring well in the Yellow Sandstone Member of the Bat Mountain Formation just above the contact of the Kelly Wells Limestone Formation. The borehole cuttings from BLM #1 were nearly identical to the materials encountered in BLM #1. The Yellow Sandstone unit is a medium-grained sandstone with lens of conglomerate. The well was screened in the lower 30-foot section of the formation.

3.3 BLM #2

BLM #2 was cased to 2,700 in November of 2004 in the lower Tertiary rocks under Cooperative Agreement No. CE-FC08-02RW12162. The well was deepened in this contract year to 3,340 feet bgs, and is currently in a lower section of the Titus Canyon Formation. The depth to the LCA at BLM 32 is unknown.

3.4 Static Water Levels and Temperature

The static water level in the LCA was 95.62 feet bgs versus 107.35 feet bgs in the Tertiary aquifer well. The temperature of drilling fluids in BLM #1 was 139°F and 87°F in the Tertiary well. This data suggest a strong upward gradient in the LCA. The water level in BLM #2 does not represent an actual static water level in Titus Canyon Formation because of drilling fluids in the open borehole.

4.0 U.S. Geological Survey Southern Funeral Mountain Geology Mapping

A *Geologic Map of the Southern Funeral Mountains and Adjacent Groundwater Discharge Sites, Inyo County, California and Nye County, Nevada* was prepared by Chris Fridrich[1], James McAllister, Ren Thompson, Janet Slate[1], Michael Machette[1,] and Ibrihim Cemen (Figure 4). The map presented in Figure 4 is a preliminary U.S.G.S. publication that is currently under final review. A legend and description of geological map units is provided at the end of this section in Table 4. As a preliminary U.S.G.S. publication, the information provided on the map and in the following discussion of the map and geology of the study area is subject to changed. **Use and reproduction of this section of our report is prohibited without the written permission of the U.S.G.S.**

The major purpose of this study has been to define the hydrogeologic framework of the southern Funeral Mountains and vicinity. This map covers the southern part of the Funeral Mountains, along with adjacent parts of the Furnace Creek, Amargosa Desert, and Opera House basins (Figure 4). It covers three full 7.5-minute quadrangles, large parts of four others, and slivers of four more. The boundaries of this map were drawn to include all of the known proximal hydrogeologic features that may affect the flow of groundwater that discharge from the springs of the Furnace Creek area (see hydrologic map). These springs provide the major water supply for Death Valley National Park.

This study built on previous mapping (Figure 4) by McAllister (1970; 1971; 1973; 1976), Slate and others (2000?), Çemen (1983), and, for a very small area, Wright and Troxel (1993). Of the above, the surficial geology map of Slate and others is the only one that was largely just compiled for this new map; the bedrock mapping has been strongly modified based on extensive new field work, which was conducted by Fridrich (from 1999 to 2006), by Thompson (mainly from 1998 to 2001), and by Machette (from 1993 to 1994?). Several refinements are present on this new map, relative to the previous maps. First, numerous holes were filled where there were either gaps or very sketchy areas in the coverage by previous maps. Second, a new regional tectono-stratigraphy (Fridrich, unpublished data) was applied in classifying the Cenozoic strata whereas, in the previous mapping, a number of different stratigraphies had been used. Several new Ar^{40}/Ar^{39} dates were done in the current study to develop the constraints needed to apply the new stratigraphy. Third, a consistent level of detail was developed throughout the current map, whereas the previous maps varied greatly in their detail.

In the majority of cases, detail was added to create the current map; however, a few details were omitted. For example, McAllister's maps of the Furnace Creek basin (1970; 1973) were done in a style resembling that of outcrop maps, and that extreme detail of outcrop geometry was generalized for the current map. Additionally, McAllister (1971) distinguished upper and lower map units of the Devonian Hidden Valley Dolomite in part of the study area. That formation is mapped as a single unit here because problems were encountered in trying to extend the distinction throughout the rest of the map area. All subdivisions of formations of the late Proterozoic to late Paleozoic sequence on the current map were done using widely used modern classification schemes, such as those applied by Monsen and others (1992).

Figure 4. U.S.G.S. Preliminary Geological Map of Southern Funeral Mountain Range.

Geologic map of the southern Funeral Mountains and adjacent groundwater discharge sites, Inyo County, California and Nye County, Nevada

By Chris Fridrich[1], James McAllister[2], Ron Thompson[1], Janet Slate[1], Michael Machette[1] and Ibrahim Comeau[2]

UNIT LIST

Surficial Deposits

Qayy Alluvium in annually active channels (Holocene)
Qay Alluvium in frequently active channels (Holocene)
Qp Playa deposits (Holocene)
Qayo Alluvium in terrace deposits slightly above active channels (Holocene)
Qls Landslide Deposits (Holocene and Pleistocene)
Qc Colluvial Deposits (Holocene and Pleistocene)
Qai Intermediate-age alluvium (Pleistocene)
Qao Older alluvium (Pleistocene)
Qm Marls of groundwater discharge origin (Pleistocene)
QTa Old alluvium (Early Pleistocene and Pliocene)
QTx Rock-fall breccias (Early Pleistocene and Pliocene)

Bedrock

Badwater Group (~4 Ma to present):
QTf Funeral Formation (late Pliocene and early Quaternary)
Tby Funeral Basalt (late Pliocene)
Tby2 Oxidized vent facies of Funeral basalt (late Pliocene)

Nemo Group (~6.5 Ma to ~3 Ma) = Furnace Creek Formation
Tfz Capping travertine (late Pliocene)
Tfu Upper mudstone (late Pliocene)
Tfcu Upper conglomerate (late Pliocene)
Tfp Felsic tuff (late Miocene to late Pliocene)
Tf Dominant Playa facies (late Miocene to late Pliocene)
Tfg Gypsiferous facies (late Miocene to late Pliocene)
Tfb Greenwater Volcanics (late Miocene to late Pliocene)
Tfrx Rock-avalanche breccias (late Miocene to late Pliocene)
Tflx Giant block breccias (late Miocene to late Pliocene)
Tfc Basal conglomerate (late Miocene to late Pliocene)

Navadu Group (~12 Ma to ~6.5 Ma) = Artists Drive Formation
In the Funeral Mountains:
Tnp Playa deposits (middle to late Miocene)
Tnl Limestone-dominated lacustrine sediments (middle to late Miocene)
Tng Alluvial gravels (middle to late Miocene)
Tnrx Rock-avalanche breccias (middle to late Miocene)
Tnlx Giant-block landslide breccias (middle to late Miocene)
Tnfx Fault breccias (middle to late Miocene)
In the Furnace Creek basin:
Tnu Upper member (middle to late Miocene)
Tnm Middle member (middle to late Miocene)
Tnl Lower member (middle to late Miocene)
Tab Basalt (middle to late Miocene)

Owlshead Group (~14.5-to-~12-Ma)
Tts Yellow sandstone of Bat Mountain (lower to middle Miocene)
Ttg Cobble conglomerate of Bat Mountain (lower to middle Miocene)
Ttk Kelley's Well Limestone (early to middle Miocene)

Hell's Gate Group (~16 to ~14.5 Ma)
Thr Fluvial red sandstone (early to middle Miocene)

Titus Canyon Group (~30-to- ~19-Ma)
Ttc Titus Canyon Formation (late Oligocene to early Miocene)
Tpl Tuff and lake-bed unit (late Oligocene to early Miocene)
Tpg Basal conglomerate unit (Oligocene)

Mp Perdido Formation (Mississippian)
Mt Tin Mountain Limestone (Mississippian)
Dl Lost Burro Formation (Devonian)
DSh Hidden Valley Dolomite (Silurian and Devonian)
Oes Ely Springs Dolomite (Ordovician)
Oe Eureka Quartzite (Ordovician)
Op Pogonip Group, undivided (Ordovician)
Opa Antelope Valley Formation (Ordovician)

Opn Ninemile Formation (Ordovician)
Opg Goodwin Limestone (Ordovician)
Nopah Formation, undivided (Cambrian)
Cnc Smoky and Halfpint Members, undivided (Cambrian)
Cns Smoky Member (Cambrian)
Cnh Halfpint Member (Cambrian)
Cnd Dunderberg Shale Member (Cambrian)
Cb Bonanza King Formation, undivided (Cambrian)
Banded Mountain Member, undivided (Cambrian)
Cbbu Banded Mountain Member, Upper part (Cambrian)
Cbbl Banded Mountain Member, Lower part (Cambrian)
Cbp Papoose Lake Member (Cambrian)
Cc Carrara Formation (Cambrian)
Cz Zabriskie Quartzite (Cambrian)
ZCw Wood Canyon Formation, undivided (Cambrian and Late Proterozoic)
Cwu Upper Member (Cambrian)
Zwm Middle member: (Late Proterozoic)
Zwl Lower member: (Late Proterozoic)
Zs Stirling Quartzite, undivided (Late Proterozoic)
Zse E Member: (Late Proterozoic)
Zsd D Member: (Late Proterozoic)
Zsc C Member (Late Proterozoic)
Zsb B Member: (Late Proterozoic)
Zsa A Member: (Late Proterozoic)
Zjo Johnnie Formation (Late Proterozoic)

Figure 4 (Continued). Key to U.S.G.S. Preliminary Geological Map of Southern Funeral Mountain Range.

The northern limit of this map is a function of the northwestward termination of the major (Paleozoic carbonate) aquifer of the southern Funeral Mountains. The Funeral Mountains continue northward of the map limit, and the central and northern Funeral Mountains are covered on the above-mentioned map by Wright and Troxel (1993)- where this map and the Wright and Troxel map join, significant disagreements are present that could not be resolved in this study. The vast majority of these disagreements concern the locations of contacts, rather than their nature. In this study, structures were located by GPS and by photogrammetry, using a PG plotter and modern air photos. In contrast, Wright and Troxel mapped on air photos less detailed than those available today, and transferred their mapping to topographic base maps by hand. Their map is of excellent quality, but the locations of some contacts may lack precision.

4.1 Geologic Summary

The rocks that comprise exposed bedrock in the southern Funeral Mountains consist mainly of a late Proterozoic to late Paleozoic sequence of marine sedimentary strata. These strata were deposited on the continental shelf and slope of North America during the opening of the Pacific Ocean and are commonly referred to as a miogeoclinal sequence. The preserved thickness of this sequence in the Funeral Mountains has been measured at 7.5 km (McAllister, 1974). Pennsylvanian and Permian strata are not preserved in this area, and the uppermost part of the Mississippian section is also missing. The thickness of a complete miogeoclinal section in this area is estimated at roughly 9 km.

The miogeoclinal sequence overlies a middle- (and earliest late-) Proterozoic sequence known as the Pahrump Group, which represents the fill of early rift basins that were premonitory to the opening of the Pacific Ocean. The Pahrump Group, in turn, overlies Paleoproterozoic (~1.7 Ga) high-grade metamorphic rocks – schists, gneisses, and amphibolites – referred to hereafter as the crystalline basement. Neither the Pahrump Group nor the crystalline basement rocks are exposed in the map area; however, they are well exposed to the north, in the central and northern Funeral Mountains (Wright and Troxel, 1993).

The Death Valley region, including the map area, underwent tectonic contraction from latest Paleozoic through late Mesozoic time. The miogeoclinal rocks of region have thus been strongly deformed. This deformation is manifest in the southern Funeral Mountains as two major thrust faults, the Cleary and Schwaub Peak thrusts, and as large folds, hanging wall anticlines and footwall synclines mainly, that are related to these thrust faults. Both of these thrust fault systems and their related folds have been strongly obscured by subsequent basin-range extensional faulting.

Late Cenozoic terrestrial sediments that are divided into three major sequences locally overlie the miogeoclinal sequence: pre-basin-range, syn-basin-range, and post-basin-range. The pre-basin-range sediments are generally conformable to the underlying miogeoclinal strata, except in the immediate vicinity of Mesozoic contraction structures in which the rocks were tilted. Despite the common conformability of bedding above and below the basal Tertiary contact, on the scale of the whole mountain range the oldest

Tertiary strata are found overlying formations ranging from those near the top, to those near the base of the ~9 km thick miogeoclinal sequence. Thus, a vast amount of erosion occurred in the region during the Mesozoic and early Tertiary eras, and no rocks of that age-range are found in the map area.

In some areas, this pre-extensional erosion exposed miogeoclinal sediments that have been weakly metamorphosed. This metamorphism is of (lower?) greenschist facies, with a trivial degree of recrystallization, and only slight development of axial cleavage found only in the most pelitic rocks and, even then, only in the centers of tight folds. This is the maximum degree of metamorphism found in the rocks that are overlain by the pre-basin-range sequence as well as in all locally derived clastic found in this sequence. All exposed rocks that are metamorphosed more than that have been exposed by tectonic denudation during subsequent Basin-Range tectonism.

The pre-basin-range sediments are not pre-extensional; rather, the earliest stages of Cenozoic extension formed broad shallow basins that trapped sediments, but did not form basin-range topography. Fluvial sediments in this sequence contain pebble- to boulder-size clastic derived in large part from distant source areas to the west that are now separated from the map area by several basins and ranges. Some clastic may have been transported from sources areas as far west as the current eastern range-front of the Sierra Nevada, as the rock types of these clastic are rare or absent in ranges east of there. The pre-basin-range sequence is divided into two groups, the Titus Canyon and Hell's Gate Groups, which are separated by a disconformity or subtle angular unconformity. At this regional disconformity, sediments corresponding to the interval from ~19 to ~16 Ma are largely if not entirely absent throughout the Death Valley region, apparently owing to nondeposition (Fridrich, unpublished data).

The syn-basin-range sequence is divided into four groups: the Owlshead (~16 to ~11.5 Ma), Navadu (~12.5 to ~5.5 Ma), Furnace Creek (~7.5 to ~3 Ma), and Badwater Groups (~4.5 Ma to present). These groups are allostratigraphic units, which are separated by unconformities that young to the northwest across the region; hence, the 1 to 2 m.y. overlap between the groups. Each of these groups represents a different stage of tectonic evolution during basin-range extension. The diachronous boundaries between these stages represent short intervals of radical change in the style, magnitude, and focus of tectonic deformation, which evidently resulted from changes in the regional stress regime. Deposition rates for the syn-basin-range sequence are much higher than those for the pre-basin-range and, especially, the post-basin-range sequences.

The post-basin-range sequence consists of those sediments that postdate the local cessation of basin-range extension. The base of this sequence young to the southwest across the Death Valley region, reflecting the migratory nature of basin-range extension. This sequence is absent by definition in Death Valley proper (physiographic feature) because the basins that comprise Death Valley are still tectonically active. The base of the post-basin-range sequence is marked by the up section burial of significant faulting and tilting, as well as by a strong (about one order of magnitude) decrease in deposition rate relative to the underlying syn-basin-range strata. Some tilting and faulting are locally found within the post-basin-range sequence as a consequence of feeble late-stage tectonism that has followed basin-range tectonism in some abandoned basins. For example, the Stateline fault, found in the northeaster corner of the map, has continued to be weakly active into the Holocene, despite that this fault cuts through basins that ceased subsiding significantly in the middle to late Miocene.

The southern Funeral Mountains are a large uplift flanked on three sides by basins. The Furnace Creek basin lies to the southwest of the mountain range, across the Furnace Creek fault. This fault is a large (10's of km of offset) right-lateral strike-slip fault with lesser but significant (km's) down-to-the-southwest offset. The Opera House basin lies to the southeast of the range, and the mapped basin-range boundary is a dip slope, as discussed below. The Amargosa Desert basin complex lies to the northeast of the Funeral Mountains, and a broad, complex system of faults is present in that part of the basin that borders the range.

The major fault in this last-mentioned system, the Stateline fault, is a right-lateral strike-slip fault that extends far to the southeast, where it is also known as the Pahrump-Stewart Valley fault. The major strand of the Stateline fault is at least 7 km outboard (northeastward) of the Funeral Mountains range-front, within the southern part of the Amargosa desert basin. This fault is coincident with a strong linear anomaly in the aeromagnetic data (Blakely, 2003?), and has numerous small Holocene and late Pleistocene scarps along its trace, the vast majority of which are located east of the map area (Menges and Fridrich, unpub. data). The area having these scarps extends only onto the easternmost 2 km of the map. None of these are shown on the map because local mining activity and extensive mantling by groundwater discharge deposits has strongly obscured the scarps in this area, such that their original geometry is unclear.

Where it is possible to tell (east of the map), these scarps along the Stateline fault formed by oblique thrust faulting, and show subequal amounts of horizontal and vertical slip (Menges and Fridrich, unpub. data). Field relationships along the fault indicate it is almost strictly a horizontal motion fault. The vertical components of slip locally observed on scarps are related to the formation of pressure ridges and similar contractional structures along this strike-slip fault. In contrast, most of the other faults in the ~7 km wide fault system on the northeast side of the southern Funeral Mountains are oblique-slip or normal faults.

The very broad development, adjacent to the southern Funeral Mountains, of the fault zone associated with the Stateline fault is a local feature. The Stateline fault has numerous bends and step-over along its trace, and, in this locale, there evidently is a releasing bend. Associated with that releasing bend is a normal fault system, which is located south of the main trace of the Stateline fault. And it is this subsidiary normal fault system that forms the boundary between the southern Funeral Mountains and the Amargosa Desert basin, rather than the main strand of the Stateline fault itself.

The northeastern range-front of the southern Funeral Mountains is strongly digitated, reflecting the fact that the easternmost part of the range consists of a series of contiguous hogbacks, which plunge northward, in a tilted-domino-style pattern. Abundant Tertiary rocks are present on the east-facing dip-slopes of these hogbacks. These Tertiary rocks, which are less resistant than the underlying miogeoclinal strata, have been preferentially eroded, and are largely covered by Quaternary surficial deposits in the north-plunging half-grabens between the hogbacks. Detailed gravity data (Jansen and others, 2005) show that there also are numerous small northwest-striking normal faults across which the Funeral Mountains block steps down to the northeast on the margin of the Amargosa Desert basin. The zone of structural down-stepping extends over most of the area between the range-front and the streambed of the Amargosa River and is almost entirely mantled by Quaternary alluvium. Only a very few faults of this northeastward down-stepping system are exposed near the range front.

In detail, the gravity data show that a minority of northwest-striking faults within the northeast-down-stepping system area have down-to-the-southwest offset (i.e., offset that opposes the dominant pattern). These data also show that the dominantly northeast-striking faults that control the tilted-domino extensional faulting pattern in the range project across this same area, such that these two nearly orthogonal fault-sets crosscut each other. Based on gravity data, the northeast-striking faults appear to project out only to a major down-to-the-northeast fault that is concealed under the streambed of the Amargosa River.

From a structural geology standpoint, this concealed fault under the river may be the ultimate northern boundary of the Funeral Mountains structural block against the Amargosa Desert basin. The top of the miogeoclinal rocks is relatively shallow under most of the area between the range-front and the Amargosa River, averaging perhaps 1 km depth, and is much deeper northeast of the river. Drilling in this area between the erosional range-front and the river has shown that the alluvium exposed on the surface is relatively thin ($\leq$50 m) throughout this area.

Six small uplifts are present adjacent to the fault that is concealed under the Amargosa River. These six uplifts can also be divided into three that lie to the northeast of the concealed fault, and another three that lie to the southwest. Of those that lie to the northeast, two are composed of Titus Canyon Group pre-basin-range sediments, and one consists of late Proterozoic Stirling Quartzite, the oldest formation of the miogeoclinal sequence. It is unclear if this poorly exposed quartzite is in place or if it is an exposure of a landslide deposits that is part of the Titus Canyon Group. The three uplifts that lie to the southwest are all composed of late Pleistocene alluvial gravels, which are domed. Owing to the doming, beds on the sides of these small uplifts that face the mountain range are locally back-tilted toward the range, despite that the range is the source of these alluvial fan gravels; thus bedding must originally have sloped away from the range.

The Furnace Creek fault, along the southwest flank of the southern Funeral Mountains, consists of several strands in a zone that at least locally is 2 to 3 km wide. The name Furnace Creek fault was once applied to the whole strike-slip fault system that extends from the eastern flank of the Resting Spring Range northwestward to the north end of Death Valley (physiographic feature). The name Furnace Creek fault is now reserved for the inactive part of this fault, which extends from the northwest corner of the map southeastward. The active part of this fault, to the northwest of map area, is now called the northern Death Valley fault (Machette and others, 2001). Near the northwest corner of the map, the Furnace Creek fault cuts late Pliocene (~2 Ma) but no younger sediments whereas, in the south-central part of the map, the timing of abandonment is stratigraphically bracketed between ~4.5 and ~3 Ma.

The internal structure of the southern Funeral Mountains is dominated by normal faults, which mainly strike between north-south and northeast-southwest, and dip west or northwest. At least some, and probably most of these faults have a subsidiary component of strike-slip offset, which is mainly sinistral, as indicated by rakes. A small number of northwest-striking faults are also present in the range and, where discernable, the sense of oblique-slip on these is dextral. The components of strike-slip strain on these faults are thus conjugate and reflect an overall pattern of dextral (clockwise) deformation, as is found throughout the rest of the Death Valley region, excepting areas proximal to the Garlock fault.

Whereas the majority of these faults that are internal to the southern Funeral Mountains are high in angle, some of the largest are strongly listric and dip as gently as 15° at the lowest exposed structural levels. The very strong flattening of the largest faults, with declining elevation, suggests that these faults may sole into a concealed detachment fault at fairly shallow depth. This inference is supported by regional-scale geophysical data, which show that the Funeral Mountains have anomalously high gravity (Blakely, 2003?). The gravity data could be explained if the rocks exposed on the surface are truncated at shallow depth by a detachment fault, which has high-density crystalline basement rocks in its lower plate.

Three major normal faults are exposed in the southern Funeral Mountains. From southeast to northwest, these are named the Bat Mountain, Pyramid Peak, and Red Amphitheatre faults. All three of these large faults have multiple strands. Additionally, the Funeral Mountains detachment fault is obscurely exposed near the northern boundary of the map. This detachment fault is subhorizontal and is obscure mainly because only small remnants of the upper-plate rocks are preserved in the map area, and because the fault is manifest as a thick zone of brecciated rocks – it is not a feature you can put your finger on. Field relationships along these faults exposed within the range show that: (1) they formed between ~12 and ~10.5 Ma, (2) they were active perhaps as late as ~7 Ma, and (3) they have been largely if not entirely inactive since then.

Abundant Tertiary rocks are exposed within the Funeral Mountains. These include, from oldest to youngest, the Titus Canyon and Hell's Gate Groups of the pre-basin-range sequence, and the Owlshead and Navadu Groups of the syn-basin-range sequence. All sediments younger than those of the Navadu Group (younger than ~7 Ma) within the Funeral Mountains are part of the post-basin-range sequence, and the same is true in the Amargosa Desert and Opera House basins. In contrast, the Furnace Creek basin, along the southwest margin of the range, contains strata belonging to all four groups of the syn-basin-range sequence, indicating that this basin remained tectonically active long after basin-range tectonism had stopped throughout the rest of the map area. Post-basin-range strata are, however, present within the Furnace Creek basin. The age of the strata at the base of the post-basin-range sequence in the Furnace Creek basin ranges from ~2 Ma in the northwest part of the basin (near the northwest corner of map area) to ~3.5 Ma in the south-central part of map area, the same as the timing of diachronous abandonment of the Furnace Creek fault across the map area.

The southeastern limit of the Furnace Creek basin lies to the southeast of map area up against the western range-front of the Resting Spring Range. The Post-Basin-Range sequence is locally known as the Tecopa lake beds in this area immediately to the southeast, and the base of these "lake beds" is slightly below a 5.1 Ma tephra. Recent studies have shown that the Tecopa lake beds are actually mainly paludal rather than lacustrine deposits (M. Rehies, USGS, oral comm., 2000). Thus there are syn-basin-range strata of the ~4 Ma-to-present Badwater Group only in the northwest part of the Furnace Creek basin (only on the west half of the map) because the southeastern part of the basin was abandoned before the tectonic transition occurred that formed the formation boundary between the Furnace Creek and Badwater Groups.

The pre-basin-range strata exposed within the Funeral Mountains are similar to those exposed in the six uplifts along the major normal fault under the Amargosa River streambed, discussed above, as well as those exposed further out in the Amargosa Desert basin, in some small transpressional uplifts along the Stateline fault. In fact, there is a greater abundance of freshwater limestone and other lacustrine (deep basinal) sediments in the sections of these rocks exposed in the Funeral Mountains than there is in the age-equivalent sections exposed out in the Amargosa Desert basin, which include fluvial gravels. Thus, there is no evident relationship between modern basin-range topography and the variations in thickness and lithology that are found in these strata. This indicates that the area of the Funeral Mountains was not a mountain range when these pre-basin-range sediments were deposited; rather, it was part of a broad shallow basin, as was the adjacent part of the Amargosa Desert basin. Moreover the presence of fluvial clasts in these deposits that were derived from source areas far to the west indicates that basin-range tectonism had not yet begun in this part of the Death Valley region (before ~15 Ma).

The Pre-Basin-Range sequence thins greatly southward across the most easterly promontory of the Funeral Mountains, which is known as Bat Mountain. This thickness change has been interpreted by Çemen and others (1999) as evidence that the Furnace Creek fault, at the southwest margin of the Funeral Mountains, had formed and was active, such that it controlled depositional patterns in the pre-basin-range strata. Although far from iron-clad, this interpretation is very plausible.

The oldest group of the Syn-Basin-Range sequence, the Owlshead Group, is thick and well exposed on the dip-slope range-front at the southeastern limit of the Funeral Mountains – on the eastern face of Bat Mountain. Fragmentary exposures of these strata are also found in areas immediately downthrown on the Bat Mountain and Pyramid Peak faults. None of these exposures show facies or thickness changes that bear any geometric relationship to the large northeast-striking faults that are internal to the Funeral Mountains uplift; rather, these faults simply offset these rocks, which include a thick freshwater limestone, named the Kelley's Well Limestone, in all three locations. The Owlshead Group strata appear to progressively thicken to the southeast across the whole southeastern part of the southern Funeral Mountains; however, the very fragmentary exposure of these strata to the northwest of Bat Mountain places some uncertainty on this conclusion.

Owlshead Group strata correlative to those exposed on Bat Mountain are exposed on the opposite side of the Opera House basin, on the north flank of the Resting Spring Range, several kilometers to the southeast of map area. In this last-mentioned exposure, these strata are faulted against the moderately metamorphosed miogeoclinal rocks that form the core of the Resting Spring Range near its northern tip. This fault, which is the master fault of the Opera House basin, is a detachment fault based on its gentle dip, as well as the fact that the rocks in its lower plate constitute a metamorphic core complex of sorts. Alluvial conglomerates at the base of the Owlshead Group section in this location include metasedimentary clasts, such as phyllites, derived from the lower plate of the detachment fault, proving that these strata are fill of the Opera House basin that were deposited coeval with slip of the master detachment fault of this basin, which we name the Opera House detachment fault.

The Opera House detachment fault extends under the whole of the Opera House basin, and probably extends under the southern Funeral Mountains as well. The presence of Owlshead Group strata throughout the southeastern part of the southern Funeral Mountains indicates that the Opera House basin once extended over this part of what is now the mountain range, apparently as a southeastward-thickening wedge. Subsequence tectonic development, during the interval in which the Navadu Group strata were deposited, formed the normal faults that are internal to the Funeral Mountains, and also changed the geometry of the Opera House basin, such that part of it is now uplifted as the southeastern part of the southern Funeral Mountains.

As discussed above, the Owlshead Group and pre-basin-range strata show no thickness or lithologic changes that have any demonstrable relationship to the internal faults of the Funeral Mountains. In contrast, the Navadu Group strata in this range have features indicating they were deposited during the major slip along these faults. In the narrow half-grabens developed immediately downthrown on the Bat Mountain and Pyramid Peak faults, Navadu Group strata are very thin and only locally preserved, but consist exclusively of landslide megabreccias derived from the scarps of these faults. Navadu Group strata are much thicker and better preserved in the broad half-graben on the downthrown side of the Red Amphitheatre fault system, where they include alluvial conglomerates and interbedded freshwater limestones and playa claystones, as well as landslide megabreccias and giant gravity slide blocks derived from the adjacent fault scarp.

Tertiary strata exposed in the uppermost part of the Red Amphitheatre drainage are in the upper plate of the Funeral Mountains detachment fault rather than that of the Red

Amphitheatre fault system. Lithologically, these strata are much like those of the Navadu-Group fill of the Red Amphitheatre half-graben; however, the provenance of the clasts in these strata in the upper part of the drainage clearly tie them to the detachment fault, rather than to the Red Amphitheatre fault system. Clasts, including megabreccia blocks, in these strata are derived from the lower plate of the detachment fault, which includes late Proterozoic formations that are not exposed in the scarp of the Red Amphitheatre fault. This exposure of the Funeral Mountains detachment fault, in the upper part of the Red Amphitheatre drainage, is near to the location where this fault originally day lighted. Exposures of this very low angle detachment fault extend ~35 km to the northwest and enclose the Funeral Mountain metamorphic core complex, which is the lower plate of the detachment.

4.2 Hydrogeology of the Southern Funeral Mountains

The miogeoclinal sequence of the southern Funeral Mountains consists of a lower, mainly upper Proterozoic siliciclastic confining unit, ~3.5 km thick, and an upper unit, the Paleozoic carbonate aquifer, ~4 km thick. Well to the north, in and around the Nevada Test Site, a second major siliciclastic-confining unit is present that divides the Paleozoic carbonate aquifer into upper and lower units (Winograd and Thordarson, 1975). But in the map area, the section that is age-equivalent to the upper siliciclastic confining unit is mostly carbonate; hence there is just one Paleozoic carbonate aquifer in the southern Funeral Mountains. Whereas this aquifer is commonly referred to as the "deep carbonate aquifer" throughout the Death Valley groundwater system, the rocks that comprise it are exposed throughout most of the southern Funeral Mountains. The Paleozoic carbonate aquifer is confined throughout a large part, and perhaps the majority of its regional extent, but is unconfined in most of the southern Funeral Mountains, proper. It is confined in those parts of the Funeral Mountains structural block where the Paleozoic rocks are overlain by Tertiary sediments, the vast majority of which act as confining units.

Within the section that is designated as the Paleozoic carbonate aquifer, there are numerous relatively thin horizons of interbedded siliciclastic rocks, including especially the Cambrian Dunderberg Shale (end), and the Ordovician Eureka Quartzite (Oe) and Ninemile Shale (On). Whereas these units are thin relative to the whole aquifer; their thickness is not trivial; for example, the measured thickness of the Eureka Quartzite is 120 m. Nonetheless, the Paleozoic carbonate aquifer section as a whole is so extensively broken by faults with offsets of this size or greater (see map sheet) that these siliciclastic interbeds within it cannot function as effective large-scale confining units. And this is confirmed by field observations. In this study, only one seasonal perched spring with trivial flow was found at the top of the Ninemile Shale where it crosses a canyon within the range; otherwise there was no discernable hydrologic effect from these siliciclastic breaks within the Paleozoic carbonate aquifer. Moreover, hydrologic tests conducted in drill-holes throughout the region also support this conclusion (Winograd and Thordarson, 1975). On a regional basins, the Paleozoic carbonate aquifer is too faulted and fractured for these thin siliciclastic interbeds within it to act as effective confining units.

Faulting within the exposed Paleozoic carbonate rocks is essentially fractal. Thus to map these rocks, we were forced to select a limit on the smallest-offset faults that would be shown. The map presents a very accurate picture of the geometry of the large- and intermediate-scale faults, as well as the spatial variation in the degree of faulting throughout the range. But it does not, and cannot, convey the actual extent to which the rocks of the southern Funeral Mountains are tectonically shattered. Whereas the large- and intermediate-scale faults of the range have a fairly regular geometric pattern, the unmapped smaller faults largely form bridging structures between the larger faults, and thus are oriented "every which way." This is hydrologically important because there is only trivial matrix permeability within the carbonate aquifer; the permeability is in the fractures. And, because the rocks are shattered, the permeability is very large in every direction. There certainly is anisotropy, but there are no directions lacking strong permeability in the carbonate aquifer.

North of the Funeral Mountains block (north of the Amargosa River), there are two aquifers. The first of these is an unconfined alluvial aquifer composed of the Quaternary gravels, which mantle the surface and locally extend to a depth of at least ~120 m. It is possible that these gravels are as old as uppermost Pliocene at the downward transition into impermeable playa claystones. This alluvial aquifer has been extensively drilled and provides the water supply for the town of Amargosa Valley, Nevada and the adjacent "farm district." The second is the Paleozoic carbonate aquifer, which is confined in most parts of the Amargosa Desert basin.

Table 4. Description of Map Units:

Surficial Deposits

Qayy **Alluvium in annually active channels (Holocene)**—Sand, silt, and gravel, unconsolidated

Qay **Alluvium in frequently active channels (Holocene)**—Sand, silt, and gravel, unconsolidated

Qp **Playa deposits (Holocene)**—Silt and minor evaporites

Qayo **Alluvium in terrace deposits slightly above active channels (Holocene)**—Sand, silt, and gravel, unconsolidated but with minor soil development

Qai **Alluvium in terrace deposits moderately higher than active channels (Pleistocene)**—Sand, silt, and gravel, unconsolidated but with moderate soil development

Qao **Older alluvium (Pleistocene)**—Sand, silt, and gravel, weakly consolidated, with strong soil development

Qm **Marl (Pleistocene)**—Calcareous siltstone and similar lithologies formed as ground-water discharge deposits, mainly of paludal origin

QTa **Old alluvium (Early Pleistocene and Pliocene)**—Sand, silt, and gravel, consolidated and strongly dissected

Bedrock

CENOZOIC

Post-Tectonic Sequence (~2 Ma to present)
Unconsolidated alluvial gravels, and much lesser playa claystones, fluvial sandstones and gravels, various types of ground-water discharge deposits, and eolian sand

SYN-BASIN-RANGE SEQUENCE – CONSISTING OF:

BADWATER GROUP (~4 MA TO ~2 MA)
Funeral Formation (late Pliocene and early Quaternary) – Consisting of:

TQa **Alluvium (late Pliocene and early Quaternary)** – Poorly consolidated alluvial fan gravels with angular to subangular clasts to >1 m; clasts derived from the Paleozoic rock formations exposed in the adjacent southwestern range-front of the southern Funeral Mountains; maximum exposed thickness of ~700 feet (~200 m)

TQb **Basalt (late Pliocene and early Quaternary)** – Unit consists of a single phenocryst-poor olivine basalt flow, the uppermost flow of the Greenwater Volcanics, which otherwise is part of the Furnace Creek Formation of the Nemo Group, described below; maximum thickness of ~30 feet (~10 m)

TQls **Landslide deposits (late Pliocene and early Quaternary)** – Rock-avalanche breccias exposed as channel fills on the east flank of Bat Mountain and as tongues extending out from Bat Mountain onto the alluvial apron to the east; composed of clasts derived primarily from the Kelley's Well Limestone (Ttk) and the Fluvial red sandstone (Ttr); age assignment to Funeral Formation based on geomorphic grounds – inverted topography and partial preservation of primary depositional form; maximum exposed thickness of ~50 feet (~15 m)

Nemo Group (~6.5 Ma to ~3 Ma)

<u>Furnace Creek Formation</u> (late Miocene to late Pliocene) –Consists of:

Tfs **Sedimentary fill of the Furnace Creek basin (late Miocene to late Pliocene)** – Interbedded playa claystones, siltstones, and sandstones, matrix-supported alluvium, and lesser cobble- to boulder-bearing turbidites, and travertine deposits; clasts in the alluvial deposits are derived both from the Artists Drive Formation of the Black Mountains and from Paleozoic and late Proterozoic rock formations of the Funeral Mountains; clasts in the turbidites derived exclusively from the Funeral Mountains

Tfb **Greenwater Volcanics (late Miocene to late Pliocene)** – Mostly phenocryst-poor olivine basalt flows and associated vent-area scoria deposits; locally interbedded with alluvial gravels of Tfs

Tfrx **Rock-avalanche breccias (late Miocene to late Pliocene)** – Breccias composed of clasts of various Paleozoic rock formations exposed along the southwest range-front of the southern Funeral Mountains; transitional to Giant block breccias (Tflx)

Tflx **Giant block breccias (late Miocene to late Pliocene)** – Genetically related to rock-avalanche breccias (Tfrx) but composed of clasts that are large enough to map and identify at 1:24,000 scale; rock formations from which the giant blocks were derived shown in parens

Navadu Group (~12 Ma to ~6.5 Ma)

<u>Artists Drive Formation</u> (middle to late Miocene) –Consists of:

Tnp **Playa deposits (middle to late Miocene)** – Claystones, commonly gypsum-bearing, and lesser siltstones and sandstones, typically moderately consolidated and pale yellow in color, with rare interbedded tuffs that resemble the ~10-to-~7-Ma Shoshone Volcanics

Tnl **Limestone-dominated lacustrine sediments (middle to late Miocene)** – Much like Tnp, but containing a large fraction of freshwater limestone and marl beds interbedded with the claystones, siltstones, sandstones, and tuffs

Tng **Alluvial gravels (middle to late Miocene)** – Alluvial gravels that were deposited in small basins formed along major Miocene normal faults in the southern Funeral Mountains; clasts were derived from various Paleozoic rock formations

Tnrx **Rock-avalanche breccias (middle to late Miocene)** – Breccias composed of clasts of various Paleozoic rock formations exposed in the southern Funeral Mountains; transitional to Giant block landslide breccias (Tnlx)

Tnlx **Giant-block landslide breccias (middle to late Miocene)** – Genetically related to rock-avalanche breccias (Tnrx) but composed of clasts that are large enough to map and identify at 1:24,000 scale; rock formations from which the giant blocks were derived shown in parens; contacts between giant blocks shown as dot-dash lines, solid lines denote formation contacts within giant blocks

Tnix **In-situ breccias, mostly fault breccias (middle to late Miocene)**-- Breccias developed dominantly along the Furnace Creek fault, which are assigned to the Navadu Group because the age interval of this group was the major time of motion along this fault; may include some breccias of landslide origin

<u>Owlshead Group</u> (~14.5–to–~12-Ma) – Consists of:

Tts **Yellow sandstone of Bat Mountain (early to middle Miocene)** – Volcaniclastic arkosic sandstone with minor thin conglomerate and mudstone interbeds, dominantly ochre colored;

commonly cross bedded – indicating a braided stream environment of deposition; rare pebbles were derived from various Paleozoic rock formations of the southern Funeral Mountains and vicinity; a waterlain tuff exposed at the top was dated at ~13.5 Ma (Ar/Ar/sanidine); maximum exposed thickness of ~1000 feet (~300 m)

Ttg **Cobble conglomerate of Bat Mountain (early to mid Miocene)** – Pebble to boulder (dominantly cobble) alluvial conglomerate, mainly clast supported, with a poorly sorted mixed clay-and-sand matrix; clasts are typically subangular and were derived from various Paleozoic rock formations of the southern Funeral Mountains and vicinity; also contains much lesser clasts of the Kelley's Well Limestone and the Fluvial red sandstone – observed in the basal ~50 m of the unit alone; interfingers at the base with the Kelley's Well Limestone and at the top with the Yellow sandstone; overall color as observed from a distance is medium reddish brown; maximum exposed thickness of ~1000 feet (~300 m)

Ttk **Kelley's Well Limestone (early to middle Miocene)** – Massive to thick-bedded, micritic light gray or cream colored freshwater limestone with local biostromes of finely laminated algal limestone and rare lenses of interbedded conglomerate resembling the overlying Cobble conglomerate of Bat Mountain, but not as coarse as that unit; Ttk contains numerous small rootless slump faults that strike roughly north-south and that change laterally (to the east) from being normal in displacement to reverse--these are slump faults indicating tilting prior to complete consolidation and prior to deposition of the overlying unit; maximum exposed thickness of ~320 feet (~100 m)

Hell's Gate Group (~16 to ~14.5 Ma):

Ttr **Fluvial red sandstone (early to middle Miocene)** – Pebbly sandstones and much lesser interbedded thin marls and pebble to small-cobble conglomerates, medium red to grayish green or, rarely, ochre-colored; pebbles moderately rounded and derived mainly from Paleozoic and late Proterozoic rock formations of the southwestern Great Basin – especially quartzites and black cherts, along with rare pebbles of Mesozoic granite, mainly the Hunter Mountain leucomonzogabbro; sand is arkosic, typically rich in biotite flakes, and overwhelmingly volcaniclastic; maximum exposed thickness of ~1000 feet (~300 m)

Mixed/Uncertain: either Hell's Gate Group or Pre-Basin-Range Sequence or both (~30-to-~12-Ma) – Consists of::

Tptl **Mostly freshwater limestone and lesser fluvial conglomerate (Oligocene to middle Miocene)** – Used to denote small isolated exposures of various lacustrine and fluvial rock types that could be correlative either with parts of the Transitional Sequence, described above, or with parts of the Pre-Basin-Range Sequence, described below, and that lack intercalated dateable tuffs

Pre-Basin-Range Sequence:

TTC **Titus Canyon Formation (Oligocene to Early Miocent: (~30-to-~19-Ma)** – Consists of:

Tpl **Tuff and lake-bed unit (late Oligocene to early Miocene)** – Interbedded freshwater limestones, marls, and playa claystones, with lesser siltstones, sandstones, and tuffs, moderately well consolidated except for the claystones, which are mostly poorly consolidated; tuff near the base is dated at 24.7 Ma (K-Ar), but resembles the ~27 Ma Monotony Tuff; tuffs near the top are dated at ~22.5 Ma (Ar/Ar; K-Ar) and 23.5 (K-Ar) and resemble the ~21 to ~24 Ma members of the Pahranagut Tuff; tuff filling a paleochannel at the very top was dated at ~19.5 Ma (K-Ar; Cemen, 1983); unit includes interbedded fluvial conglomerates in exposures to the northwest of Bat Mountain; maximum exposed thickness of ~400 feet (~120 m)

Tpg **Basal alluvium unit (Oligocene)** – Alluvium, moderately consolidated, consisting of subangular clasts to ~1 m, derived from locally subcropping Paleozoic rock formations, in a matrix composed of lateric red clay and lesser sand that is volcaniclastic near top of unit alone; thickness highly variable, maximum of ~650 feet (~200 m)

PALEOZOIC

Mp **Perdido Formation (Mississippian)** – Medium to dark gray limestone with interbedded lesser siltstone and sandstone beds with a capping layer of brown-weathering calcareous siltstone; top eroded; maximum preserved thickness of ~500 feet (155 m)

Mt **Tin Mountain Limestone (Mississippian)** – Mostly dark to light gray limestone commonly crinoidal or cherty, with some thin minor pale-red argillaceous beds; estimated maximum thickness of ~315 feet (~100 m)

Dl **Lost Burro Formation (Devonian)** – Basal 260 feet (80 m) consists of light gray dolomite interbedded with dark-brown weathering siltstone, sandstones, and chert beds; middle 975 feet (300 m) is mostly light gray dolomite but with some widely spaced dark gray beds; upper part is 1130 feet (340 m) of medium gray mixed dolomite and limestone overlain by light gray limestone, and then by a thin cap of silty and sandy carbonates; estimated total maximum thickness of ~2400 feet (730 m)

DSh **Hidden Valley Dolomite (Silurian and Devonian)** – Lower part is dark gray cherty dolomite; upper part is light gray dolomite that is slightly argillaceous and silty. Measured thicknesses vary from 870 feet (265 m) in southeast part of map area to 1440 feet (440 m) in northwest part of map area

Oes **Ely Springs Dolomite (Ordovician)** -- Dolomite and limy dolomite, mostly dark-gray but grading to medium gray at the top, containing abundant dark-gray chert layers and nodules 5 to 20 cm thick, estimated maximum thickness of ~500 feet (150 m)

Oe **Eureka Quartzite (Ordovician)** -- Ledge-forming, white to pink orthoquartzite, grading down into a light to medium red dolomitic sandstone at the base; estimated maximum thickness of ~400 feet (120 m)

Op **Pogonip Group, undivided (Ordovician)** – Estimated maximum thickness of ~2200 feet (~670 m) Consisting of:

Oav **Antelope Valley Formation (Ordovician)** -- Medium-gray, predominantly nodular, finely to coarsely crystalline limestone and silty limestone, massive to laminated beds.

On **Ninemile Formation (Ordovician)** -- Light- to moderate-brown or reddish brown siltstone and shale, typically finely laminated with olive-black to dark-medium-gray silty limestone or dolomite.

Og **Goodwin Limestone (Ordovician)** -- Ledge-forming, medium- to dark-gray limestone and lesser silty limestone.

en **Nopah Formation, undivided (Cambrian)** – Estimated maximum thickness of ~1700 feet (~520 m) Consisting of:

enc **Smoky and Halfpint Members, undivided (Cambrian)**

ens **Smoky Member (Cambrian)** -- Cliff-forming, very light-gray to medium-gray dolomite in indistinct medium to thick beds.

enh **Halfpint Member (Cambrian)** -- Predominantly medium- to dark-gray, thin- to thick-bedded, finely to coarsely crystalline dolomite locally containing abundant black chert nodules and layers, bedding generally very indistinct.

end **Dunderberg Shale Member (Cambrian)** -- Greenish-brown, fissile shale containing subordinate medium-gray to pale-brown thinly-bedded limestone.

eb **Bonanza King Formation, undivided (Cambrian)** -- Estimated maximum thickness of ~3600 feet (~1100 m); Consists of:

ebb **Banded Mountain Member, undivided (Cambrian)**

ebbu **Banded Mountain Member, Upper part (Cambrian)** -- Cliff-forming, finely to medium crystalline, thickly bedded; composed of three color bands of approximately equal thickness, from base to top: light gray, dark gray and medium gray.

ebbl **Banded Mountain Member, Lower part (Cambrian)**-- Cliff-forming dolomite and limestone, distinctively striped in alternating light- to dark-gray bands ranging from 0.5 to 6 m thick.

ebp **Papoose Lake Member (Cambrian)**-- Cliff-forming, mostly dark-gray dolomite and limestone intercalated with sparse but distinctive yellowish-orange silty and sandy intervals.

ec **Carrara Formation, undivided (Cambrian)** -- A heterogeneous unit of slate and lesser micaceous siltstone intercalated with prominent beds of limestone and silty limestone; estimated maximum thickness of ~1600 feet (490 m); consisting of:

ecu **Upper part** -- Intercalated thin- to medium-bedded, dark-greenish-gray slate, locally containing trilobite fragments, and lesser thin interbeds of micaceous quartzite and medium-dark-gray limestone.

ecm **Middle part** -- Cliff-forming, thickly-bedded, dark-greenish gray limestone, Girvenella (algal biscuits) characteristically are present.

ecl **Lower part** -- Similar to upper part, consists of greenish-gray, thinly interbedded slate, fine-grained micaceous siltstone, and dark-gray limestone.

ez **Zabriskie Quartzite (Cambrian)** -- Cliff-forming dark to medium purplish-red, fine- to medium-grained orthoquartzite, thick-bedded and commonly cross-stratified, common color banding typically reflects staining not bedding; estimated maximum thickness of ~800 feet (250 m);

Zew **Wood Canyon Formation, undivided (Cambrian and Late Proterozoic)** – Estimated maximum thickness of ~4000 feet (~1200 m); consisting of:

ewu **Upper Member (Cambrian)** -- Steep-slope-forming sequence of interbedded quartzite and siltstone with numerous orange dolomite beds which are most abundant at and near the base and are commonly oolitic

Zwm **Middle member: (Late Proterozoic)** -- Pale-green, very coarse grained, poorly sorted gritty quartzite with sparse siltstone interbeds, base is a thin pale-orange dolomite marker bed that is the top of the lower member

Zwl **Lower member: (Late Proterozoic)** -- Thin- to thickly bedded dark to medium brown or greenish-gray siltstone and very fine-grained micaceous quartzite; section is divided into roughly equal quarters by three prominent bands of interbedded orange dolomite, each ~15 m thick

Zs **Stirling Quartzite, undivided (Late Proterozoic),** Estimated maximum thickness of ~4800 feet (~1500 m)consisting of:

Zse **E Member: (Late Proterozoic) --** White to pale-yellowish-brown or pale red, medium- to thick-bedded, fine-grained orthoquartzite,

Zsd **D Member: (Late Proterozoic)** – Interbedded fine- to medium-grained feldspathic sandstone; siltstone interbeds common in lower part of unit decreasing in abundance upward

Zsc **C Member (Late Proterozoic)** – Dolomite, fine- to medium-grained, massive to thin-bedded, typically pale orange

Zsb **B Member: (Late Proterozoic)** – Fine-grained arkosic sandstone, micaceous siltstone, and thin beds of carbonate rocks

Zsa **A Member: (Late Proterozoic)** – Mostly fine- to coarse-grained impure sandstone, commonly arkosic and bearing characteristic jasperoid (sand to small pebble size) grains; contains abundant beds of quartz-pebble conglomerate, especially near the base, as well as platy siltstone; also contains a dolomite marker bed (dl) in upper part.

Zj **Johnnie Formation (Late Proterozoic)** – Shale and lesser carbonate rocks; only the uppermost ~300 feet (~100 m) of this thick formation is exposed in map area

5.0 Geophysical Surveys

Hydrodynamics conducted three geophysical surveys in April and May of 2007. Aquifer Science and Technology (AST), a division of Ruekert-Mielke, Inc., completed the acquisition of the geophysical data on behalf of *Hydrodynamics*. Geophysical surveys were conducted in the following three areas: the southern Funeral Mountains, the Amargosa Valley area, and the Devil's Hole area, as shown on Figure 5. The geophysical surveys used one or more of the following methods: magnetotelluric (MT), gravity, three-component time-domain electromagnetic induction (TEM), and high-resolution electrical resistivity (resistivity). A summary of the survey work and relevant findings is provided below.

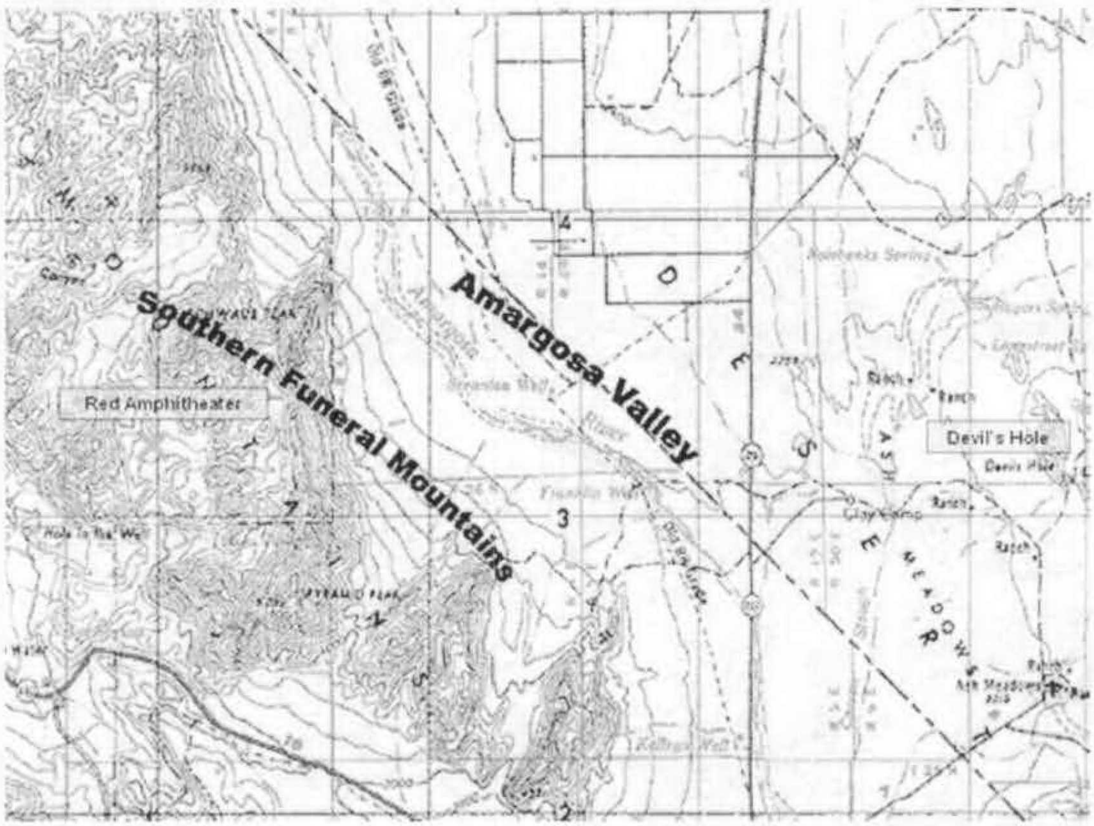


Figure 5. Location Map of Geophysical Survey Area.

5.1 Southern Funeral Mountain MT Survey

A critical factor in demonstrating a flow path through the Southern Funeral Mountain Range is documenting a continuous layer of saturated carbonate through the mountains. Fridrich (2003) projected the base of the carbonate aquifer through the Southern Funeral Mountains based on field mapping of the major faults of the area. He also identified two areas where a portion of the aquifer is expected to lie below the regional water table. These areas, called the spillways, represent the critical flow path for groundwater flow to the springs of the eastern wall of Death Valley. Much of this area is wilderness or too rugged to easily access with a drill rig. As a result, geophysical methods may represent the only practical means to measure the depth to water and the thickness of the carbonate aquifer.

In May of 2007, we conducted a series of MT soundings in the spillway between Schwaub Peak and Pyramid Peak in an attempt to estimate the depth to water in the carbonate aquifer and map the base of the carbonate aquifer. Figure 6 shows the approximate location of the Red Amphitheater transects relative to the location of the spillways. Figure 7 shows the location of the six MT soundings collected along the Red Amphitheater transect. We estimated that up to 2,500 feet of penetration would be needed to detect the zone of saturation using the modeled head field provided by Bredehoeft (2005).

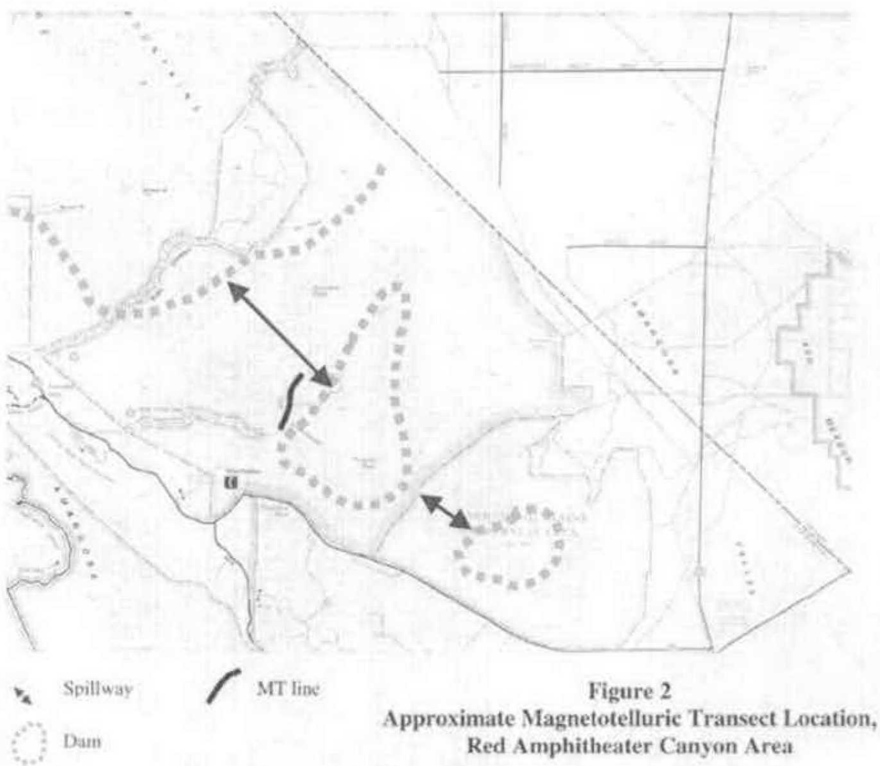


Figure 6. MT Transect through Red Ampitheater – Canyon.

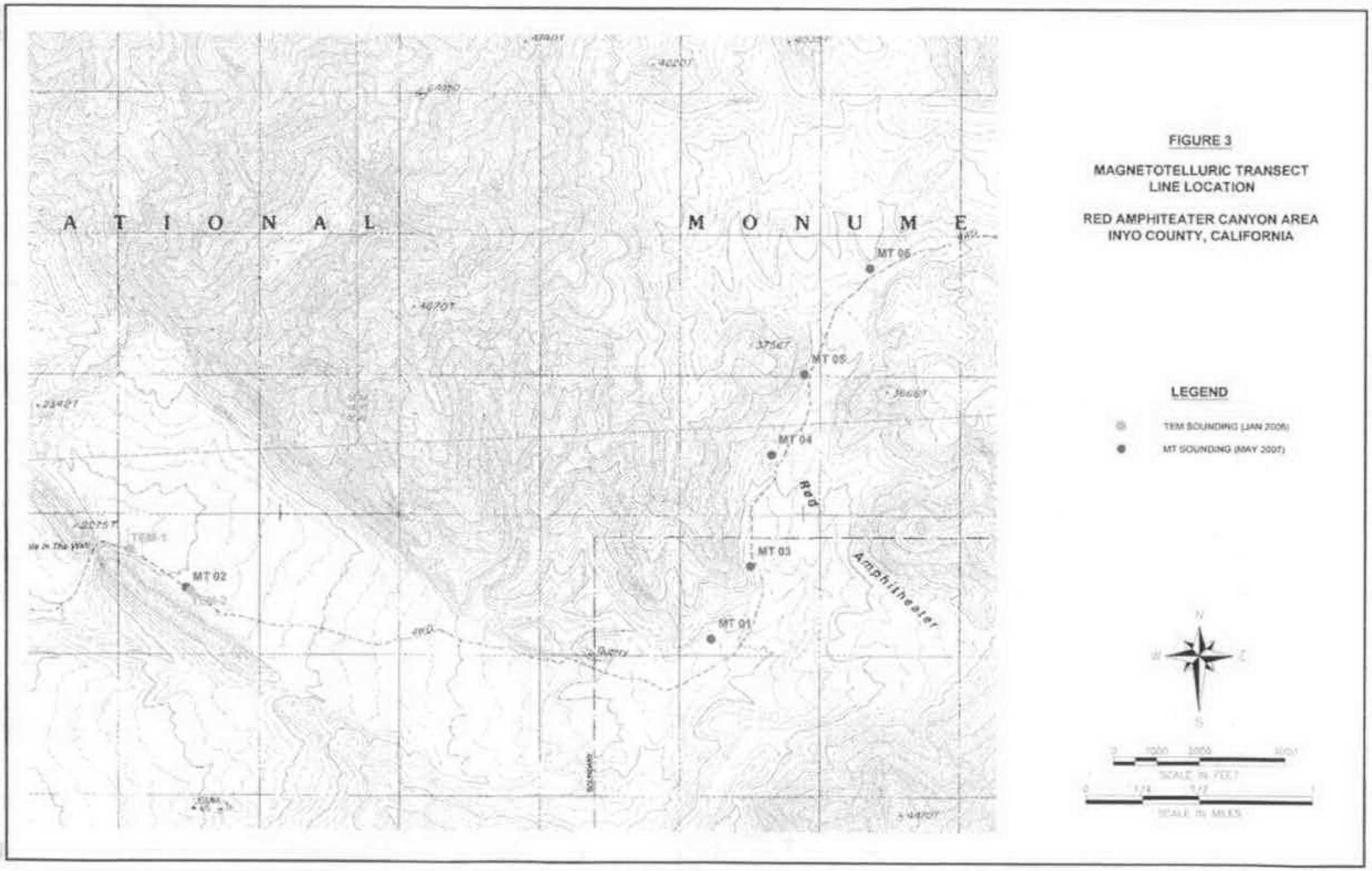


Figure 7. Location of Red Amphitheater Transect Location.

All of the soundings except MT2 were conducted in a designated wilderness area that prevented vehicle access into the site. The survey work was conducted using a Geometrics Stratagem MT system using the high frequency magnetic coils. Low frequency coils were not available at the time of this survey.

5.1.1 MT Methodology

The magnetotelluric (MT) method determines the earth's subsurface electrical resistivity distribution by measuring time dependent variations of the earth's controlled and natural electric and magnetic fields. Electric and magnetic field intensities are measured for a certain frequency or frequency range to determine resistivity values. The resistivity structure can be used to determine subsurface geologic and hydrogeologic conditions. Field data consist of MT sounding curves, which are log-log scale plots of apparent resistivity versus frequency. Apparent resistivities at high frequencies are influenced by generally shallow or nearby features and apparent resistivities at low frequencies are influenced by structures at greater depth and distance. Bostick transformations (Bostick, 1977) and forward and inversion modeling software are used to process the data and calculate formation resistivity.

The origin of low frequency MT source fields is caused by complex interactions between the earth's magnetic field and the solar wind. This interaction distorts the field into a comet shaped configuration referred to as the magnetosphere. Earth currents (telluric currents) are induced by complex magnetospheric variations and ionospheric currents. Telluric currents flow everywhere within the earth. The ionosphere and the earth surface form a wave guide where electromagnetic fields propagate between the two boundaries and are incident upon the surface of the earth with a large vertical component (Schumann resonance). Therefore, a fundamental assumption for MT measurements is that the source fields impinge on the earth as uniform plane waves and penetrate the subsurface in an essentially vertical direction.

The Stratagem MT system (Geometrics, Inc.), used in this study, uses both natural and man-made electromagnetic signals to obtain a continuous electrical sounding. Manmade, or controlled sources are generally used to supplement a band of weak natural energy that often occurs at intermediate to higher frequencies. This band of energy is generally used for more shallow investigations. It is often not necessary to use a controlled source for surveys that have a relatively deep zone of interest given the typically strong signals in the lower frequency bands.

The system requires the measurement of four rectangular vector field components at each surface station. Two directions of the electric field (E_x and E_y) and two directions of the magnetic field (H_x and H_y) are measured. By comparing the orthogonal components of the electric and magnetic field measurements, the vertical changes in subsurface resistivity are determined. By comparing the two orthogonal data sets, the electrical anisotropy of the system can be determined.

5.1.2 MT Field Procedures

The MT survey was designed to provide subsurface geologic information down to depths of several thousand feet. The objectives of the survey were to: 1) map the depth to the zone of saturation in the carbonate aquifer, 2) identify the geoelectrical contrast across the Furnace Creek fault, 3) and evaluate the capability of the MT method to map deeper subsurface structural conditions in the survey area.

The field data was collected using a Stratagem Magnetotelluric system made by Geometrics, Inc. The natural MT field was strong at the time of the survey, even at the higher frequency range. As a result, the natural MT signal was sufficient and it was not necessary to use a controlled source audio frequency transmitter to acquire shallow data. Data was collected using two 50-meter electric orthogonal dipoles and two orthogonal magnetic field sensors. Data was collected in the high, medium, and low frequency range at each station. Geoelectric strike for this survey was determined based on estimated trends of the major basin and range faults that formed the individual peaks of the southern Funeral Mountains. Two large transform faults are also present in the area, the Furnace Creek and State Line faults. Many smaller faults are present in the area. These faults are oriented at about 45 degrees west of north in the immediate area.

Geoelectrical strike was assumed to be approximately 45 degrees east of north. One dipole was oriented perpendicular to geoelectrical strike and was called the Transverse Magnetic, or TM orientation. The other dipole was oriented parallel to geoelectrical strike and was called the Transverse Electric, or TE orientation. The TE and TM magnetic dipoles were oriented perpendicular to the respective electric dipole. In an isotropic media, the TM and TE data sets for each sounding should produce very similar results. Significant variations between the TE and TM data sets indicate a geoelectrical anisotropy in the subsurface. Geoelectrical anisotropy typically indicates the presence of linear conductors such as fractures or faults that are vertical or steeply dipping or some other geologic fabric in the subsurface. Given the geologic setting of the site, these features are most likely to represent faults or conductive fractures that contain water or clay rich fault gouge.

The locations of the MT soundings in the Red Amphitheater area are shown on Figure 7. Sounding 1 was conducted a short distance into the wilderness area. Soundings MT3 through MT6 were conducted at approximately one-half mile intervals heading north–northeast along a drainage cutting through rock mass that primarily consisted of the Paleozoic carbonate rocks. Sounding MT2 was located a short distance east of the Hole in the Wall on the west side of the Furnace Creek fault.

The data quality the soundings was generally good from about 15 to 30 Hz., to greater than 50,000 Hz. Soundings MT3 and MT4 both experienced low signal strength from about 2,000 Hz. to 6,000 Hz. This caused a minor decrease in resolution in the shallow portion of the data. Given the expected depth to the water table (about 2,000 feet), the lower frequency data is of more interest and the loss of some the mid-range data frequency is not significant.

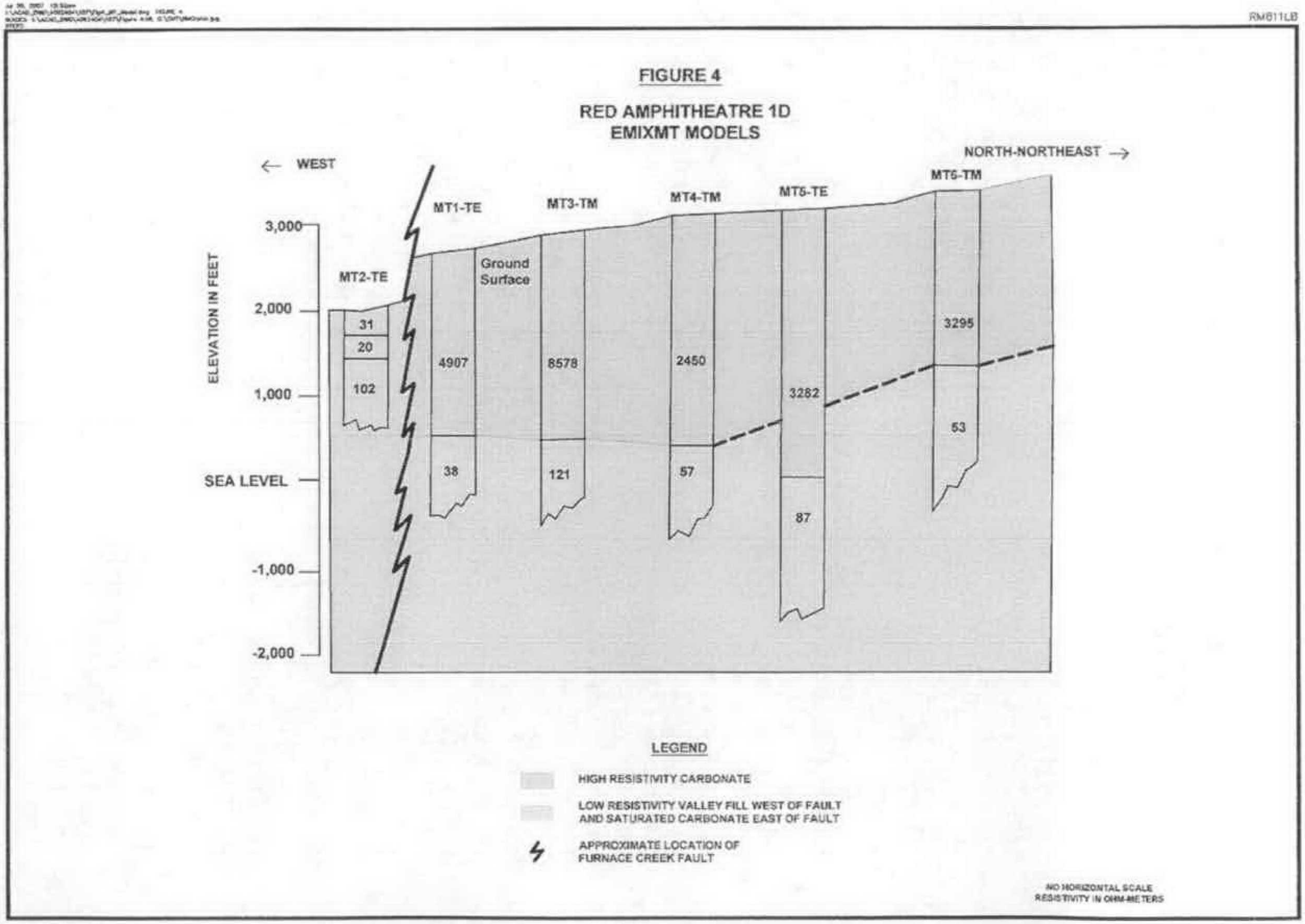


Figure 8. Cross-Section of Red Amphitheater MT Soundings.

5.1.3 MT Data Processing

The MT data was processed using the Geometrics Imagem software package, which is a two dimensional (2d) Bostick transform method, and using the Interpex Ltd EMIX MT package, a one dimensional (1d) analytical method that assumes horizontal isotropic layers. The results of the 1d analysis for the Red Amphitheatre Canyon data are presented in Appendix B, Table 1A.

The error term of the 1d models ranged from about 8.8% to over 90%, indicating that several of the soundings were not suitable for 1d analysis, probably due to strong anisotropic conditions in the subsurface. The 1d interpretation of most soundings required masking many noisy data points to produce soundings with smooth, interpretable curves. The 2d analysis produced a consistent geoelectrical section without masking any data points and is considered to be a more reliable representation of the subsurface.

5.1.4 Southern Funeral Mountains MT Survey Results

The 1d analysis produced a reasonable fit with the field data for a two-layer system for sounding MT1, and MT3 through MT6. The models generally consisted of a high resistivity layer (greater than 1,000 Ohmm meters [Ohmm]) over a conductive layer. Figure 8 is a geoelectrical cross-section constructed using the 1d model of each sounding (TE or TM) that produced the lowest error term. Several thin surface layers were detected by the soundings but excluded from the cross-section due to the compression of these layers on the vertical scale of the section. The horizontal scale is relative and the transect line bends sharply between MT2 and MT1.

The depth to the conductive layer was generally between about 2,000 to 2,600 feet. The depth to the conductive layer was anomalously deep (approximately 3,000 feet) at sounding MT5. This sounding has the highest error term even after masking many data points, suggesting that there is some noise in the data. Sounding MT2 detected low resistivity material to the minimum depth of over 500 feet. The penetration of this sounding was limited due to the higher conductivity (lower resistivity) basin fill sediment present on the west side of the Furnace Creek fault.

The low conductivity layer on Figure 8 may represent the zone of saturation in the carbonate aquifer. The elevation of the contact varies fairly smoothly from an elevation of about 520 feet at MT1 to 1,320 feet at MT6, with the exception of the anomalous results from MT5. Bredehoeft (2005) predicted water table elevations of approximately 1,575 feet at MT1 and 1,600 at MT6. The elevation of the contact between the high and low resistivity layers is lower than the modeled water table elevations by approximately 280 to 1,055 feet. This deviation is probably due to some combination of errors in the MT measurements and interpretation and some smaller error in the modeled heads. The large change in layer characteristics between soundings MT1 and MT2 is believed to indicate the transition from basin fill deposits to the Paleozoic and Tertiary rocks that occurs across the Furnace Creek fault.

Figure 9 presents the results of the 2d (Bostick transform) interpretation of the Red Amphitheater transect. The vertical scale is in meters and shows over 700 meters (2,300) feet of penetration on the western end of the transect at MT2, and almost 3,300 feet (1,000 meters) of penetration on the north-northeastern end near MT6. The horizontal scale is relative and the transect line bends sharply between MT2 and MT1.

The modeled data shows significant variations in resistivity both laterally and vertically across the profile. The modeled resistivity of the subsurface material beneath MT2 is generally less than 100 Ohmm and probably represents basin fill deposits on the west side of the Furnace Creek fault. The resistivity of the subsurface increases significantly from MT1 to MT5 as the transect progresses into the carbonate rock mass. The shallow materials on soundings MT1 through MT4 above about 50 meters (164 feet) have low to intermediate resistivity values between about 10 to 100 Ohmm, indicating a mixture of fine grain and coarse grain sediment in the wash. Below about 50 meters the resistivity of the subsurface is typically 200 Ohmm or higher. A dramatic increase in resistivity (to over 5,000 Ohmm) occurs at MT5, which may indicate a transition from a mixture of Tertiary rocks and Paleozoic carbonate rocks at soundings MT1, MT3, and MT4, to more Paleozoic carbonate rocks at soundings MT5 and MT6, as mapped by Fridrich, Blakely and Thompson (2003).

A significant drop in resistivity (to about 100 Ohmm) occurs at a depth of about 2,500 feet (775 meters) at soundings MT4, MT5, and MT6. This contact occurs at an elevation of about 550 feet at MT4 to 760 feet at MT6. These elevations are very similar to the contact on the 1d geoelectrical cross-section (Figure 8). This contact may represent the water table in the carbonate aquifer, although the elevation is lower than predicted by Bredehoeft (2005).

5.2 Amargosa Valley MT Survey

A pronounced gravity anomaly has been detected on regional gravity and aerial magnetic data along the eastern wall of Carson Slough from Death Valley Junction into the Ash Meadows area (Blakely 2000). The anomaly is assumed to be caused by a fault and has been called the gravity fault. Blakely (1998) hypothesized that the offset of the fault may truncate permeable formations and form a hydraulic barrier in the alluvial aquifer and potentially in the carbonate aquifer.

In January 2006 we conducted 11 deep TEM soundings along three profile lines in the Ash Meadows area of Amargosa Valley to see if the location of the gravity fault could be detected by other surface geophysical methods. The depth of investigation of the TEM soundings was limited to about 1,000 feet due to the low resistivity of the basin fill deposits in the area.

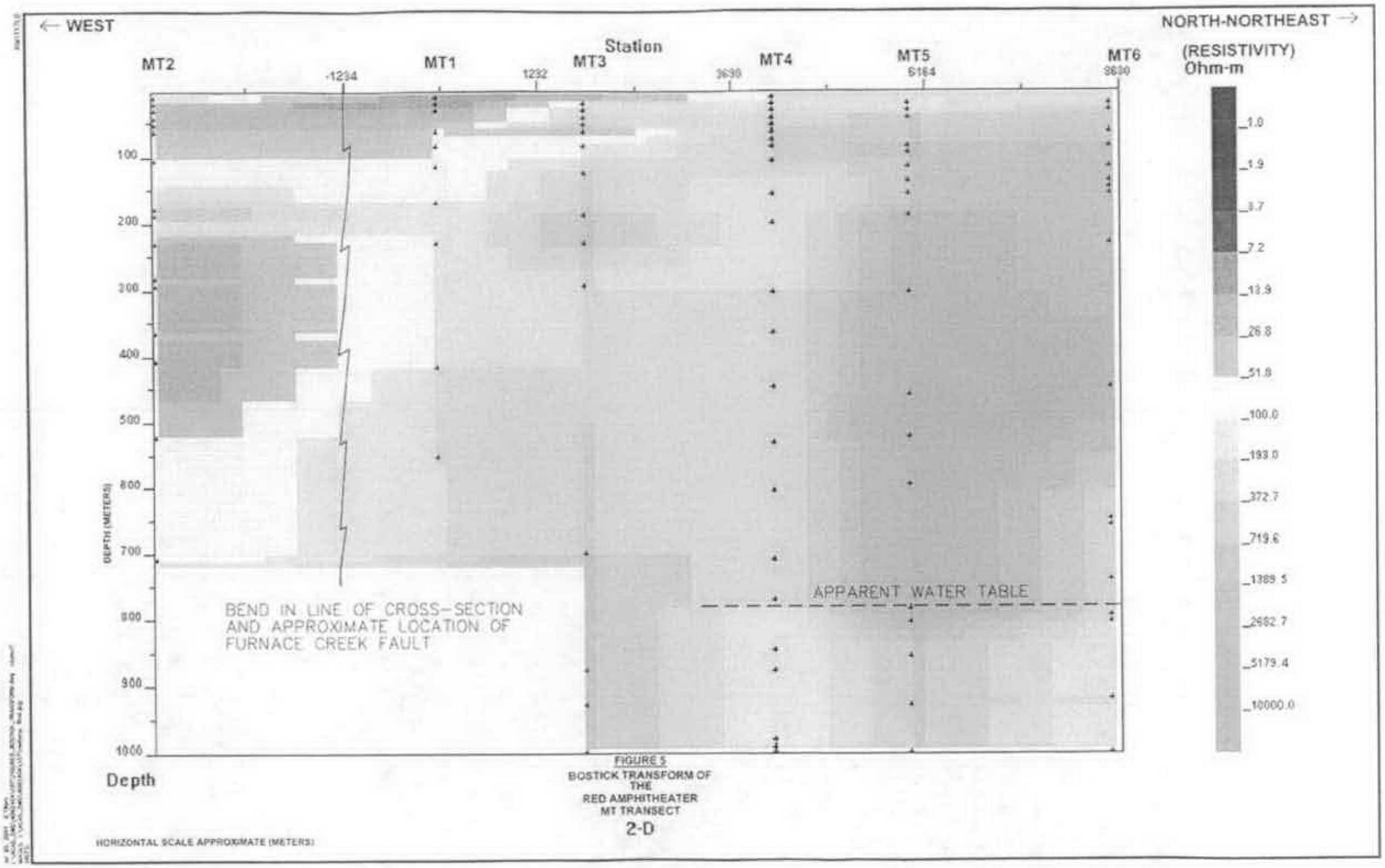


Figure 9. 2d Bostic Transform Interpretation of Red Amphitheater Transect.

In April 2007 we conducted a MT transect along Imvite Road in an attempt to increase the depth of investigation and estimate the depth to bedrock in the Carson Slough area. The MT survey methodologies, procedures, and processing for the Imvite Road transect were consistent with the methods employed to complete the Red Amphitheatre Canyon survey, as described above.

In addition to the TEM soundings that were completed in January 2006, we also conducted gravity surveys in the Ash Meadows area of the Amargosa Valley to confirm the presence of a major fault in the area (the Gravity Fault) and define the shape of the basin floor. The gravity survey consisted of approximately 19 miles of gravity data along four profile lines with a station interval of 500 feet. The gravity data indicated an area of high-density material near the Carson Slough that is believed to represent dense bedrock, probably Paleozoic carbonate rock.
In April 2007 we collected additional gravity data to tie in the 2006 data collected in the Ash Meadows area to the data we collected in previous years west of Highway 29/127 in the Bat Mountain area. The 2007 MT and gravity survey methodologies, procedures, and processing for the Imvite Road tie line, including a discussion of the results are discussed below.

5.3 Amargosa Valley MT Survey Results
Nine MT soundings (MT7 through MT15) were collected along Imvite Road in May 2007. The locations of the MT soundings are shown on Figure 10. Figure 11 presents the results of the 2d (Bostick Transform) interpretation of the Imvite Road transect. The penetration of the soundings is controlled by the resistivity of the subsurface. A thick sequence of low resistivity material (less than 10 Ohmm) was encountered at all soundings on Imvite Road, which significantly limited the penetration of the survey. The soundings obtained a depth of investigation of over 1,200 feet (370 meters) on the southwestern end of the transect at MT15 and about 500 feet (150 meters) on the northeastern end near MT7. The maximum penetration occurs at MT13 where the higher resistivity soils allowed approximately 1,600 feet (490 meters) of penetration.

The section shows significant variations both laterally and vertically across the profile. The resistivity of the shallow materials is low, generally below 10 Ohmm. Similar resistivity values were measured by the TEM soundings conducted in 2006. The resistivity of the subsurface below about 600 feet (180 meters) is higher, generally about 10 to 200 Ohm. This is similar to a higher resistivity mound observed on the Imvite Road TEM profile in the 2006 survey. The low resistivity layer appears to extend to depths of over 650 feet (200 meters) on the northeastern half of the line.

Several of the MT soundings were modeled using 1d analysis to confirm the results of the Bostick Transform. Review of the modeled 1d data indicates that the depth of investigation and sensitivity to vertical changes were essentially the same. As a result, no further 1d analysis of the MT data along Imvite Road was completed and the limited 1d analysis completed is not presented in this report.

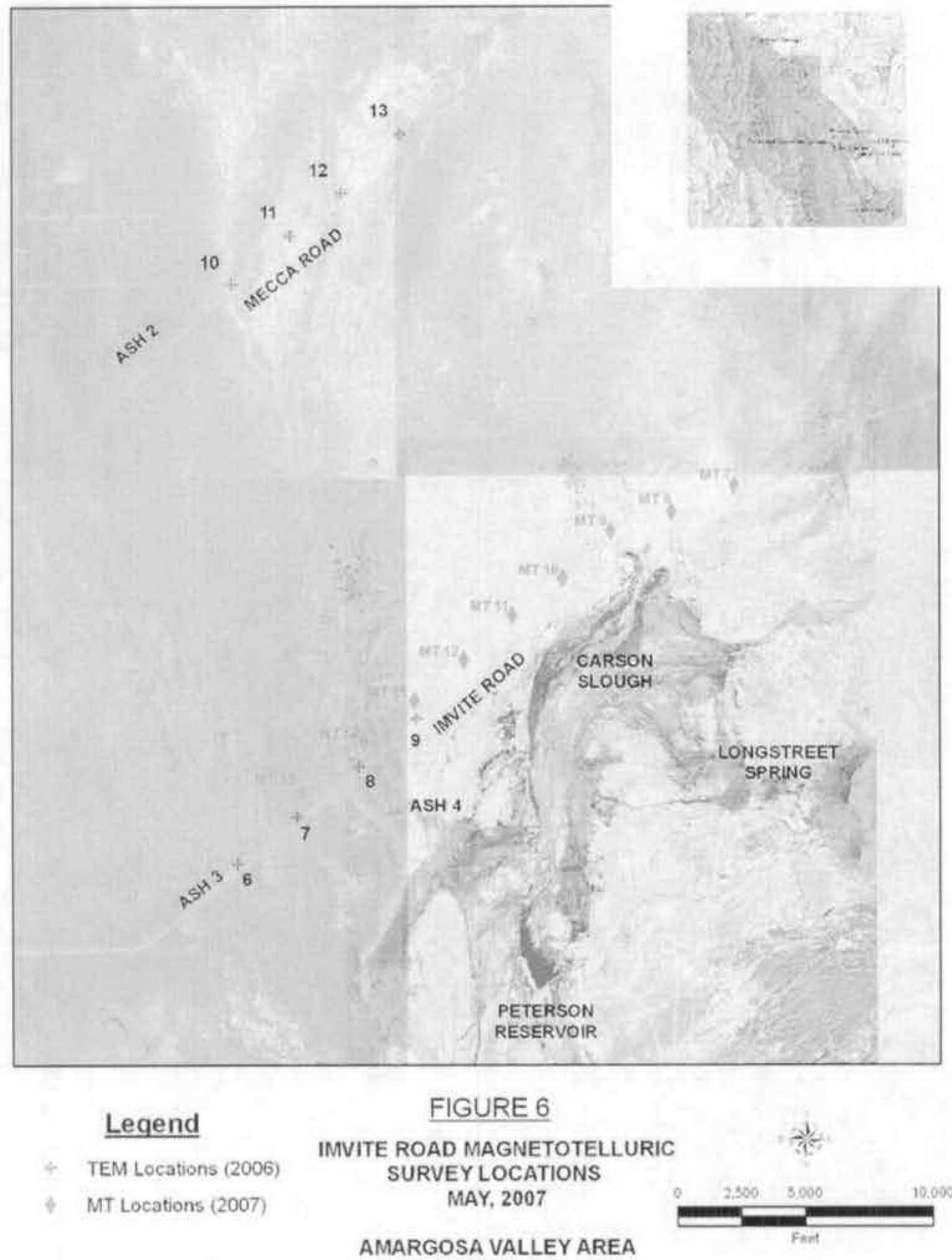


Figure 10. Location of Imvite Road MT Sounding.

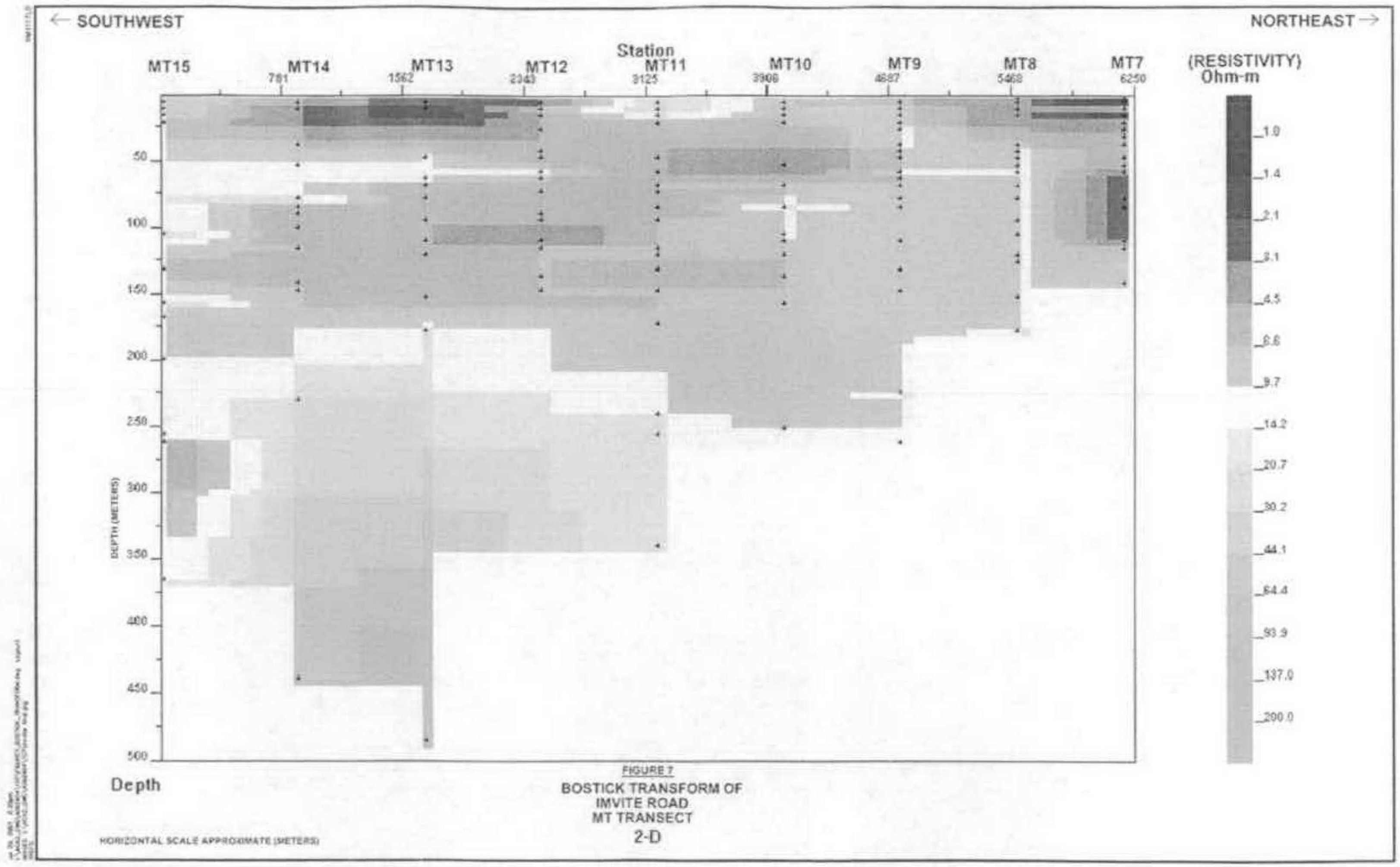


Figure 11. 2d Bostic Transform interpretation of Invite Road transect.

The depth of investigation of the MT data appears to have been severely limited by the low resistivity deposits on the Imvite Road profile. The depth of investigation was insufficient to determine if high resistivity bedrock is present near the northeastern edge of the line. Assuming an average resistivity of between 5 to 10 Ohmm for the basin fill deposits, it would be necessary to record energy below about 5 Hz. to achieve greater than about 1,500 feet of penetration. This is beyond the capability of the standard Stratagem system using high frequency coils. It may be possible to detect bedrock in this area using specialized low frequency magnetic coils. Unfortunately the low frequency coils were not available for this survey.

5.4 Gravity Tie Between Ash Meadows and Funeral Mountains

Two profile lines of gravity data were extended from previously completed gravity lines in the western portion of Amargosa Valley to the previously completed gravity lines in the Ash Meadows area. The purpose of the gravity lines was to tie the geophysical data from the Bat Mountain area to the work completed by AST and the USGS in the Ash Meadows area. Tie Line 1 connected gravity line Grav 19 with gravity line ASH 1 with. Gravity line Grav 15 was connected to gravity line ASH 3 with Tie Line 2.

5.4.1 Gravity Tie Line Methodology and Field Procedures

The data were collected using a LaCoste & Romberg (L&R), Model G (meter number G-400) gravimeter equipped with an Aliod 100 electrostatic nulling beam and digital display. Forty-seven gravity stations were occupied along the two profiles. At each station one gravity measurement was obtained after allowing the digital output of the meter to stabilize for approximately 2 to 4 minutes. The gravity stations were generally spaced at 500-foot intervals along each profile. Gravity measurements were also obtained periodically throughout the day at a base station (typically before occupying the first and last stations on a given line). The base station is located at the NE corner of Highway 373 and the Bob Ruud Memorial Highway, which leads into Ash Meadows. This station was picked because it is along Tie Line 1 and could be occupied numerous times during the survey.

The latitude, longitude, and elevation at each gravity station were surveyed prior to obtaining a gravity measurement. A Ruekert/Mielke surveyor using a Trimble total station global positioning system (gps) instrument surveyed each of the gravity stations. The fieldwork was conducted on April 19, 2007. The locations of the gravity lines, including the station locations of the tie lines, are shown on Figure 12.

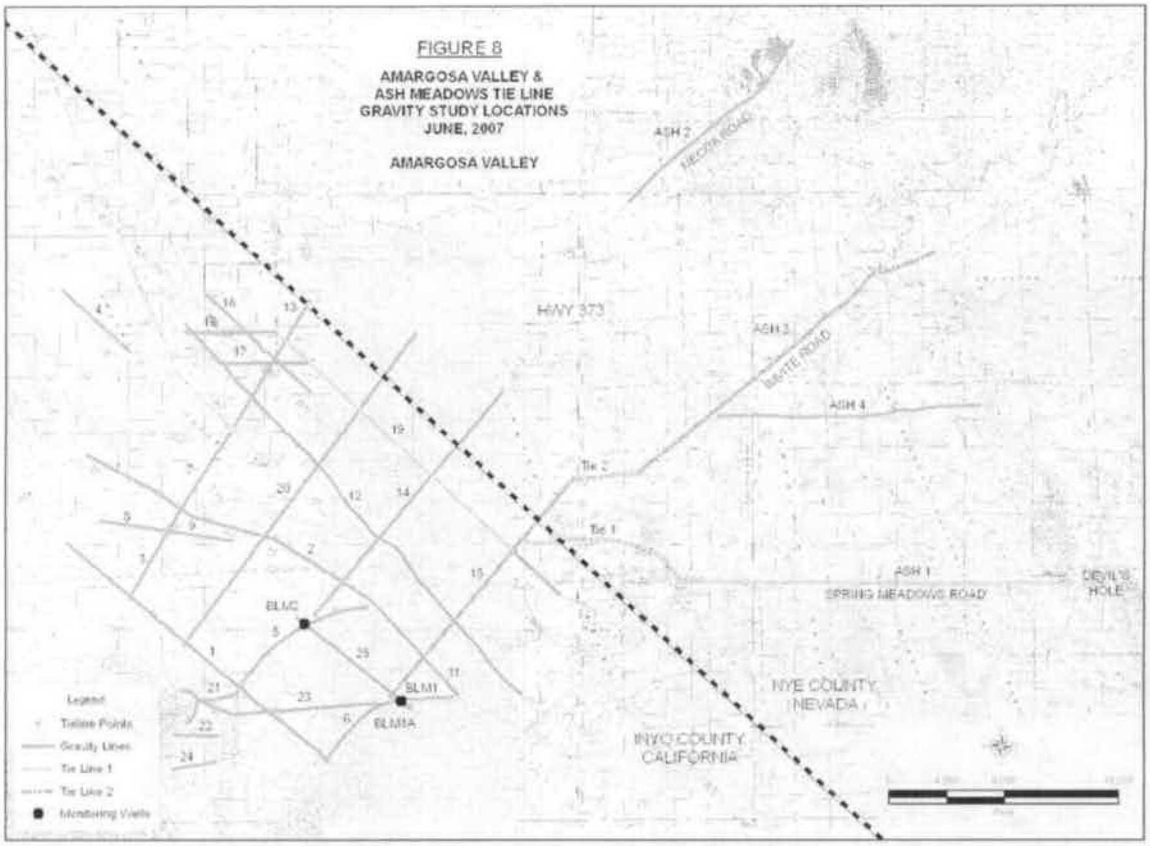


Figure 12. Location of Gravity Tie Line Stations.

Corrections to the field data (processing) were performed using Excel spreadsheets and GravMaster™, a Geotools Corporation gravity data processing software. The data were processed in the same manner as the gravity data collected previously in the Amargosa Valley (Hydrodynamics, 2006). The raw data from the Bat Mountain, Ash Meadows, and Tie Line data were normalized to the middle data set to plot the three sets of data together. This allowed the data to be modeled without breaks between the data that was collected during different years.

5.4.2 Gravity Tie Line Results

The gravity data is included in Appendix C. Figures 13 and 14 illustrate the interpreted depth to bedrock obtained from the modeled gravity data. Each gravity profile shows the entire length of gravity data including both of the gravity lines that were collected previously and the tie line. Tie Line 1 is approximately 81,000 feet long and Tie Line 2 is approximately 57,000 feet long.

The gravity data profiles show the bedrock highs associated with the mountains on the west and east sides of the Amargosa Valley. The gravity data also shows a bedrock high near the state line fault. There are two deep troughs between the bedrock high at the state line and the east and west bedrock highs near the edges of the Amargosa Valley. This is generally consistent with the gravity inversion done by the USGS using regional data

(Blakely, 1998). The shape of the bedrock surface is consistent with a positive element related to the State Line fault system, which is a right lateral strike slip fault. The steep slope on the bedrock surface to the east of the State Line Fault System represents a normal fault on the floor of the basin that trends roughly north-south and lies approximately 2 miles west of Devil's Hole. The normal fault is believed to represent the gravity fault. On the west side of the State Line Fault system the Bat Mountain and Pyramid Peak fault blocks project downwards very steeply into the Amargosa Valley. Smaller buried bedrock knobs in the area appear to be portions of mountain blocks sheared off by splays of the State Line Fault.

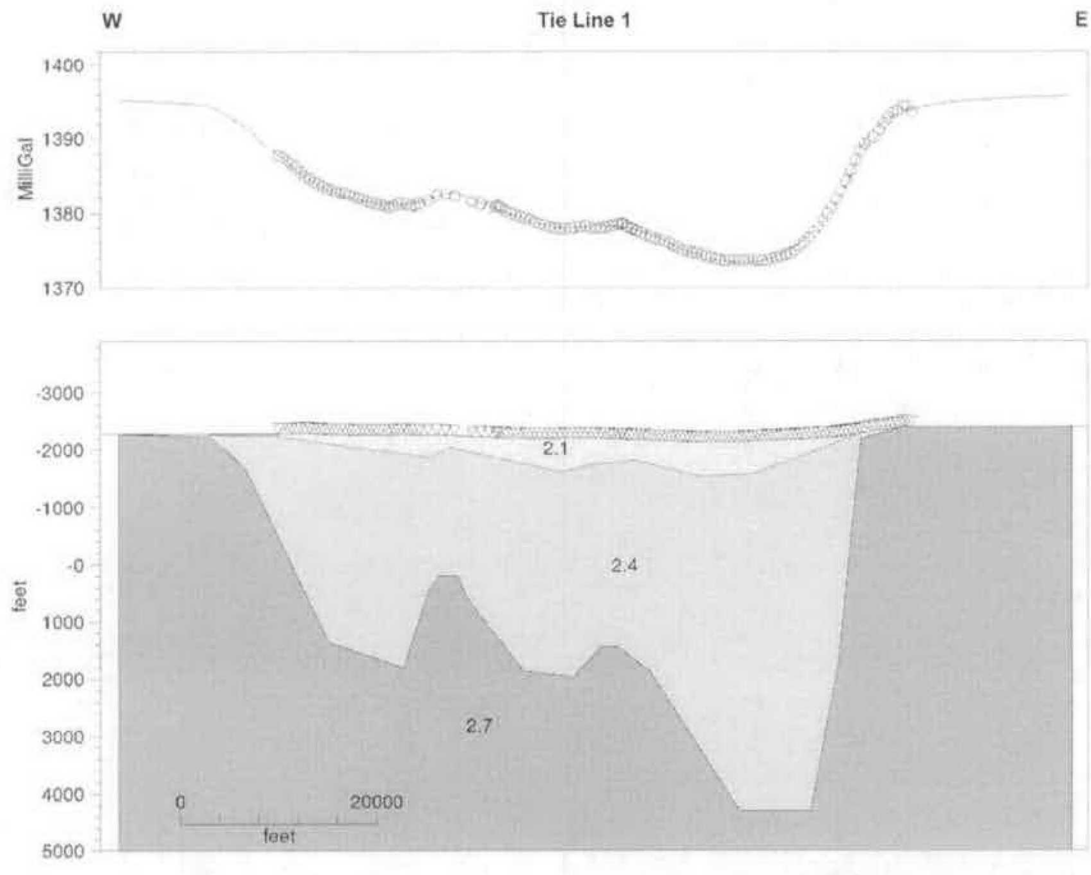


Figure 13. Gravity Model of Tie Line 1. Includes GRAV 14, TIE 1 and ASH 1 data.

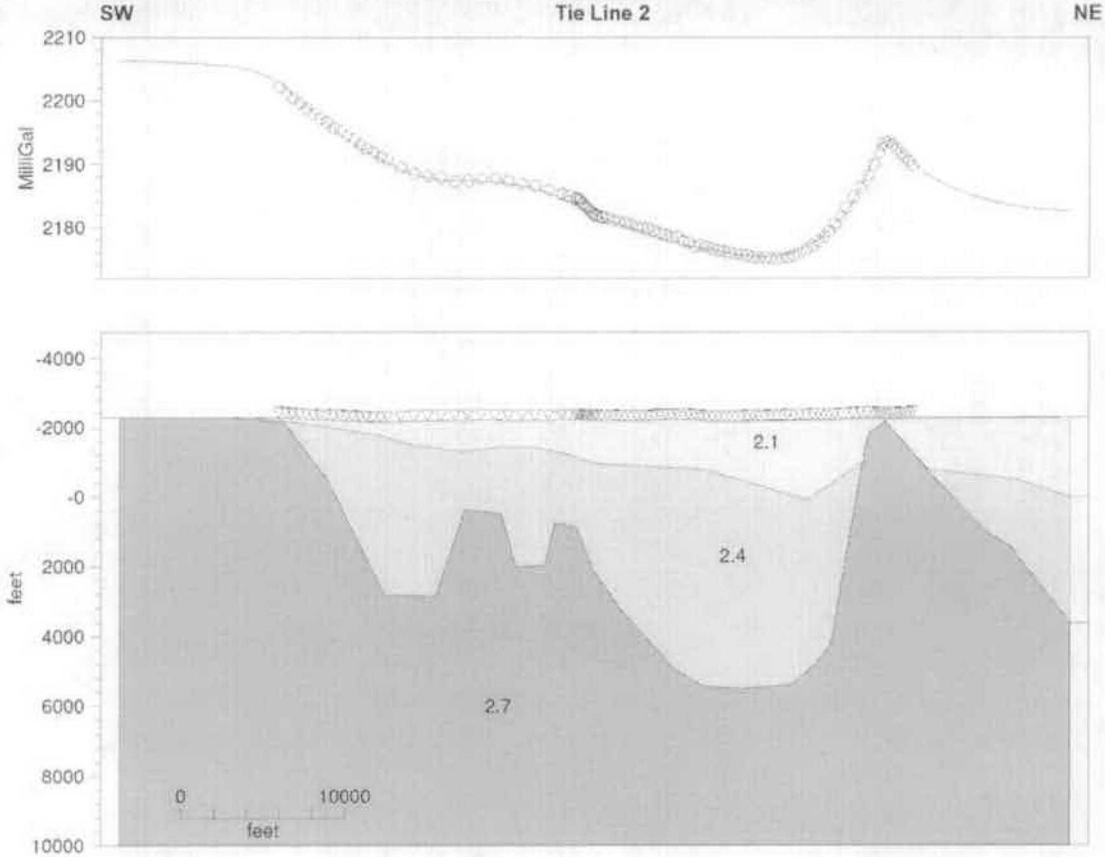


Figure 14. Gravity Model of Tie Line 2. Includes GRAV 15, TIE 2, and ASH 3 data.

In July of 2005, a gravity line was run between monitoring well BLM1 and the eastern tip of Pyramid Peak. Figure 15 shows a geologic map (Fridrich, 2003) with a detailed geologic cross-section (A-A') produced from detailed field mapping in the area in conjunction with the drilling log of BLM1. The gravity line was run in 2005 to determine if the gravity data could be reconciled with the assumed structure of the bedrock surface. A modeled section of the gravity line is shown beneath the geologic cross section. The modeled gravity section shows the Carbonate Aquifer extending into the basin from the Bat Mountain and Pyramid Peak mountain blocks into a basin filled with Tertiary and Quaternary units. A generalized density section based on the stratigraphic column from exposures in the Southern Funeral Mountains and the log of BLM1 was used to model the gravity data. The model results agree closely with Fridrich's cross-section and suggest that the depth to the Carbonate Aquifer can be estimated from the gravity data if the stratigraphic column is known.

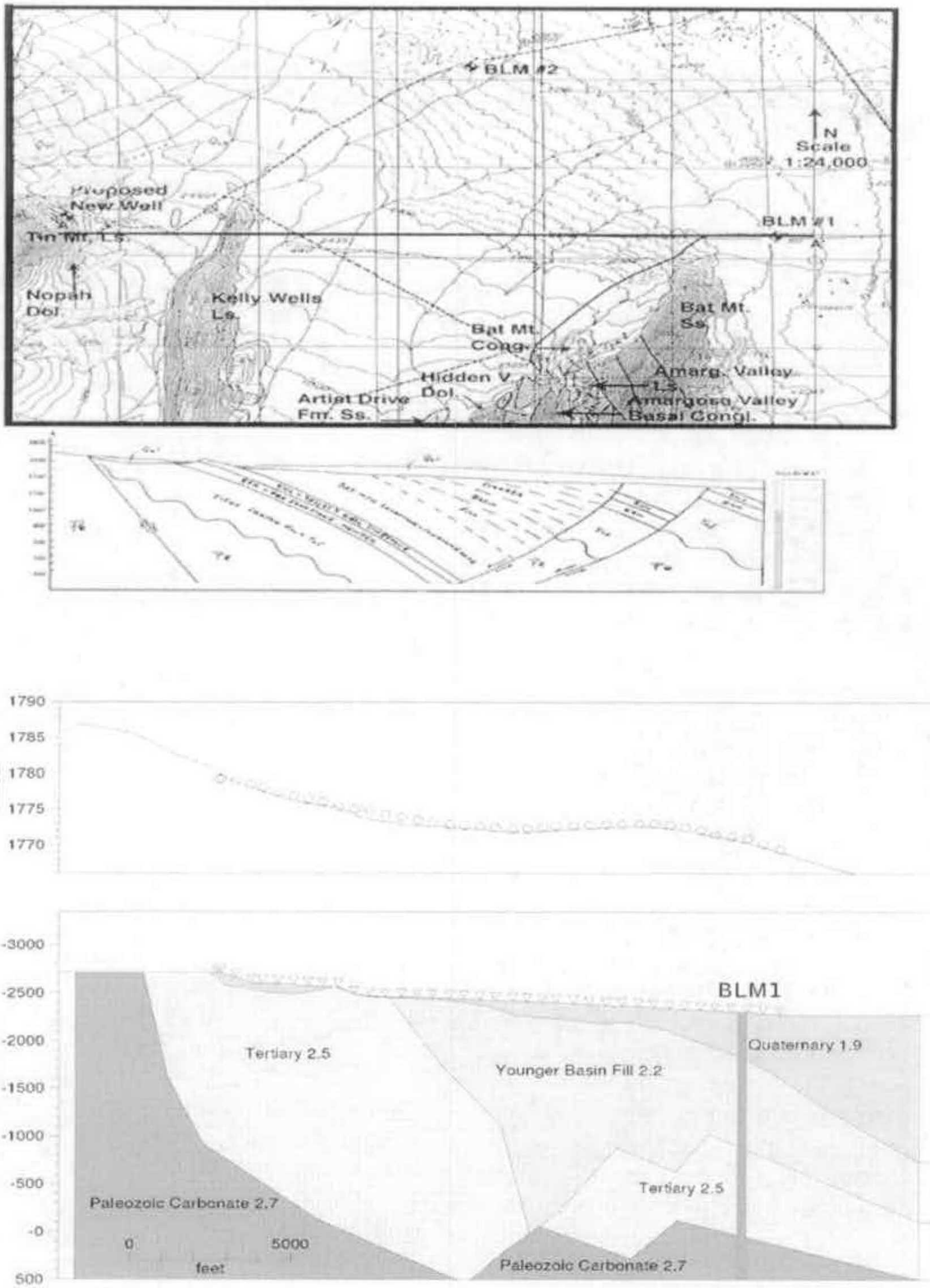


Figure 15. Geological Profile through an Eastern Portion of the Southern Funeral Mountains.

5.5 DEVIL'S HOLE RESISTIVITY THREE COMPONENT TEM AND GRAVITY SURVEYS

Devil's Hole is formed by a collapse structure along a fracture system in the Bonanza King Formation of the regional Carbonate Aquifer (Cutillo, 2006). The hole is a window into a large linear fracture that is known to be over 300 feet deep and extends laterally along a linear fracture. The full depth and lateral extent of the feature have not been fully explored. Additional caverns, such as Brown's Room, that are part of the Devil's Hole fracture system are known to be present in the area. While Devil's Hole is a fracture controlled feature numerous solution cavities are present in the outcrops adjacent to the hole indicating that solution features or karst features are likely to be present associated with the fracture system forming Devil's Hole. The orientation and extent of the fracture system supporting Devil's Hole and associated karst features are of interest in terms of predicting the response of Devil's Hole to changes in the aquifer system from natural or anthropogenic causes.

Limited test surveys conducted adjacent to Devil's Hole in January 2006 (Hydrodynamics, 2006) indicate that gravity and electrical methods may be appropriate geophysical techniques to map the fracture system supporting Devil's Hole. In April of 2007 we a gravity survey combined with a 3 component TEM survey and a high resolution electrical resistivity survey in the area around Devil's Hole in an attempt to further map the karst or fracture system adjacent to Devil's Hole.

The orientations of most of the survey lines around Devil's Hole were chosen to be roughly perpendicular the orientation of the fracture zone visible at the surface adjacent to Devil's Hole. Efforts to run lines perpendicular to this orientation were limited by the steep topography on Devil's Hole Ridge and the lack of soil cover to plant electrodes west of Devil's Hole. As a result, the survey design has an inherent bias toward higher sensitivity to fractures or voids that run parallel to the Devil's Hole fracture system (north-northeast). It is likely that fractures and voids that trend roughly perpendicular to this orientation are present in the subsurface but could not be detected by our survey due to the line orientations.

5.5.1 Devils Hole Resistivity Methodology

The method of electrical resistivity incorporates the introduction of an electrical current into the ground through a pair of current electrodes while measuring the resultant voltage field in the ground at an offset pair of potential electrodes. The purpose of the resistivity survey is to delineate lateral and vertical variations in the subsurface material. High-resolution multi-node resistivity systems use a cable system with multiple conductors to connect many electrodes to a switching box. The switching box selects pairs of current and potential electrodes to make resistivity measurements. The spacing between current and potential electrodes, the spacing between the electrode pairs, and the position of the center of the electrode arrays are changed from one measurement to the next in a systematic way to provide resistivity measurements to different depths and at different positions along a profile line. These systems can make hundreds of measurements in a matter of a few hours. The data can be interpreted to produce a high-resolution two-dimensional section that shows the lateral and vertical changes in resistivity along the profile line.

5.5.2 Devils Hole Resistivity Field Procedures

A geophysical survey consisting of eight high-resolution resistivity profiles was conducted in the vicinity of Devil's Hole between April 15 and 18, 2007. The locations of the resistivity profiles are shown on Figure 16. The resistivity data were collected using a SuperSting™ model R1 IP, with a Swift™, multi-node resistivity imaging system, manufactured by Advanced Geosciences, Inc., (AGI) of Austin, Texas. Survey profile locations were determined in the field on the basis of site access, terrain, and position relative to the inferred fracture trend of Devil's Hole. The latitude, longitude, and elevation of each resistivity line end point were surveyed using a Trimble, total station global positioning system (gps) instrument.

The spacing between electrodes was 5 meters on all lines except for Line 4, which has an electrode spacing of 10 meters. Between 42 and 56 electrodes were used for each sounding depending on site conditions. Portions of the survey area consisted of bare carbonate bedrock where electrodes could not be installed and resistivity surveying was not practical.

5.5.3 Devils Hole Resistivity Data Processing

The modeling package EarthImager™ was used to model the field data. The modeled data was interpreted to provide estimates of the depth to bedrock, thickness of the unconsolidated zone, and identify fractures and voids in the carbonate rock. The data was modeled using a topography correction in the inversion process to account for the topographic relief at the site.

5.5.4 Devils Hole Resistivity Survey Results

The locations of the resistivity lines adjacent to Devil's Hole are shown on Figure 16. Review of the data indicates that the data quality was generally very good except for Line R1. Line R1 was collected on the first day of the field activities when the soil was extremely dry resulting in very high electrical contact resistance between the ground surface and the electrodes. We attempted to reduce the contact resistance by wetting the soil around the electrodes with salt water with little improvement. The high contact resistance on line R1 resulted in very noisy data that necessitated removal of a significant number of data points during the modeling process, which resulted in poor data quality in the processed section. Resistivity lines R2 through R8 were collected after a heavy rain event on the evening of April 15. This precipitation sufficiently moistened the surficial materials so that fairly low contact resistance was attained and the data quality was significantly improved. The modeled resistivity profiles are included in Appendix D.

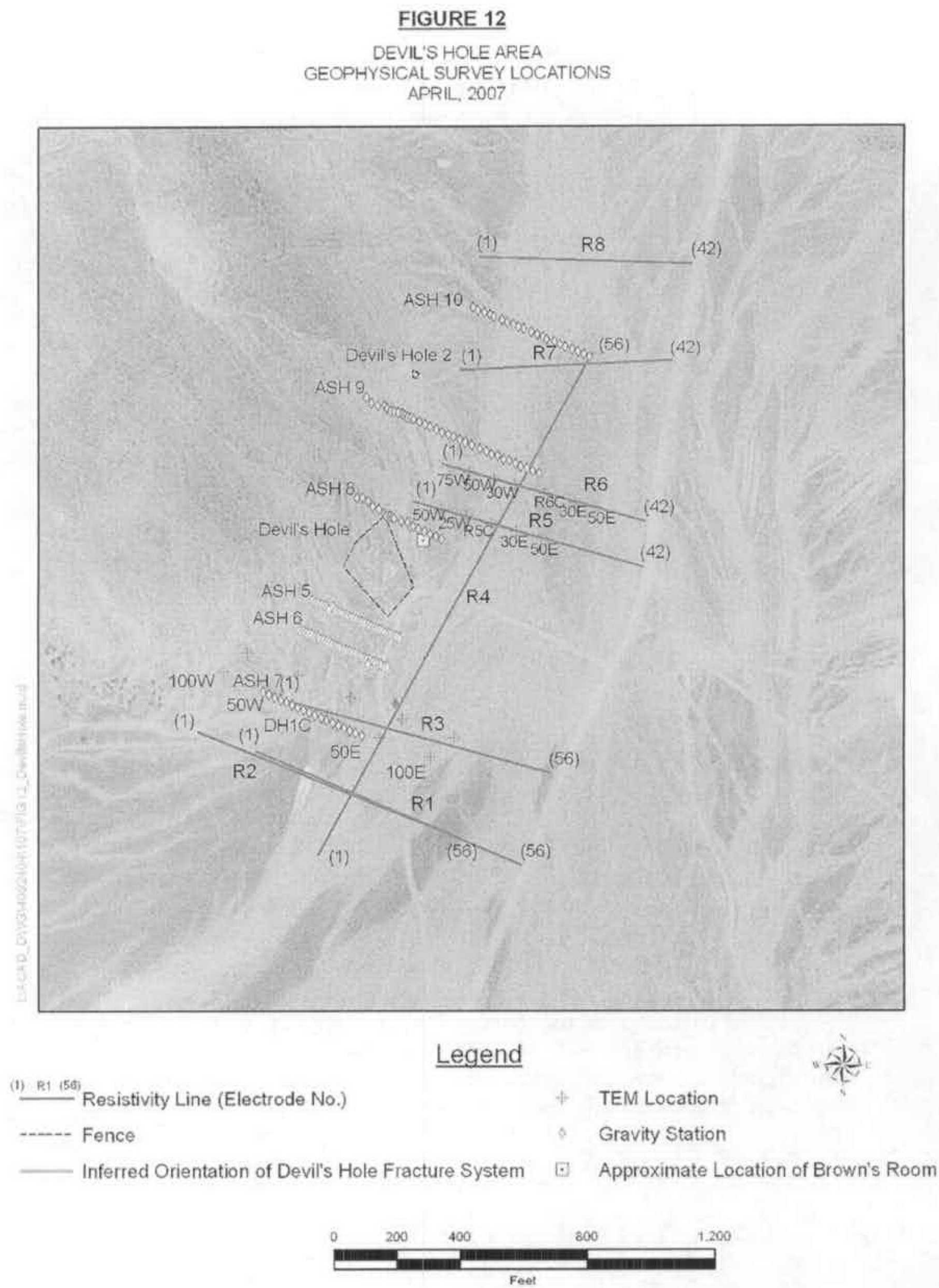


Figure 16. Devil's Hole area geophysical survey locations.

Review of the modeled resistivity data indicates the presence of medium to high resistivity material characteristic of sand and gravel, with varying amounts of silt and clay, overlying carbonate bedrock. Each of the modeled resistivity lines is plotted with a resistivity scale of 17 Ohmm as the lower limit and 3,000 Ohmm as the upper limit. Generally, the color scale and corresponding lithology typical for those resistivity ranges are represented as follows: fine grain clay-size sediment is shown in dark blue; clay, silt, and sand mixtures are shown as light blue; silty fine sand is shown in bluish-green, sand with variable silt is shown in green; sand and gravel with minor silt is shown in yellow and orange; and, clean unsaturated sand and gravel and carbonate rock is shown in red. Zones of fractured or karstified carbonate rock are shown as yellow to blue areas within the bedrock. The depth of penetration of the resistivity lines vary from about 150 feet on the shorter lines to over 300 feet on the longest line.

A brief discussion of the results obtained at each of the resistivity lines follows.

Resistivity Line R1

Resistivity line R1 is oriented in a northwest-southeast direction approximately 600 feet south of Devil's Hole. The data quality of this line is poor due to the in very high electrical contact resistance caused by the dry soil conditions. While the modeled data is not clear or consistent, we are still able to roughly interpret the high resistivity (>500 Ohmm) carbonate in the west half of the profile at a depth of approximately 100 feet. At about station (sta) 492, the bedrock appears to drop off sharply to a depth of greater than 200 feet. The majority of the unconsolidated material beneath R1 consists of low resistivity (from <20 to 60 Ohmm) sediment. Several near surface pockets of high resistivity material are present along the entire profile. More high resistivity zones would likely be present but many of the very high resistivity data points were removed during the data editing process to reduce the effects of the high contact resistance on this line

Resistivity Line R2

Resistivity line R2 is located parallel to and along the same transect as R1, with the southwestern end of R2 being shifted to the southwest of the end of R1 by approximately 200 feet. R2 was collected as a check on the data quality obtained at line R1.
The data quality of line R2 is much better than R1 and indicates that many of the small features detected on R1 are artifacts of the high contact resistance problem. The shallow layer on Line R2 is primarily composed of a thin layer of low to intermediate resistivity sediment. A zone of very high resistivity sediment is present at the surface from about sta 459 to sta 787. The upper material is underlain by a thick sequence of low resistivity sediment.

An area of low intermediate-to-intermediate resistivity material is present in the western one third of the profile at a depth of approximately 100 feet. This unit is interpreted to represent carbonate bedrock with varying degrees of fracturing and karstification. At about sta 260, the bedrock appears to drop off sharply to a depth of greater than 200 feet. This feature may represent the edge of a fault block on the western side of the basin. A zone of lower resistivity in the carbonate bedrock is present at about sta 98 to the west end of the line. This may represent area of low resistivity material in the bedrock, such as a fracture or karst zone.

Resistivity Line R3

Resistivity line R3 is located approximately 400 feet south of Devil's Hole and 200 feet north of resistivity lines R1 and R2, and is oriented in a northwest-southeast direction. The shallow zone is primarily composed of intermediate to very high resistivity sediment and is underlain by a thick sequence of low resistivity silts and clays. High resistivity carbonate is present from the west end of the line at a depth of approximately 50 feet to about sta 98, where the rock appears to dip fairly steeply to the east-northeast from to greater than 100 feet at sta 197. The slope of the rock is gentler to the northeast to about sta 394, where it then drops off sharply to a depth of greater than 200 feet. Review of the modeled data does not indicate the existence of any fractures or karst features in the upper portion of the bedrock surface beneath this profile. The medium to high resistivity feature at a depth of greater than 100 feet in the far-east part of the line does not appear to be supported by the field data, and is likely an artifact of the modeling process.

Resistivity Line R4

Resistivity line R4 is located approximately 250 feet east of Devil's Hole, and is orientated parallel to the fracture zone at Devil's Hole in a south-southwest to north-northeast direction. The orientation of the line was chosen to see if any of the east-west trending faults mapped previously (Carr, 1986) crossing Devil's Hole Ridge extend to the east of Devil's Hole below grade on the block of carbonate rock forming Devil's Hole Ridge. The modeled data indicates the presence of a large area of low resistivity material in the upper carbonate surface between sta's 600 and 934. On either side are areas of very high resistivity material more characteristic of dense carbonate bedrock. The high resistivity bedrock material extends to approximately sta 197 to the south and sta 1736 to the north. This low resistivity zone near the center of the line may represent a fractured or karstifed zone forming an extension of the fault mapped by Carr (1986) that crosses Devil's Hole Ridge from the west and bifurcates around Devil's Hole to the north and south.

Resistivity Line R5

Resistivity line R5 is located approximately 250 feet north of Devil's Hole and 700 feet north of resistivity lines R3, and is oriented in a northwest-southeast direction. An upper layer of very high resistivity surface material is present from about sta 262 to the east end of the line, and thickens from west to east. This upper layer is underlain by a thick sequence of low resistivity sediment. Very high resistivity carbonate is present at the surface from the west end of the line to about sta 48. This carbonate is observed to dip almost vertically into the basin and may represent the edge of a fault block on the western side of the basin. A large resistivity anomaly characteristic of a fault or karst feature is present in the upper carbonate surface between about sta's 64 to 259. This feature appears to lie in the same general orientation from Devil's Hole as Brown's Room, but is about 120 feet farther to the northeast of Devil's Hole than Brown's Room.

Resistivity Line R6

Resistivity line R6 is located parallel to and approximately 150 feet north of R5. The resistivity signature for this line is similar to that of line R5, with a layer of very high resistivity surface material present from about sta 194 to the east end of the line, and the layer thickening from west to east. This upper layer is underlain by a thick sequence of low resistivity sediment. On the west end of the line, the dip of the carbonate appears to be much more shallow than on line R5, displaying a gradual dip to the east until about sta 400, at which point the depth to rock appears to by greater than 200 feet. The modeled resistivity of the rock appears to be much less resistive from about sta 162 to the east. This reduction in resistivity may be due to fractured or weathered zones. There also appears to be a resistivity low in the rock between sta's 48 to 97 and sta's 309 to 325. These areas may represent fracture zones or karst features in the bedrock.

Resistivity Line R7

Resistivity line R7 is located approximately 650 feet north of R6 and is oriented from west to east, with the west end of the line being approximately 225 feet east of Devil's Hole 2. This line shows a thin and undulating layer of very high resistivity surface material from about sta 176 to sta 570. The upper layer is underlain by a thick sequence of low resistivity sediment to depths of between approximately 50 to 120 feet. High resistivity carbonate bedrock is present on the west half of the line at depths of between about 40 feet beneath the surface near station 100 and greater than 170 feet on the east end of the line. The bedrock high at sta 100 appears to be an isolated feature, or knob of high resistivity dense rock, with the rock dipping sharply to the east and west. The steep knob on the bedrock surface may represent a fault block or pinnacle structure with the bedrock on either side of the knob removed by faulting or weathering processes.

Resistivity Line R8

Resistivity line R8 is located parallel to and approximately 330 feet north of R7. The resistivity signature for this line is somewhat similar to that of line R7, with a thin layer (several feet to 25 feet) of very high resistivity surface material present from about sta 80 to sta 558. The upper layer is underlain by a thick sequence of low resistivity sediment to a depth of between approximately 40 to 50 feet. Two knobs of high resistivity material are present at depth on the west half of the line that appears to indicate bedrock highs. Bedrock appears to be greater than 200 feet on the eastern third of the line.

The high resistivity knobs between stas 64 and 350 form a saddle with two positive elements with a low resistivity zone in between. The rock dips moderately to the east to the east of the saddle. The areas between the saddle and to the west of the saddle, where the rock appears to drop off sharply, could represent a faults or fracture zones.

Figure 17 illustrates the location of low resistivity zones within the carbonate bedrock observed on the resistivity profiles. A zone of karstification or higher density fracturing has been interpolated between the anomalies. This zone illustrates our interpretation of a zone of the bedrock that is believed to have higher secondary porosity any may represent a preferential flow path in the carbonate aquifer. This feature is orientated roughly north-northeast and is generally parallel to the observed orientation of the fracture zone around

Devil's Hole. This feature may represent a combination of parallel linear fractures in the rock with solution enlargements along and between the fractures, forming an anastomosing pattern along a generally linear trend parallel to the orientation of the Devil's Hole Fracture system.

5.6 Three Component TEM Methodology

Three component TEM soundings are a modification of standard TEM soundings designed to increase the sensitivity to dipping conductive bodies, such as faults or fractures. Standard TEM soundings are conducted with a receiver coil that has its axis oriented vertically. This arrangement provides the maximum sensitivity to nearly vertical magnetic fields caused by horizontally layered strata. A fault creates a dipping or nearly vertical planar feature that disrupts the horizontal layers. The fault plane and associated fractures are often electrically conductive. The presence of a dipping electrical conductor provides a wave-guide that channels some of the induced energy from the TEM transmitter to flow along the dipping plane. The eddy currents induced in the fault plane are not horizontal, which creates a magnetic field that has a significant horizontal component. Using standard one dimensional data acquisition and analysis either misses the horizontal signals altogether, or makes a measurement of a distorted vertical field component that cannot be properly interpreted. In simple surveys these three-dimensional effects are usually ignored. In cases where the three-dimensional response is strong the soundings cannot be interpreted by one-dimensional methods. However, if the magnetic field is measured in three components, the response of the dipping conductors can be recognized and used to determine the location of the fault.

5.6.1 Three Component TEM Field Procedures

The three components TEM measurements were made by positioning the transmitter coil near the assumed location of the fracture zone and then making three component readings along a perpendicular transect line. Three component readings were made at the center of the transmitted loop and at distances of either 25 or 30 meters, 50 meters, and 75 meters east and west of the center of the loop as site conditions allowed. The magnetic field was measured in three components by making sequential readings with the receiver coil orientated vertically (Z component), and then in each of the two principal horizontal directions (X and Y components). A Geonics EM57 system with a 50-meter transmitter coil was used to make the measurements.

5.6.2 Three Component TEM Data Processing

The data was processed through a comparison of the ideal response of a horizontally layered earth to the observed field data (Hoekstra and Blohm, 1990). Disruptions of the normal decay curve in the vertical component (Z direction) or significant energy in the horizontal components (X or Y direction) are indications of the presence of a dipping conductor. The location of the maximum magnetic field response indicates the position of the conductor.

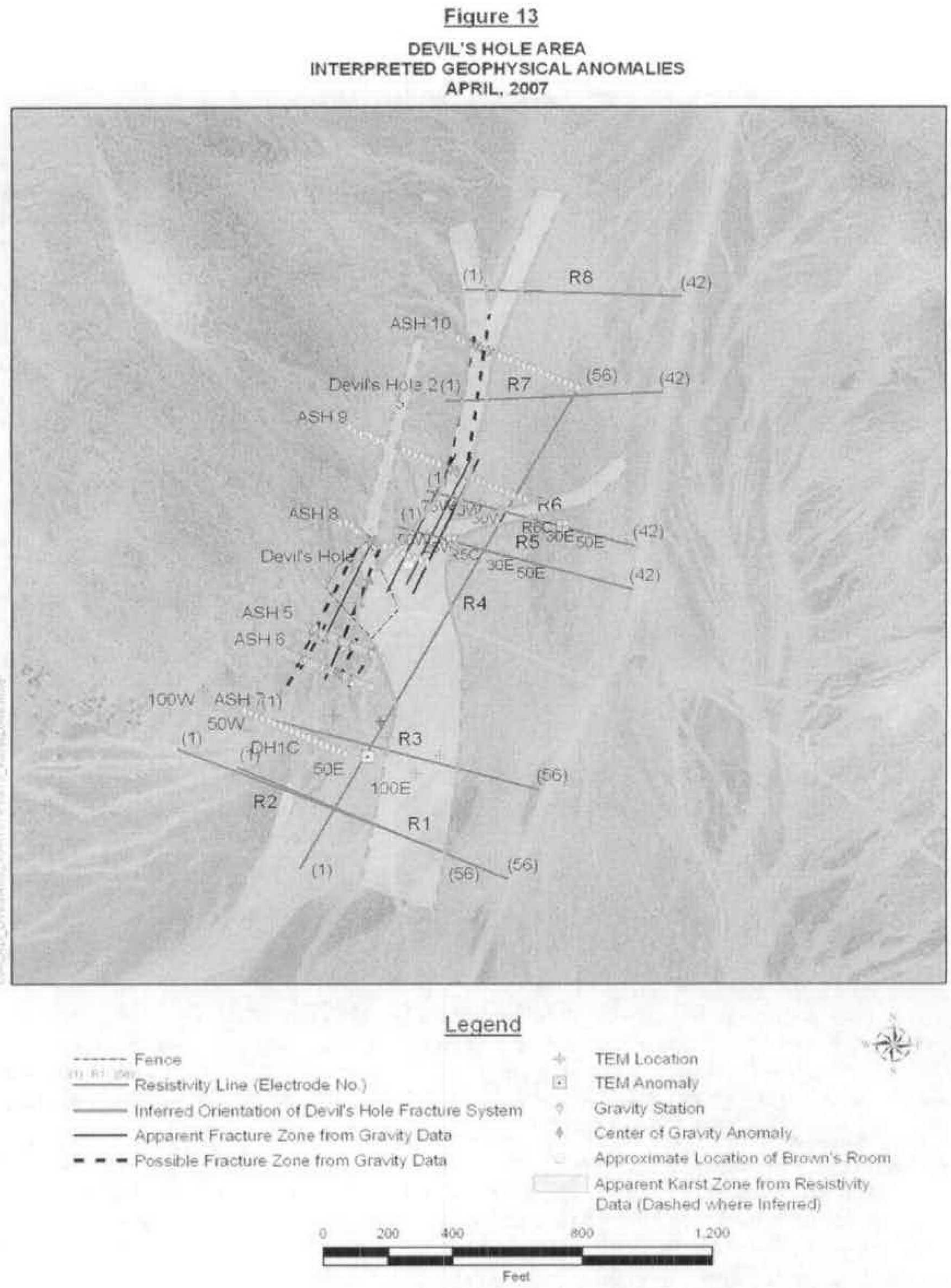


Figure 17. Interpreted Geophysical Anomalies in the Devil's Hole Area.

5.6.3 Three Component TEM Survey Results

The locations of the three component TEM soundings are shown on Figure 17. The data was processed through a comparison of the ideal response of a horizontally layered earth to the observed field data (Hoekstra and Blohm, 1990). Disruptions of the normal decay curve in the vertical component (Z direction) or significant energy in the horizontal components (X or Y direction) are indications of the presence of a dipping conductor. The location of the maximum magnetic field response indicates the position of the conductor.

Figures 18 and 19 illustrate the results of graphical analysis of three component TEM data along Devils Hole resistivity lines R5 and R6, respectively. Shown on each of the graphs are the Z (vertical), X, (north-south), and Y (east-west) orientations for the TEM soundings at a time of 0.105 milliseconds (mSec). Review of the data indicates the presence of a large anomaly in the Z component on both lines R5 and R6. The magnitude of these anomalies was largest on the Z component on the 0.105 mSec time window, the earliest window recorded.

The fact that the Z component shows the largest response suggests that the conductor causing the anomaly may have a more horizontal shape rather than a steeply dipping conductor. This may be consistent with the relatively wide conductive bodies observed in the resistivity data that are believed to represent zones of fractures or karstified zones in the shallow part of the carbonate bedrock. The fact that the response is greatest in the earliest time window indicates that the conductive boy is relatively shallow (in the upper 100 to 200 feet), which is also consistent with the depth of investigation of the resistivity data.

On line R5, the anomaly is located on the western half of the line, centered 25 meters west of center. This anomaly appears to correlate with an anomaly in the resistivity data on line R5, and near the location of Brown's Room. On line R6, the anomaly is located between center and 30 meters east of the center of the line. This anomaly appears to with the low resistivity anomaly on R6 at sta 325.

5.7 Devil's Hole Gravity Survey

The locations of the gravity lines adjacent to Devil's Hole are shown on Figure 17. Four additional gravity lines were collected in the area, one south of previous lines ASH5 and ASH6, two lines north of Devil's Hole and south of Devil's Hole 2, and one line north of Devil's Hole 2. The Gravity survey was conducted using the same Gravimeter that was used to collect the tie line data.

The procedure for collecting the data near Devil's Hole is slightly different than the procedure used to collect the tie line data. Ninety-two gravity stations were occupied along the four profiles. At each station one gravity measurement was obtained after allowing the digital output of the meter to stabilize for approximately 10 minutes. The gravity stations were spaced at 10 or 20-foot intervals along each profile. Gravity measurements were also obtained periodically throughout the day at a base station (typically before occupying the first and last stations on a given line and every few hours). The base station is located at a surveying monument immediately south of the Devil's Hole observation deck.

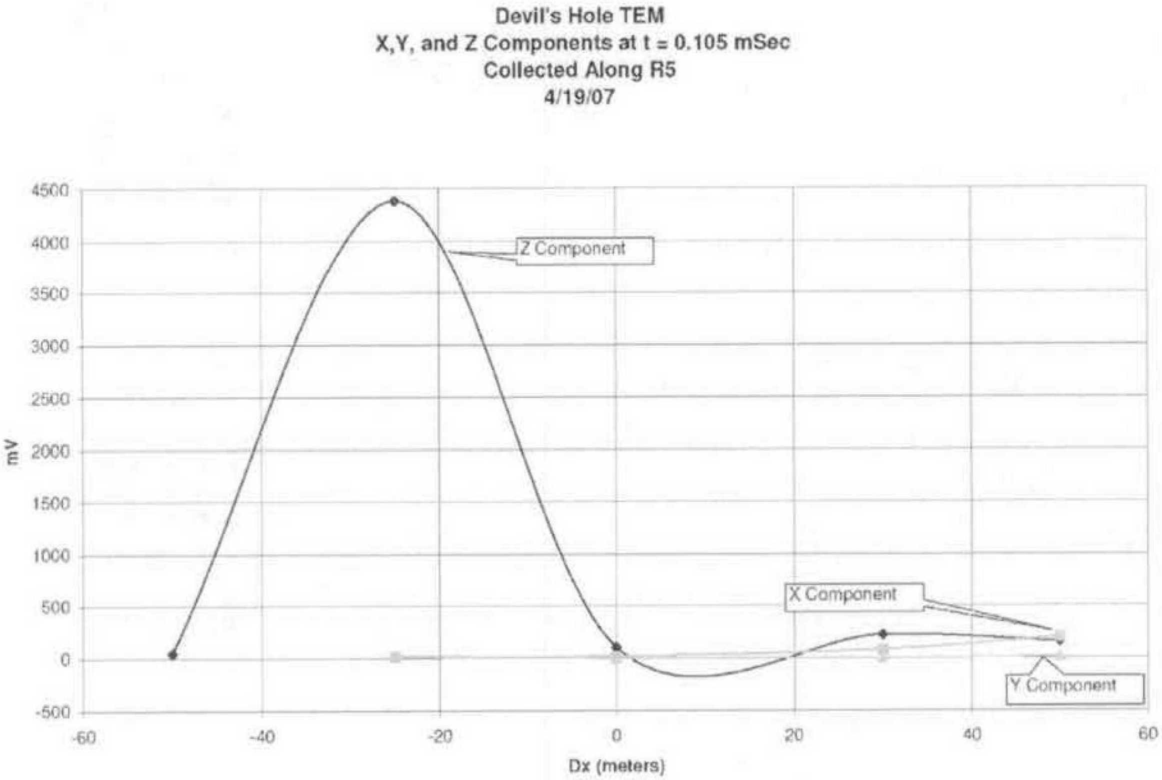


Figure 18. Graphical Analysis of Three-Component TEM Data Along Resistivity Line R5.

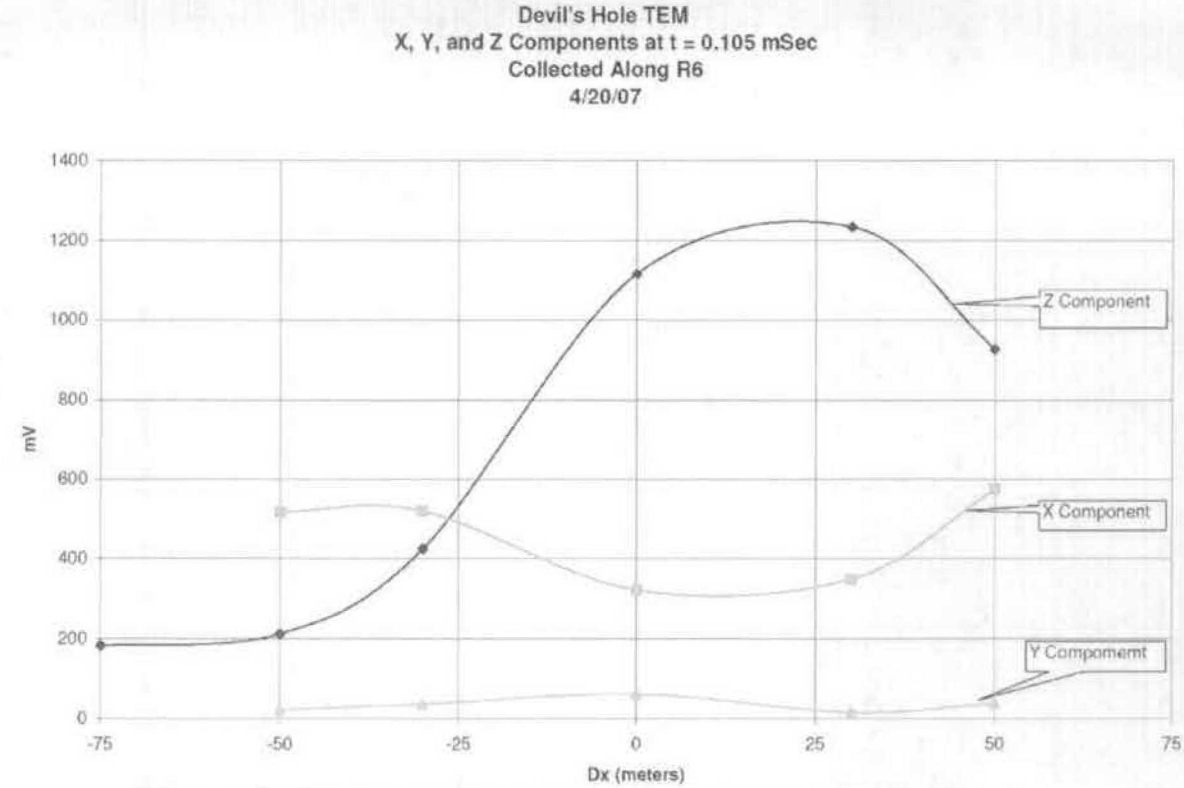


Figure 19. Graphical Analysis of Three Component TEM Data Along Resistivity Line R6.

The latitude, longitude, and elevation at each gravity station were surveyed prior to obtaining a gravity measurement. A surveyor using a Trimble total station global positioning system (gps) instrument surveyed each of the gravity stations. The fieldwork was conducted from April 16 through April 19, 2007. The Gravity survey data processing for the Devil's Hole area was consistent with the methods employed to process the previous gravity data.

The gravity data, corrections, and modeled gravity profiles are located in Appendix C. In general the anomalies detected by the gravity survey were on the order of tenths to hundredths of a milligal (mgal) and were well within the sensitivity range of the G-400. The sensitivity of the data to small features depended on whether the gravity survey was conducted directly on bedrock or if it was on the fill overlying the bedrock. Where the rock was close to the surface small scale individual voids could be detected. Where the rock was deeper below the surface only larger features could be detected such as zones of weathered bedrock or larger karst features. Lines ASH5 and ASH6 were conducted directly over the bedrock and individual voids were identified. Gravity line ASH8 was the only survey conducted at this time that was conducted directly on the rock surface. The gravity profile indicated a lower density feature that corresponds to Brown's Room on the east end of the line. There is also a narrow lower density area that could correspond to a narrow fracture feature that trend from Devil's Hole up to Devil's Hole 2.

Gravity lines ASH7 and ASH 10 were conducted on the fill and it is much harder to identify individual voids. The gravity profiles for these lines show competent bedrock and a weathered bedrock surface with more deeply incised weathered karst zones. The gravity profile Line ASH7 corresponds to the bedrock surface detected by Resistivity Line R3. The unconsolidated material over bedrock is thickest at this line and as a result the sensitivity to features in the bedrock appears to be the lowest. A wedge of weathered rock of between 20 to 50 feet thick on top of the higher density bedrock is necessary to match the gravity data and the resistivity data. Line ASH10 also has significant layer of unconsolidated material above rock. The gravity profile for Line ASH10 indicates that there is weathered bedrock over competent bedrock and a deeper low-density feature that is interpreted to be a karst feature.

Line ASH9 was conducted directly on the rock with fill on the east end of the line. The data is noisy to the west end with three points that appear to be bad data. A lower density weathered zone of variable thickness is needed to match the gravity and resistivity data at this line. The gravity profile shows a deep lower density feature that corresponds to the outcrop of rock dipping into the valley. This feature aligns with the inferred karst feature detected by the resistivity data on line R6.

Line ASH8 was also conducted primarily on bedrock. A layer of lower density weathered rock is needed to match the gravity and resistivity data at this line. A shorter wavelength gravity anomaly was modeled near the center of the line and a wider feature was modeled on the eastern end of the line. These features were modeled with density values of 1 to represent water filled voids. The void on the eastern edge of the line corresponds to Brown's Room, which is a void with an air filled chamber above a water filled fracture.

5.8 Summary of Geophysical Survey Results

The results of the geophysical survey provided useful information to support the regional hydrogeological investigations. The MT survey detected a conductor at depth in the Red Amphitheatre area that may indicate the depth to water. The resistivity work around Devil's Hole found several electrically conductive anomalies in the carbonate bedrock that appear to represent fracture zones or karstified zones. The pattern of the anomalies suggests the presence of a karst zone or complex fracture network following the trend of fracture zone that Devil's Hole lies within. The three-component TEM survey appears to have detected conductive anomalies near the location of two of the resistivity anomalies. The gravity survey indicates that there are areas of weather bedrock interpreted to represent karstified zones and apparent voids in the bedrock parallel to the Devil's Hole fracture system.

The results of the individual geophysical methods are summarized as follows:

<u>MT</u>

- Generally, the MT data quality was good. In the Red Amphitheater area of the southern Funeral Mountains, the MT 1d analysis produced a good fit with the field data for a two-layer system for the MT soundings to the east of the fault. The models generally consisted of a high resistivity layer (greater than 1,000

Ohmm over a conductive layer. Most soundings required masking of noisy data points to produce soundings with smooth, interpretable curves. The 2d analysis produced a consistent geoelectrical section that achieved approximately 1,600 feet (500 meters) of penetration on the west half of the line (soundings MT1 and MT2), and approximately 3,300 feet (1,000 meters) of penetration on the east half of the line soundings MT3 through MT6).

- The high conductivity basin fill material limited the depth of investigation of the MT survey in the Amargosa Valley area along Imvite Road. The gravity fault was not detected due to the limited penetration of the survey.

Resistivity

- With the exception of the data collected along line R1, the resistivity data was predominantly good and provided the source for clean modeling results.

- The modeled resistivity data indicates the presence of numerous anomalies in the bedrock surface that may represent fractured, faulted, or karstic carbonate rock.

- The pattern of the anomalies suggests the presence of a karst zone or complex fracture network following the trend of fracture zone that contains Devil's Hole.

Three Component TEM

- Review of the data indicates the presence of a large anomaly in the Z component on both R5 and R6. On line R5, the anomaly is located on the western half of the line, centered 25 meters west of center. This anomaly appears to correlate with an anomaly in the resistivity data on line R5, near the location of Brown's Room. On line R6, the anomaly is located between 30 meters east of the center of the line. This anomaly appears to correspond with the low resistivity anomaly on R6 at approximately 325 feet from the west end of the line.

Gravity

- Review of the gravity data for the two tie lines across the Amargosa Valley indicates that the bedrock surface has highs and lows that correspond to the State Line and Gravity Fault. This is generally consistent with the gravity inversion done by the USGS using regional data (Blakely, 1998).
- Review of the gravity data in the Devil's Hole area indicates that when the survey was conducted directly on the rock surface individual voids could be modeled based on the anomalies. When the surveys were conducted on fill overlying the bedrock it was not possible to identify individual voids, but the larger fracture and karst features were represented by lower density and modeled as weather bedrock.

Review of the data from Gravity Line ASH8 indicates a large void that corresponds to Brown's Room.

6.0 Analysis of Geochemical Data

Springs have proven useful in the characterization of flow systems because they are integrated samples of a ground-water flow system reflected in a single point of discharge. The geochemical composition and physical characteristics of spring waters can be representative of an entire ground water flow system, and therefore very conducive to regional ground water studies. The geochemical composition of springs can provides clues to the source, travel path, mixing of waters, and other processes within the ground water system.

Our evaluation of the geochemical composition of the springs of DVNP and the Yucca Mountain study area first established the chemical composition of the spring waters, which is provided in this section of the report. Secondly, we compared the regional geochemical composition, concentrations of isotopes, and the regional geological conditions to evaluate the source of the spring waters relative to the Lower Carbonate Aquifers below Yucca Mountain.

A comprehensive Death Valley National Park geochemical database was compiled from the two sources of 1) Inyo County geochemical data, and 2) U.S. Department of Energy comprehensive geochemical database. The database was evaluated by first plotting chemical sampling data point locations to identify the source of the water sample. Each water sample point geochemical data set was then entered into spreadsheet for analysis. The data sources were groups by geographic region primarily by mountain block or basin area. The data was then plotted for each grouping on a Piper type diagram. In additional, stable isotopes of deuterium and oxygen-18, uranium isotopes of $^{234}U/^{238}U$, and strontium isotope ^{87}Sr. The stable isotope data was only evaluated from spring samples collected in Hydrodynamic's 1998 study (Bredehoeft, et. al, 1998 available at www.hydrodynamics-group.com). The locations of geochemical data sources are shown on Figure 20. Our comprehensive Death Valley geochemical database is provided in Appendix E.

6.1 Chemical Composition of Springs (Piper Analysis)

Piper diagrams are an acceptable method to portray the chemical composition of spring waters. A trilinear "Piper" diagram (Piper, 1953) is a technique for displaying water chemistry data. The method graphically shows the relative concentrations of major cations (Ca^{+2}, Mg^{+2}, and K^{+}) and anions (CO_3^-, HCO_3^-, and SO_4^-). Spring water of similar compositions will plot at or near the same position on a Piper diagram; this suggests a common source.

Hydrodynamics performed a Piper analysis of 28 water samples from Death Valley National Park in 1998 to determine if relationship exist for water samples from springs within the same mountain block or basin area (Bredehoeft, et. al, 1998). Additional water samples collected by Hydrodynamics in the Park and data from the DOE data set were combined with the 1998 to perform a new Piper analysis of major mountain block and basin areas. The results of our 1998 and current analysis are provided in Figures 21 to 29.

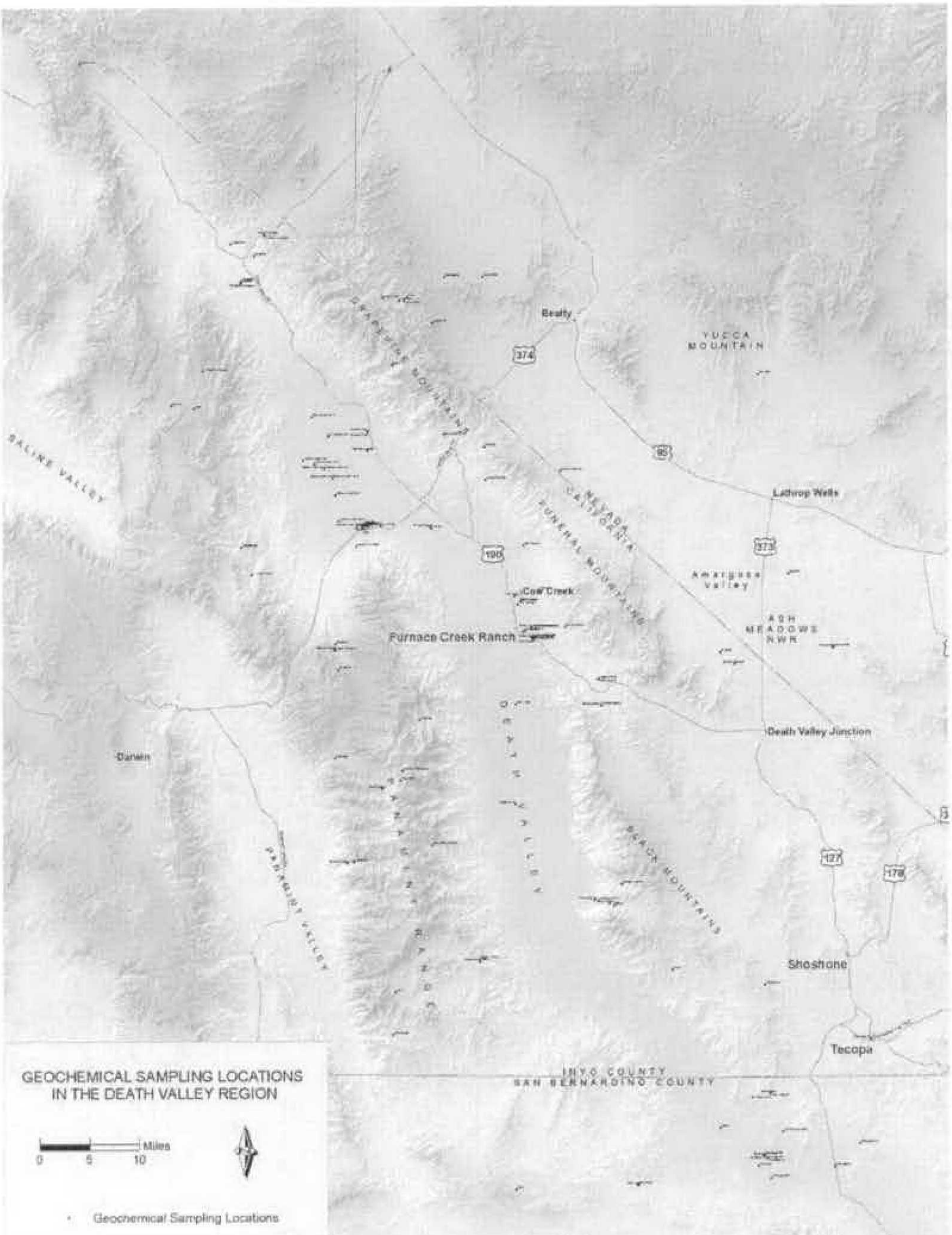


Figure 20. Location of Death Valley Regional Geochemical Data Collection Point.

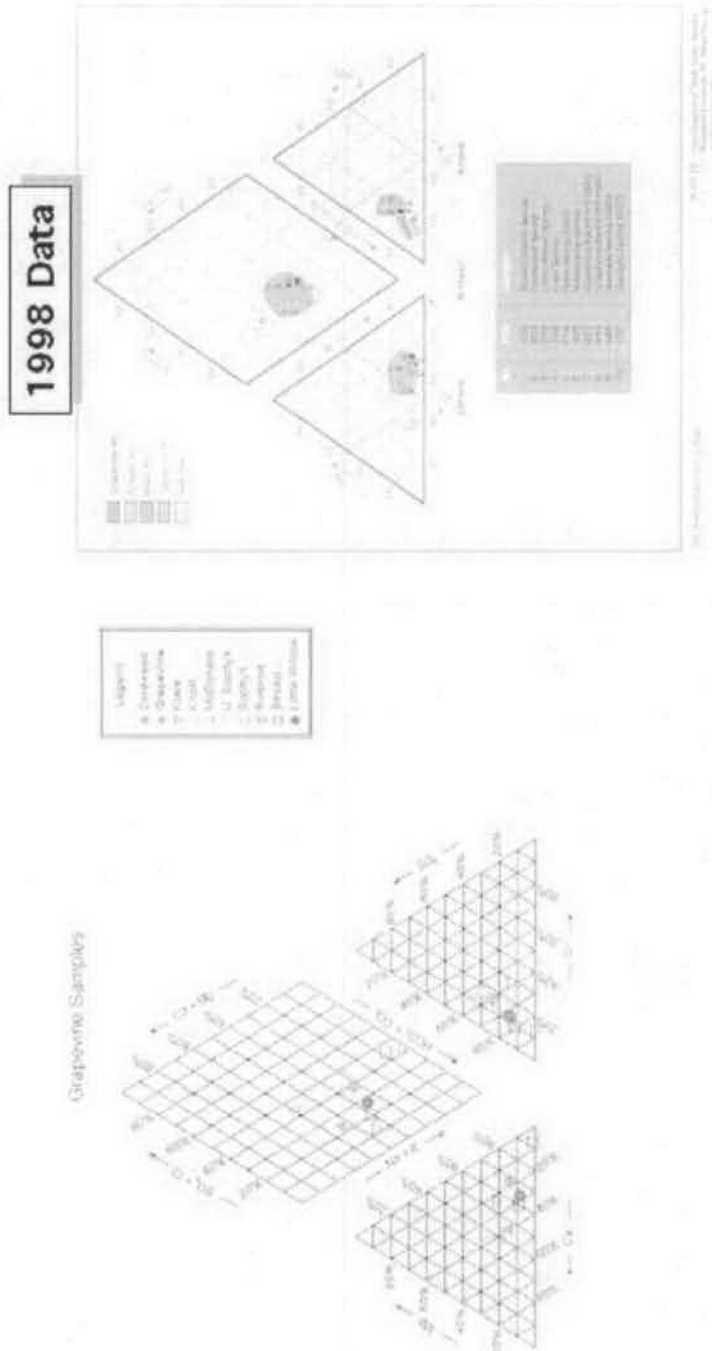


Figure 21. Piper Analysis of Grapevine Mountain Range Samples.

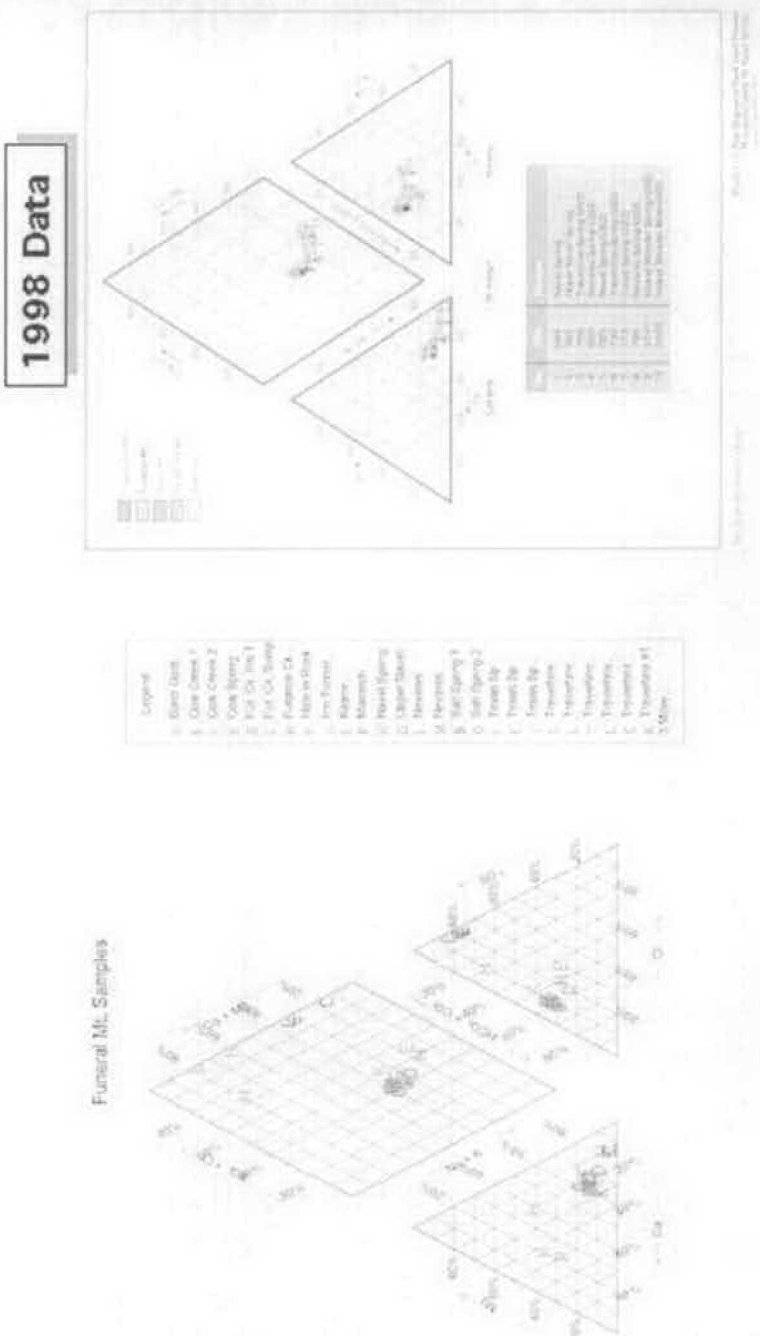


Figure 22. Piper Diagram of Funeral Mountain Range Samples.

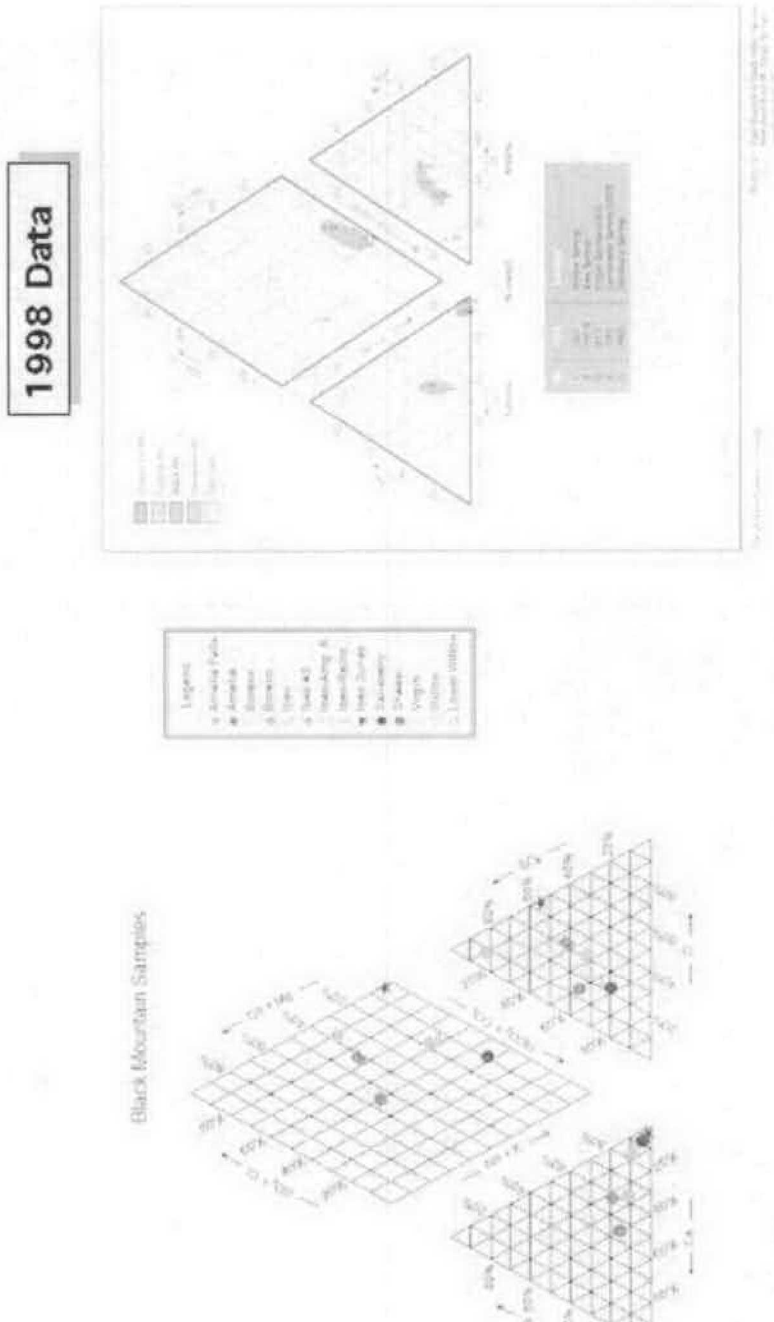


Figure 23. Piper Diagram of Black Mountain Range Samples.

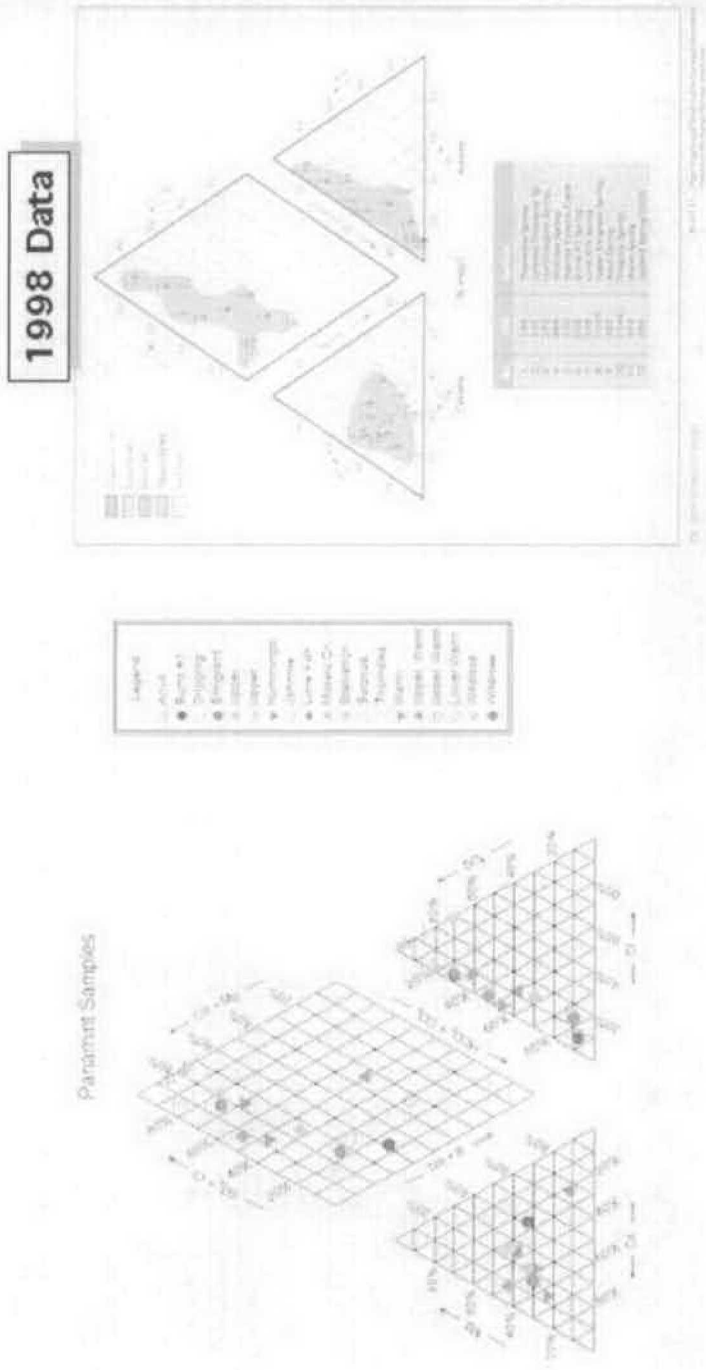


Figure 24. Piper Diagram of Panamint Mountain Range Samples.

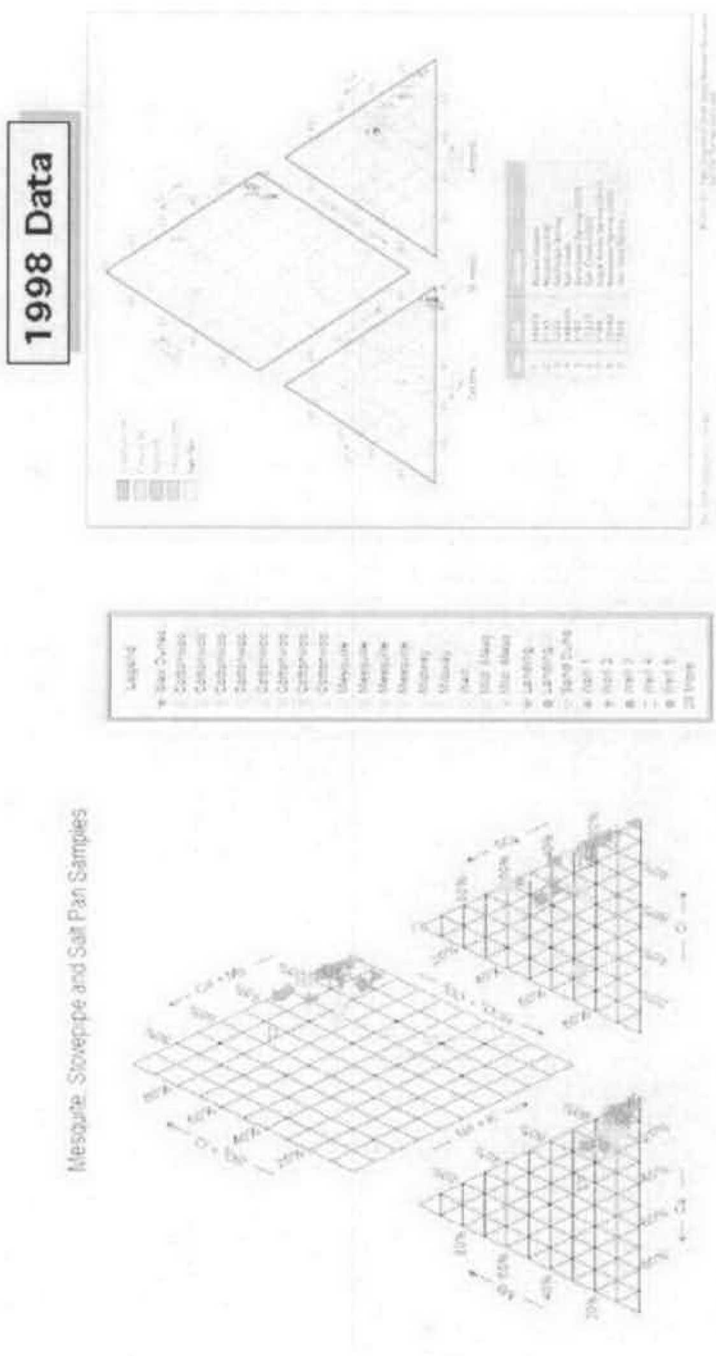


Figure 25. Piper Diagram of Mesquite, Stovepipe Wells and Salt Pan Samples.

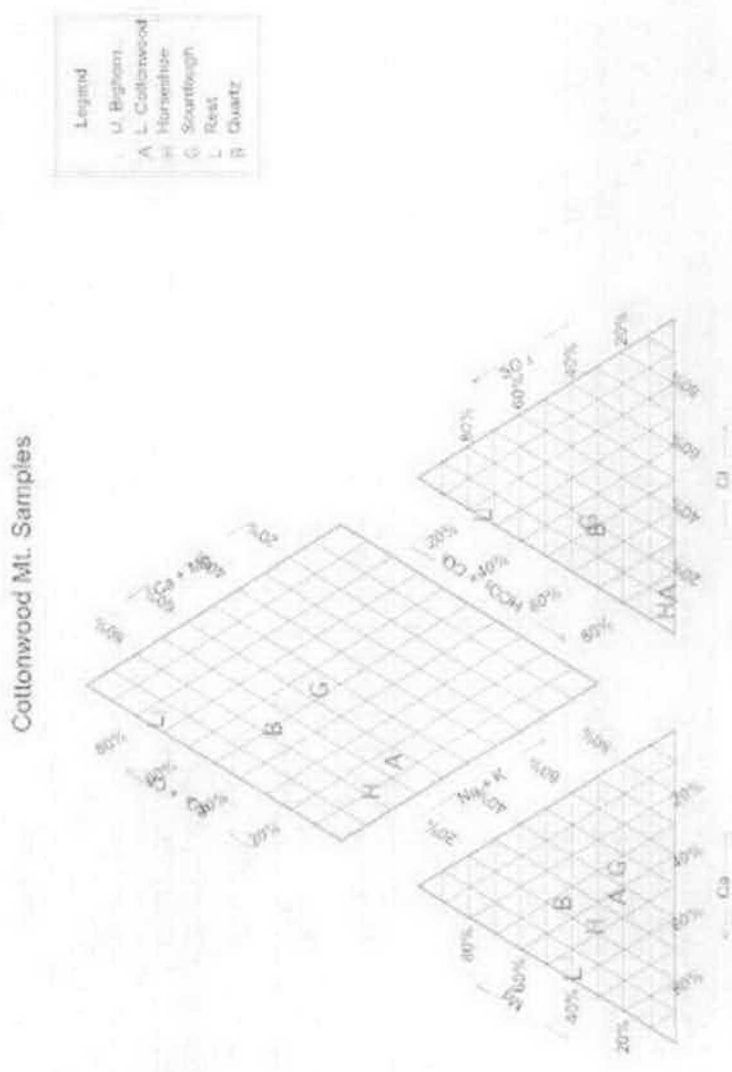


Figure 26. Piper Diagram of Cottonwood Mountain Range Samples

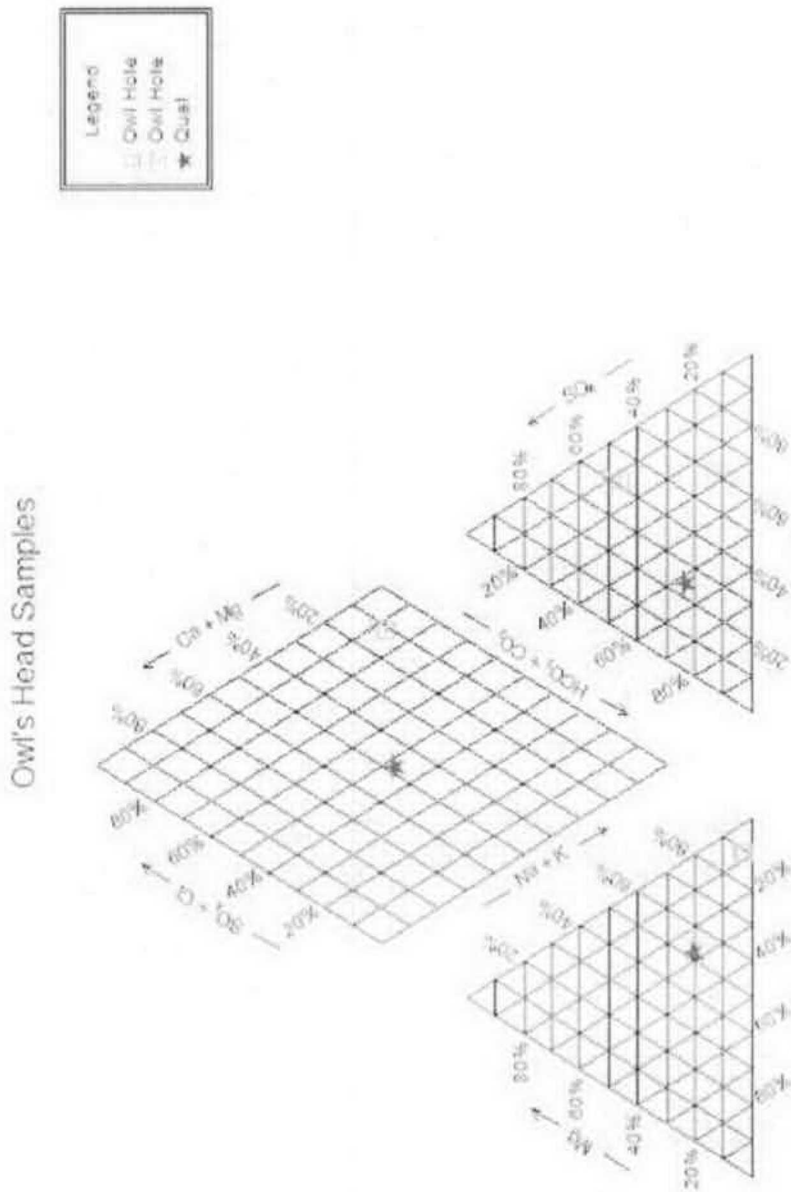


Figure 27. Piper Diagram Owl's Head Mountain Range Samples.

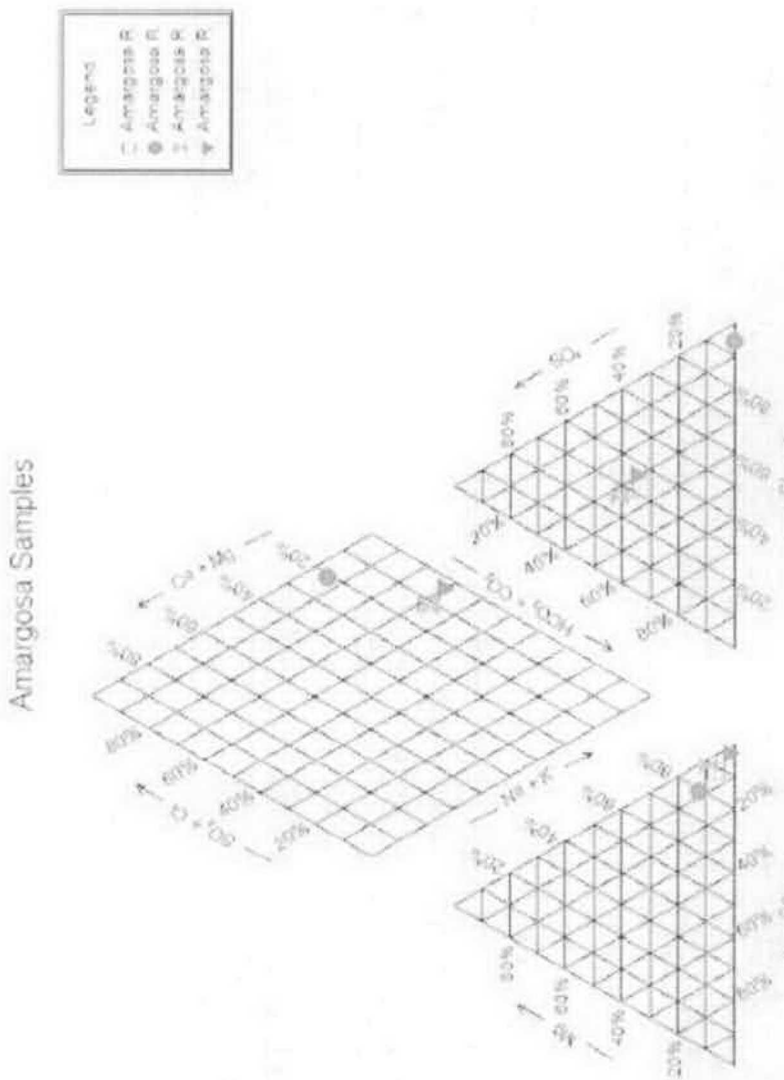


Figure 28. Piper Diagram of Amargosa River Samples.

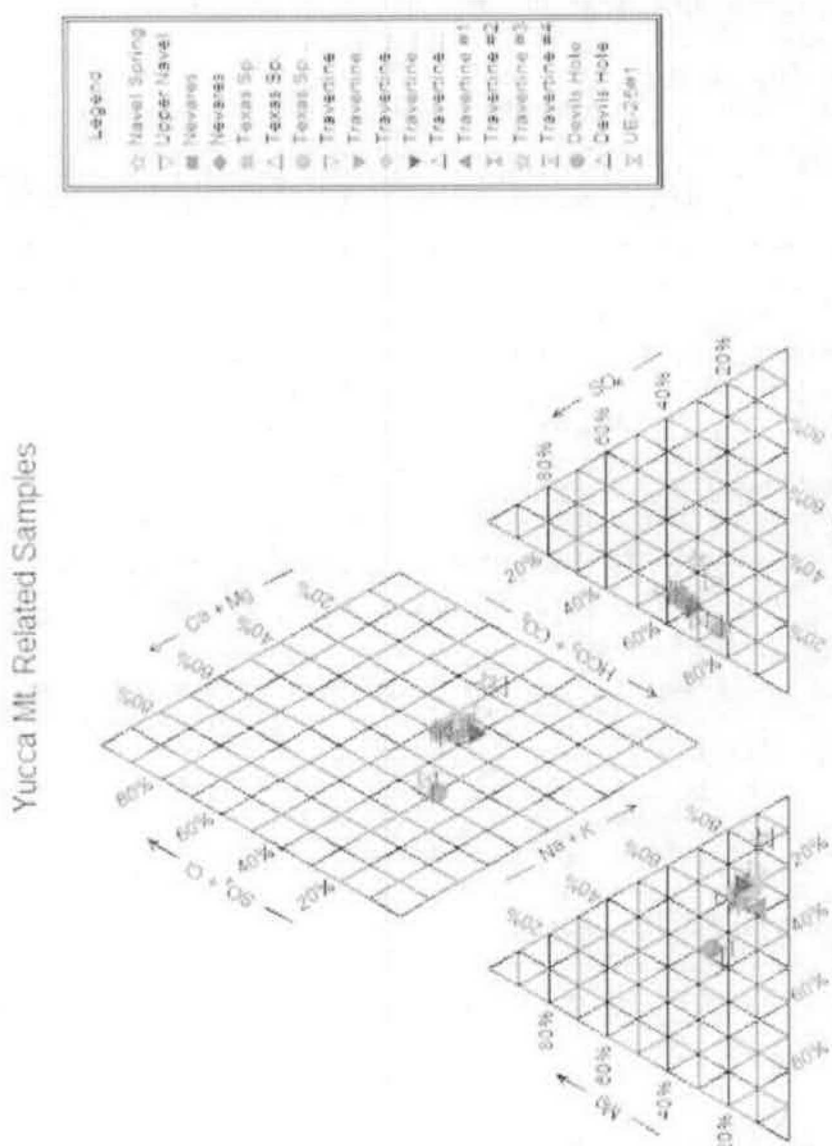


Figure 29. Piper Diagram of Lower Carbonate Aquifer Samples.

The Piper diagrams of the DVNP springs, in general, indicate a very close match of chemical compositions for springs within a give mountain block with the exception of water samples from highly mineralized mining sites. A description of the chemical composition of spring waters by mountain block is provided below.

Grapevine Springs Piper

The Piper diagram plot of the Grapevine springs indicates that all but two of the springs are located near the top of the recharge system (Plate 21). The very high HCO_3^- concentrations and very low concentrations of Na^+, Cl^-, SO_4^-, and Mg^{+2} indicate a very young ground water source. The springs sampled are at higher elevations near the winter snowfields, and are discharging from rhyolitic bedrock. Discharge rates ranged from a trace to over 20 gpm, and springs are located near intermittent creeks. The Stainger and Daylight springs differ from the other Grapevine springs in that they are localized intermittent seeps that pond water at the surface where it evaporates. Daylight spring was dry during our visit in May of 1998.

Funeral Mountain Springs Piper

The Piper diagrams of the Funeral Mountain springs have very similar chemical compositions (Plate 22). These spring waters have high concentrations of Na^+, K^+, and Mg^{+2}, and intermediate concentrations of HCO_3^-, SO_4^- and Cl^-. This indicates water discharging from these springs has followed long travel paths. The source rock for these springs is carbonate. These springs are known for their association with travertine deposits at the spring orifices. The significance of these springs will be discussed in Section 6.0 and 7.0 of this report.

Black Mountain Springs Piper

The Black Mountain springs can be described as a mixed bag of sources, based on the wide range of chemical compositions on the Piper diagrams (Plate 23). The Ibex, Lemonade and Salisburg springs have similar chemical compositions, but are not geographically near each other. The high concentration of NaCl and moderate concentration of HCO_3^- in these three spring waters indicates a small-localized ground water flow path. Water discharging from these three springs was observed to pond, and eventually evaporates. The Willow spring is unique in that it plots near the center of the piper diagram (Plate 23). Willow spring is the discharge point for Gold Valley. Gold Valley is a higher altitude colluvial filled valley. The valley is composed of a wide range of metamorphic and igneous rocks. The chemical composition and location of Willow spring in Gold Valley suggest the source of water is discharge from the colluvial materials and basement rock.

Panamint Mountain Springs Piper

The Piper diagram for the Panamint Mountain range springs reflect a range of composition that are indicative of their source rocks (Plate 24). The chemical composition of these springs shows very high concentrations of Ca^{+2}, and very low concentrations of NaCl and Mg^{+2}. The wide ranges of HCO_3^- and SO_4^- are indicators of the maturity of the water. A mature water will have a higher concentration of SO_4^- and a lower concentration of HCO_3^-. The opposite is true for intermediate-mature water. The more mature waters are from springs discharging from carbonate rocks, like Dripping spring. The C^{14} determined age of Dripping spring is about 7,000 years. The relatively higher concentrations of $CaSO_4$ in this water indicate a source of gypsum and/or other hydrothermally deposited minerals. There are a number of higher altitude small mining operations, near the Lime Kiln spring that are associated with hydrothermal deposits.

Mesquite, Stovepipe Wells and Salt Plan Springs Piper

The Piper diagrams for the Death Valley Salt Pan springs are totally dominated by evaporation processes, with concentrations of NaCl exceeding that of seawater in some springs (Plate 25). These waters have essentially no concentrations of Ca^{+2}, Mg^{+2}, and HCO_3^-. The concentrations of SO_4^- are low to moderate suggesting these waters had sulfates in them prior to evaporation. The composition of the Eagle Borax Spring is similar to Panamint Mountain springs, which suggest this is a fault controlled spring source.

Cottonwood Mountain Springs Piper

Six water samples were collected from the Cottonwood Mountain Range in the past five years (Figure 26). The Piper analysis of these samples is consistent with the range of chemical constituents in Panamint Mountain springs. Geologically the Cottonwood Mountain range is an extension of the Panamint Mountain range to the north. They are of similar rock type and reflect the very high concentrations of Ca^{+2}, and very low concentrations of NaCl and Mg^{+2} as well as a higher concentration of SO_4^- and a lower concentration of HCO_3^-.

Owl's Head Mountain Springs Piper

Only three flowing springs were identified in the Owl's Head Mountain area southern portion of the Panamint Mountain Range (Figure 27). All three springs are closely associated with small mining operations. The chemistry of the three Owl's Head Mountain springs is not closely related.

Amargosa River Piper

Three of the four Amargosa River water samples show similar water chemistry (Figure 28) with one sample showing a higher concentration of evaporative salts. The chemistry of the Amargosa River is not closely related to the chemistry of adjacent mountain blocks.

LCA Sample Piper

Major ion and cation data from UE25p1, Devil's Hole, and the major Funeral Mountain springs were plotted on a Piper diagram (Figure 29). The graph shows the chemistry of

UE25p1 and Devil's Hole are nearly identical, and are closely associated with the major Funeral Mountain spring sources.

Winograd and Thordarson (1975) used the major ion chemistry of the ground water in the lower carbonate aquifer to suggest the source of recharge. For the carbonate springs in Death Valley they suggested three potential recharge areas: 1) the Nevada Test Site area, 2) the Amargosa Desert, and 3) the area to the east in the Spring Mountains that supplies much of the Ash Meadow springs.

Winograd and Thordarson (1975) based their interpretation on the major ion chemistry of waters from these areas. The major ion constituent chemistry of water from well 16/48-17a1 in basin-fill alluvium, on the west side of the Amargosa Desert, is very similar to water from Navares, Texas, and Travertine springs in the Furnace Creek. The major ion chemistry of water from the Ash Meadows regional springs, that also discharge from the lower carbonate aquifer, are similar; however the Ash Meadow water has less Na+K and Cl+SO4. The chemistry of the Pahrump Valley—Spring Mountain waters are significantly different; they have almost no Na+K and Cl+SO4.

Our simple Piper analysis support conclusions from Winograd and Thordarson (1975) that the major ion constituent chemistry of water from well 16/48-17a1 in basin-fill alluvium, on the west side of the Amargosa Desert, is very similar to water from Navares, Texas, and Travertine springs in the Furnace Creek.

6.2 Stable Isotopes of Deuterium and Oxygen-18

Craig (1961) defined a relationship between deuterium and oxygen-18 that he defined as the ***meteoric water line (MWL).*** Craig suggested that precipitation from all over the world should fall along the MWL. It is this hypothesis of Craig's that forms the basis for much of the use of deuterium and oxygen-18 as tracers in water. Plate 30, adapted from Thomas et al. (1996), shows the relationship between deuterium and oxygen-18 for ground water from our area of interest. The Modern Water Line (MWL) is shown as a guide to average composition trends (Craig, 1961). Frequently, waters of the Great Basin plot slightly to the right of the MWL. This is because of evaporation during liquid precipitation in the generally dry atmosphere.

The stable isotopes of deuterium and oxygen-18 are useful in the interpretation of a spring source; these isotopes provide a signature of the recharge source, a means to evaluate the evaporation history of the water, and a means to evaluate certain rock-water reactions. The analysis of these isotopes can allow a constrained interpretation of ground water flow path. The isotope data is especially useful (when combined with other parameters), such as general water chemistry, type of spring source rock, and discharge rates.

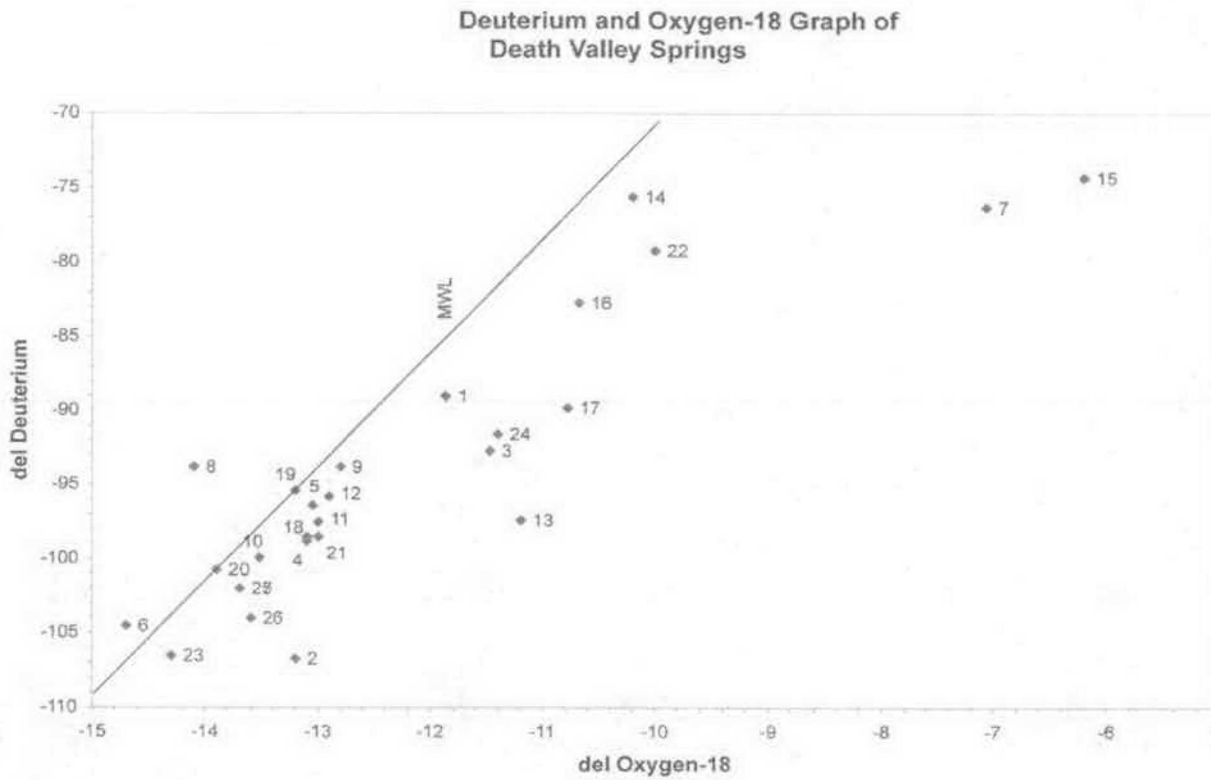


Figure 30. Deuterium and Oxygen-18 Graph of Death Valley Springs.

Figure 30 (Continued). Key to Data Points

No.	Sample Name	d18O, ‰	d2H, ‰
1	Anvil Spg 980708	-11.9	-89.0
2	Buried Wagon Spg -042398	-13.2	-106.7
3	Burns#1 Spg 061698	-11.5	-92.7
4	Cordwood Spg 052798	-13.1	-98.8
5	Dripping Spg 980709	-13.0	-96.4
6	Hummingbird Spg 050198	-14.7	-104.5
7	Ibex Spg 061898	-7.1	-76.3
8	Johnnie Shoshone Spg 050198	-14.1	-93.8
9	Knoll Spg 052798	-12.8	-93.8
10	Lime Kiln Spg. 061698	-13.5	-99.9
11	Little Willow Spg 052798	-13.0	-97.5
12	McDonald Spg 061698	-12.9	-95.8
13	McLean Spg 042398	-11.2	-97.4
14	Navel Spg 042398	-10.2	-75.6
15	Owl Hole Spg 980706	-6.2	-74.3
16	Salisbury Spg 061798	-10.7	-82.7
18	Saratoga Spg 061898	-10.8	-89.8
19	Strozzi Ranch Spg 050298	-13.1	-98.5
20	Surprise CynCrk Spg 052998	-13.2	-95.4
21	Thorndike Spg 050198	-13.9	-100.7
22	Upper Emigrant Spg 980707	-13.0	-98.5
23	Upper Navel Seep 042398	-10.0	-79.2
24	Wildrose Spg 052998	-14.3	-106.5
25	Willow Spg 043098	-11.4	-91.6
26	Texas Spring	-13.7	-102.0
27	Nevares	-13.6	-104.0
28	Travertine	-13.7	-102.0

6.2.1 Deuterium and Oxygen-18 for Death Valley Samples

A considerable portion of the precipitation in the higher mountains is snow. Water samples from this water source plot on or just above the MWL, which is evident in the deuterium and oxygen-18 values for the Grapevine and some of the Panamint springs. For example, Johnnie Shoshone spring, a higher altitude spring in the Panamint Mountain range, plots to the left of the MWL. The spring has a relatively small catchment area, with recharge from a large number of winter snowstorm events. The higher altitude Panamint Mountain range's Hummingbird and Thorndike springs plot nearly on the MWL. The Wildrose spring differs from this pattern by plotting to the right of the MWL. Wildrose spring is located in the same drainage basin as these three springs, but at a lower elevation (approximately 1,250 m (4,101 feet) elevation). Discharge from Wildrose spring appears to be from a much larger drainage area. The Lime Kiln, and Upper Emigrant springs also represent discharge from relatively large drainage basins in the Panamint Mountain ranges, and plot just right of the MWL.

A number of moderate elevation springs 1,000 to 3,000 m (3,281 to 9,843 feet) in elevation show a strong shift to the right of the MWL; this reflects the influence of evaporation. Ibex and Salsberry springs in the Black Mountain range have small spring catchments that experience evaporation. The Navel Springs in the Funeral Mountain range also shows an evaporation effect, and influence from localized recharge. The Navel springs have a significantly heavier isotopic signature than the Texas, Travertine, and Nevares springs in the Funeral Mountain range. The Texas, Travertine, and Navares springs plot very close to the MWL. It is believed Texas, Travertine, and Nevares springs represent an older interbasin carbonate rock flow system. These springs also reflect more pluvial Pleistocene climate age waters, thus the lower isotopic values.

The Salt Pan springs show the greatest shift to the right from the MWL. All of the Salt Pan springs (McLean, Buried Wagon, Saratoga, Owls Hole, and Salt Creek) have gross water chemistries indicating dissolution of evaporates, primarily halite (NaCl) and some sodium sulfate minerals.

6.2.2 Interpretation of Deuterium and Oxygen-18 Data

The data from southern Nevada and southwestern California are shifted slightly to the right from Craig's (1961) global MWL. Water that has undergone evaporation becomes heavier in oxygen-18 with respect to deuterium because of fractionation caused by evaporation. This suggests that water that plots to the right of the MWL has undergone evaporation; the further the data plots further to the right of the MWL, the more evaporation is indicated.

Precipitation in the arid region that occurs in liquid form evaporates slightly during fall through the atmosphere. This explains the shift to the right in the majority of the data from this area of southern Nevada and southwestern California. Precipitation that occurs as snow or ice does not evaporate and fractionate; we expect these waters to plot closer to the MWL. Water that is strongly shifted to the right of the MWL indicates that these waters have undergone significant evaporation.

Both deuterium and oxygen-18 in precipitation are influenced by a number of factors related to moisture sources, to storm path histories, and air temperature. Deuterium and oxygen-18 concentrations in ground water in recharge areas, as represented by small-local springs and shallow wells in mountainous areas, are an integrated sample of summer and winter precipitation. Geography, especially altitude of the recharge area, is important in determining the deuterium and oxygen-18 content of recharging ground water. A further complication that may enter into interpretations is the age of the ground water.

A large, and independently derived body of evidence indicates cooler to significantly colder pluvial climates existed in the region in the not too distant past. The cooler climate should have produced precipitation that is lighter in deuterium and oxygen-18 than water recharged during the current, and warmer, interglacial climate of the region. There are two conditions for the recharge in the large regional flow systems:

1. all the recharge in these large systems is younger than the last major pluvial climate in the region—approximately 12,000 years ago, or
2. some of the water is older than 12,000 years and is pluvial.

If some of the water is older than 12,000 years, the interpretation of recharge areas based upon the deuterium/oxygen-18 isotopic composition is more complex.
Thomas et al. (1996) concluded that deuterium in water, from a set of samples from recharge areas in the Spring Mountains and the Sheep Range, did not show a trend towards lighter values with greater apparent age. He inferred the age of the water from the carbon-14 content of the water (the percent modern carbon); his ages are only relative. All the water analyzed by Thomas et al. appears to be associated with the modern MWL.

Mifflin reviewed for this study the currently available deuterium data within the region that we and other researchers collected—displayed in Plate 30, (Thomas et al., 1996). Mifflin suggested, based upon his review of the data for the region, that some of the water in the deeper parts of the flow system appears to be lighter in deuterium. Mifflin commented that the water used by Thomas et al. (1996) in their analysis is from the mountain ranges in areas where one would expect the water to be younger than 12,000 years.

Mifflin went on to suggest that deuterium is generally lighter (higher values) in the known regional carbonate springs than in the potential recharge areas as outlined by Thomas et al. (1996). Values from the basins many be more negative than -100 units (more negative values are lighter). Mifflin argues that the general relationship of light deuterium values in the basins with heavier values in the mountains indicates that we are dealing with of two different ages of water—an old, lighter water, and a more recent heavier water. Undoubtedly, any shift in the MWL occurs gradually as climate changes, and there is a continuum from light to heavier—it is not purely bimodal.

These interpretations assume that the precision of the deuterium determinations is within 1 or 2 tritium units. Tritium is hard to analyze; such precision is hard to achieve, especially when more than one laboratory does the analyses. Therefore, springs sampled for this study were not analyzed for tritium.

Regardless of the problems that attend interpretation of stable isotopic data, once the water is in the confined portions of regional carbonate aquifer flow systems the isotopic composition of the water remains unchanged, especially deuterium. The isotopic composition remains constant over considerable distances and time. The composition changes as waters from differing sources mix.

6.3 Uranium $^{234}U/^{238}U$ Isotopes

The uranium content in groundwater and ratio between the uranium isotopes of $^{234}U/^{238}U$ may provide insight into the source of the water (Ludwig et., al., 1993). Paces, et al. (1998) states:

Uranium-234 is an intermediate decay product of ^{238}U, which, if undisturbed, reaches a state of secular equilibrium, activity (decays per unit time) of the daughter is equal to that of the parent such that the $^{234}U/^{238}U$ activity ratio = 1.0 in solid materials older than several million years. In contrast, oxygenated ground waters in southern Nevada have $^{234}U/^{238}U$ ratios that are nearly always greater than those in surface runoff ($^{234}U/^{238}U$ activity ratios commonly between 1.5 and 2.0; J.B. Paces et al., USGS, written comm., 1996) or soil-zone materials (initial $^{234}U/^{238}U$ ratios of 1.3 to 2.0). Therefore, elevated $^{234}U/^{238}U$ signatures are obtained by incorporating ^{234}U preferentially to ^{238}U along flow paths due to processes related to the effects of radioactive decay in the adjacent wall rock. The dominant mechanisms are preferentially leaching of ^{234}U from radiation-damaged lattice sites (Szilard-Chalmers effect), radiation-induced oxidation of ^{234}U leading to a more soluble uranyl ion, and alpha-recoil of ^{234}Th off of crystal surfaces. The amount of ^{234}U excess relative to ^{238}U is limited by rates of ^{234}U decay, water rock ratios, flow-path length, and the amount of bulk-rock dissolution from the aquifer. These factors typically result in $^{234}U/^{238}U$ activity ratios between about 2 and 4 in most southern Nevada ground water.

DVNP springs are relatively rich in uranium. Two potential sources of uranium are hydrothermal mineralization, (Panamint mountain range springs) and uranium concentrated by evaporation (Salt Pan springs).

The springs with the highest concentration of uranium are the salt pans springs of Buried Wagon, McLean, Salt Creek, Owls Hole, and Saratoga, which range between 16.22 and 25.22 parts per billion (ppb) uranium (Table 5). These springs have $^{234}U/^{238}U$ activity ratios that range between 1.25 and 1.73. The concentration of uranium in the Panamint springs of Johnnie Shoshone, Upper Emigrant, and Anvil range between 8.502 to 21.244 ppb. These springs have $^{234}U/^{238}U$ activity ratios that range between 1.25 and 2.83.

Paces, et., al. (1998) plotted uranium concentrations versus $^{234}U/^{238}U$ activity ratios for well and spring waters in the DVDB (Plate 31). Plate 31 also includes a plot of uranium concentrations versus $^{234}U/^{238}U$ activity ratios for Death Valley spring. Paces, et., al. (1998) states: *that ground water associated with carbonate, alluvial, and Precambrian-rock aquifers from Oasis Valley, Amargosa Valley, Spring Mountains and easternmost NTS (Nevada Test Site) have $^{234}U/^{238}U$ activity ratios of about 1.5 to 4.* Paces, et., al. (1998) further indicates waters from volcanic-rock aquifers beneath Yucca Mountain and western Yucca Flat commonly have values greater than 4, with anomalously high values of over 7 in shallow (saturated zone) wells. The $^{234}U/^{238}U$ activity ratio for Lower Carbonate Aquifer waters from UE-25p1 was 2.32. Paces, et., al. (1998) further indicates waters with the most elevated $^{234}U/^{238}U$ activity ratios (about 6) appear to be restricted to uranium concentrations less than about 3 ppb. The uranium concentrations and

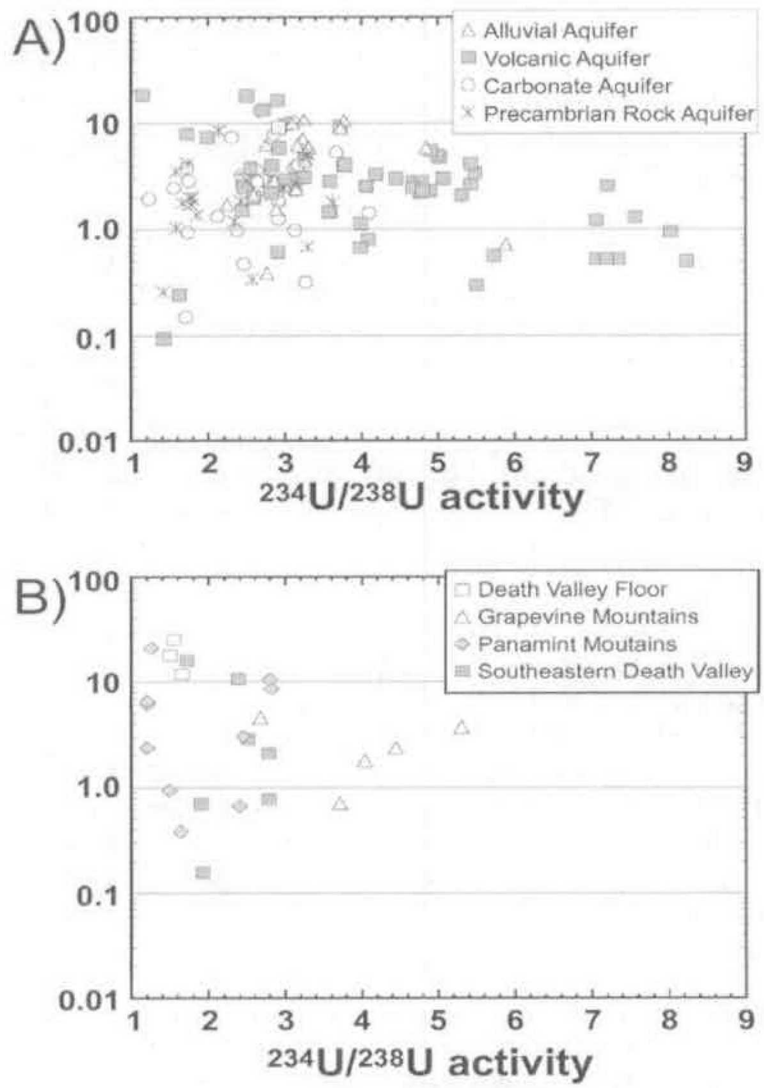
Table 5. Isotopic Composition of DVNM Sampled Springs and Creeks

No.	Sample Name	δ18O.	δ2H.	Conc. Sr. ppm	δ87Σρ	Conc. U (ppb)	Measured 234U/238U activity		Beta Analytical Data Age	C13/C12	UTM - X (m) Easting	UTM - Y (m) Northing
1	Anvil Spg 980708	-11.87	-89.0	0.1811	16.15	21.244	1.254	(0.007)	2,710+-40BP	(7.2/mil)	492357.0	3975186.0
2	Buried Wagon Spg -042398	-13.2	-106.7	23.9990	6.42	11.667	1.660	(0.022)			498166.5	4050816.3
3	Burns#1 Spg 061698	-11.47	-92.7	0.8944	4.50	3.061	2.441	(0.020)			483135.8	4027730.1
4	Cordwood Spg 052798	-13.10	-98.8	0.0236	2.09	2.377	4.439	(0.023)			493024.0	4087677.0
5	Dripping Spg 980709	-13.05	-96.4	1.0364	26.68	0.936	1.490	(0.010)	6,430+-40BP	(0.7/mil)	496409.5	4019395.5
6	Hummingbird Spg 050198	-14.70	-104.5	0.3010	28.00	0.380	1.626	(0.027)			490288.3	4008308.5
7	Ibex Spg 061898	-7.06	-76.3	0.7146	16.96	0.759	2.796	(0.021)	3,880+-50BP	(3.5/mil)	553254.0	3958614.0
8	Johnnie Shoshone Spg 05019	-14.10	-93.8	0.3365, 0.3291	21.50, 21.60	8.502	2.832	(0.017)			493610.9	4011201.6
9	Knoll Spg 052798	-12.8	-93.8	0.0232	1.17	0.718	3.702	(0.032)			494311.0	4088262.0
10	Lime Kiln Spg. 061698	-13.52	-99.9	0.4559	33.91	6.021	1.212	(0.006)			485700.0	3996422.0
11	Little Willow Spg 052798	-13.0	-97.5	0.0262	1.92	4.620	2.666	(0.014)			493841.0	4087646.0
12	McDonald Spg 061698	-12.90	-95.8	0.6199	-0.23	3.747	5.308	(0.028)			498441.0	4084069.0
13	McLean Spg 042398	-11, -11.2	-97.4	26.1898	6.52	25.222	1.546	(0.020)	1,540+-40BP	(6.9/mi)	498315.6	4050575.9
14	Navel Spg 042398	-10.0, -10.2	-75.6	0.5164	5.96	2.038	2.786	(0.018)			525503.0	4026081.3
15	Owl Hole Spg 980706	-6.20	-74.3	8.2533	6.03	10.412	2.384	(0.013)	104.8+-0.5% PMC	(11.0/mil)	531915.0	3943786.0
16	Salisbury Spg 061798	-10.68	-82.7	0.0428	1.62	0.152	1.931	(0.016)	103.5+-0.6% PMC	(15.9/mil)	552496.0	3976264.0
17	Salt Creek-980709	-0.3*	-51.8, -55.7*	3.6847	7.81	17.569	1.505	(0.046)			512139.0	4021930.0
18	Saratoga Spg 061698	-10.78	-89.8	3.0642	10.23	16.229	1.732	(0.009)			552284.0	3948472.0
19	Strozzi Ranch Spg 050298	-13.10	-98.5	0.0177	1.65	1.779	4.026	(0.029)			490402.6	4088049.6
20	Surprise CynCrk Spg 052998	-13.20	-95.4	0.4540	34.03	6.591	1.200	(0.007)			484500.0	3996239.0
21	Thorndike Spg 050198	-13.90	-100.7	0.1297	17.30	0.668	2.397	(0.028)			493285.3	4009722.9
22	Upper Emigrant Spg 980707	-13.0	-98.5	1.1121	17.36	10.396	2.806	(0.016)			482544.0	4030966.0
23	Upper Navel Seep 042398	-9.9, -10.0	-79.2	0.7697	5.85	2.807	2.519	(0.062)			525637.7	4026026.2
24	Wildrose Spg 052998	-14.30	-106.5	1.2358	10.64	2.405	1.207	(0.007)			482584.0	4013281.0
25	Willow Spg 043098	-11.40	-91.6	0.5992	4.39	0.685	1.922	(0.011)	1,850+_50BP	(10.4/mil)	528048.0	3989246.0

δ18O ανδ δ2Η φρομ ϑ.Φ. Ωηελαν, ΥΣΓΣ, Δενϖερ; Σρ ανδ δ87Σρ φρομ Ζ.Ε. Πετερμαν, ΥΣΓΣ, Δενϖερ; Υ ανδ 234Υ/238Υ φρομ ϑ.Β. Παχεσ, ΥΣΓΣ, Δενϖερ.

* High salinity affects both the precision and accuracy of stable isotope determinations.

234U/238U activity ratios for the Death Valley springs are consistent with Paces' observations for other well and spring waters in the DVDB.



Plots of uranium concentrations versus $^{234}U/^{238}U$ activity ratios for saturated-zone waters. A) Regional ground water in the Yucca Mountain vicinity (from Paces and other, 1998). B) Death Valley springs. Southeastern Death Valley category includes Navel Spring and Upper Navel Seep, Willow Spring, Salisbury Spring, Ibex Spring, Saratoga Spring, and Owl Hole Spring.

Plate 31. Uranium Concentrations Versus $^{234}U/^{238}U$ Activity Ratios.

6.4 Strontium Isotopic Ratios Analysis

The strontium isotope ^{87}Sr is a daughter of rubidium-87. Strontium chemically behaves similar to calcium and magnesium, but is not as abundant. Concentrations of ^{87}Sr and

^{86}Sr will vary for different rock types. For example, ^{87}Sr is found in greatest abundance in granitic and syenitic igneous rocks. Evaporates and marine sedimentary rocks contain abundant strontium, but normally have a lower concentration of ^{87}Sr. Igneous and volcanic rock have intermediate concentrations of ^{87}Sr. Because of this variation in concentrations of strontium isotopes by rock type, isotopic ratios of $^{87}Sr/^{86}Sr$ in ground water, expressed in per milliliters of ^{86}Sr in seawater, can provide a means of evaluating the source of the water.

The concentration of strontium and relative abundance of ^{87}Sr in the Death Valley spring waters are consistent with the general interpretations of water source areas previously discussed. For example, higher concentrations of strontium isotopes in Panamint Mountain springs are consistent for granite pluton rock type. The Tertiary pyroclastic volcanic rocks of the Grapevine Mountain springs have relatively low concentration of strontium isotopes. The relative high concentration of strontium isotope, and intermediate concentration of ^{87}Sr in the Death Valley saltpan spring water is indicative of evaporate deposits. The Willow spring in the Black Mountain range has a low concentration of strontium, and intermediate concentrations of ^{87}Sr. The low concentration of strontium is typical for a metamorphic rock type, but the intermediate concentration of ^{87}Sr suggests an eolian source from the alluvial basin sediments. The concentration of ^{87}Sr from 11.1 to 13.9 per milliliter in the Furnace Creek area springs (Travertine, Texas, and Nevares) are in the same ranges as the Big Bore and Last Chance springs, located just south of the Ash Meadows springs.

6.5 Interpretation of Regional Flow System from Geochemical Analysis

In discussing the regional flow of the area there are several areas worthy of special discussion—the relationship of the Funeral Mountain and Ash Meadow spring sources, the Funeral Mountain and Furnace Creek springs, Ash Meadows, and finally Yucca Mountain and the Amargosa Valley.

6.5.1 Relationship of Funeral Mountain and Ash Meadows Spring Sources

The Ash Meadows springs represent a window in the middle of the larger lower carbonate flow system. Up gradient from the Ash Meadow area the carbonate aquifer is confined. Water level data in BLM #1, 1A and DVNP gravity faults wells in the Amargosa Valley indicate flow is upward from the lower carbonate aquifer into the overlying alluvial fill of the Amargosa Desert basin. There may be a small amount of upward leakage.

At the west margin of the area the lower carbonate aquifer is exposed in the Funeral Mountains with hydraulic head information in BLM #1 and #1A in this area. Within Funeral Mountains there are numerous faults. The fine-grained basin fill of the Amagora Desert terminates against the Funeral Mountains; this truncates the fine-grained basin-fill deposits and thus eliminates the obvious confining layer for the lower carbonate aquifer. The Furnace Creek Fault Zone trends NW on the Death Valley side of the Funeral Mountains. It forms a barrier for further westerly flow in the lower carbonate aquifer.

The fault provides localized conduits for upward flow through the Pleistocene and Pliocene sediments; this flow forms the Furnace Creek springs.

In the zone where the majority of springs occur, a splay of the major fault zone—the Greenwater Valley Fault, meets the Furnace Creek Fault Zone. The two faults form a graben 0.64 km (0.4 mile) wide. Within the graben is highly deformed and faulted Pliocene fine-grained sediments that are overlain by less deformed Pleistocene alluvial fan deposits. The alluvial fan deposits are also faulted. It is along these faults, within the fine-grained sediments, where the larger springs occur.

The Furnace Creek Fault Zone shows evidence for repeated lateral and vertical movements. It is a regional, deep-seated, transverse fault zone that has both segments with major vertical movement, and other segments with lateral movements. It forms the east flank of Death Valley along the Funeral Mountains; further to the north it bounds the eastside of the White Mountains.

One primary splay of the Furnace Creek Fault Zone extends southward to the west of the Resting Spring Range, down the Amargosa Valley to the Tecopa area. This Furnace Creek Fault is also the regional structural feature that terminates the lower carbonate aquifer in the Tecopa area. It controls the discharge from the carbonate aquifer both in Death Valley and to the south in the Shoshone and Tecopa areas.

There is evidence of a long history of flow in the lower carbonate aquifer. Paleo-Spring features occur in the Tecopa area, along Furnace Creek, and eastward in the Ash Meadows area. In the Death Valley area the paleo-springs occur where the Furnace Creek Fault Zone and associated faults establish the westerly limit of the lower carbonate aquifer. Along Furnace Creek travertine filled veins and travertine spring deposits occur within the Pleistocene alluvial fan deposits. These paleo-spring features appear to represent a period of significantly greater flow within the carbonate system. Winograd and Doty (1980) have recognized similar paleo-springs, of uncertain age, high above Furnace Creek at altitudes much greater than the current base level.

To the south in Tecopa Valley, along the bajada flanking the Resting Spring Range, travertine spring deposits occur associated with pluvial lake, beach deposits. These springs were also controlled by north-south faults associated with the Furnance Creek Fault Zone. Morrison (1999) dated the beach deposits in the Tecopa area at approximately 200,000 years before present. The deposits formed from thermal springs during the highest stand of Lake Tecopa. Later the lake basin was breached, and the Amargosa River drained to Death Valley.

These paleo-spring features are significant in that they suggest:

1) periods of higher hydraulic head in the past—perhaps as old as the late Pleistocene, ~200,000 years ago;
2) such paleo-spring features are recognized only in areas where major faults form deep-seated barriers to interbasin regional flow; the faults cause discharge from the carbonate rock system.

Most of the paleohydrologic features in this area of the carbonate rock province are not as well dated; however, the Tecopa area features are dated at 200,000 years in age. These old features suggest that tectonic movements in the area have not changed the flow system markedly from that which existed during the Pleistocene pluvial period. The spring areas of the past have been maintained in the same areas. The thermal character of the paleo-spring features suggests deep circulation within a confined system.

6.5.2 Funeral Mountain and Furnace Creek Springs

The large springs at the base of the Funeral Mountains in Death Valley are an enigma. The discharge is too large—6.125 x 10^6 m^3 (5000 acre-feet/year)—to be recharge from the associated, nearby drainage basins in the Funeral Mountains. The suggestion is that these springs are supported by inter-basin ground-water flow in the lower carbonate aquifer.

Source of Funeral Mountain Springs

A number of investigators have hypothesized the source of these springs. Most of these ideas have been based upon the similarity of the spring water chemistry to other ground water in the region. The various investigators have used both the major ion and the isotope chemistry of the water. The question arises, after collecting and analyzing waters from another set of springs during this investigation—most of them in the vicinity of Death Valley, whether we can further constrain the source of the water for the springs of Furnace Creek.

There are several interpretations for the source of these springs. Hunt et al. (1966) suggested the source was in the Springs Mountains (south of Las Vegas) about 80 km (50 miles) to the east. In Hunt et al. (1960) the interpretation is that ground water would flow through the lower carbonate aquifer along a path through Pahrump Valley to Ash Meadows and then to Death Valley.

Winograd and Thordarson (1975) observed that ground water from the springs in the Ash Meadows Area, and in the alluvial fill along the Amargosa River are similar in gross chemistry to the water of the Furnace Creek springs. (Winograd and Thordarson (1975) published a U.S. Geological Survey Professional Paper on the geochemistry of ground water in the area of the Nevada Test Site (NTS). This publication was a long time in process. Winograd and Thordarson worked at NTS for almost a decade in the 1960s; their ideas were widely discussed long before the there Professional Paper was published.) They suggested that at least some of the recharge for both the springs at Ash Meadows and in the Furnace Creek area in Death Valley came from the north in the vicinity of NTS.

Mifflin (1968) studied the hydrochemical facies of carbonate rock flow systems in Nevada. He compared the water chemistries of all large discharge springs (greater than 9.5 L/sec. (150 gallons per minute)) within the region in which the "bedrock" is dominated by carbonate rock—his so-called “carbonate rock province”. Mifflin found that as the length of a ground-water flow path increased in the carbonate rock, the "conservative" major ions of Na+K and Cl+SO4 continued to increase in concentration. On the other hand, the Ca+Mg and HCO3+CO3 content of the water generally remained at, or close to, saturation with respect to the carbonate rocks of the aquifer. Mifflin used other supporting data, such as presence or absence of atomic bomb-derived tritium, geographic and terrain information, water budgets, and a few carbon-14 analyses that indicate apparent age of the water, to support his hypothesis. He argued that the weight of the evidence supported the idea that the length of ground-water flow path determined the widely varying concentrations of the major ion chemistry of the water. The length of the flow path is a surrogate measure for the residence time of water in the aquifer.

Mifflin (1968) went on to suggest that the flow systems as interpreted from the spring water chemistries could be subdivided into three flow systems: 1) small-local, 2) local, and 3) regional. The division between the water chemistry of "local" and "regional" springs was established by comparing the chemistry of known regional (interbasin) springs (established by evidence other than chemistry) with the chemistry of known local springs. The chemistry of local and regional springs differs by approximately one equivalent per million (epm) for Na+K and Cl+SO4.

Claassen (1985), based upon a study of hydrochemistry, suggested Amargosa Basin fill waters may be derived, at least in small part, from the volcanic terrain in the Yucca Mountain area.

Johnson (1980) studied the temporal relationships of water chemistry, discharge, and tritium content of a group of "small-local" and "local" springs along the East Side of the Ruby Mountains. Johnson's (1980) investigation reinforces Mifflin's idea of shallow flow systems for the "small-local" springs and deeper, larger flow systems for the "local" springs.

The major ion ground-water chemistry in both carbonate rock and basin-fill, regional flow systems may be quite similar. The stable isotopes of deuterium and oxygen-18 have been used to identify areas of recharge. Winograd and Friedman (1972) were the first to use the stable isotope deuterium as a tracer; they showed that deuterium varied in concentration in recharge areas within Mifflin's carbonate rock province.
Winograd and Friedman demonstrated that stable isotopes in water were a potentially powerful technique that could be used to interpret source areas for the large regional flow systems. Kirk and Campana (1980), Claassen, (1985,1986), Lyles and Hess (1988), Novak (1988), Hershey and Mizell (1995), Thomas et al. (1996), and Pohlmann et al. (1998) revisited the general spring hydrogeochemistry within Mifflin's carbonate rock province. They considered the stable isotopes of deuterium and oxygen-18, as well as other isotopes, and trace constituents in the spring waters.

Recharge to the Funeral Mountains

It is probable that some recharge to the LCA occurs through the carbonate rocks of the Funeral Mountains. This is even more probable because of the carbonate are highly fractured and faulted in the Funeral Mountains. The are no high altitude springs in the

Funeral Mountains that can be used to directly characterize the stable isotopic signature of local recharge.

At first glance, Navel spring appears that it may represent local recharge. However, Navel spring waters have stable isotope signatures that indicate low altitude recharge and some evaporation; these waters are too heavy to be representative of local recharge in the Funeral Mountains.

The major spring waters—Texas, Travertine, Nevares—are clearly too light in stable isotopes to be derived entirely from local recharge.

The total amount of local recharge in the Funeral Mountains is estimated to be approximately four times larger than the recharge in Gold Valley in the Black Mountains. Gold Valley is similar in elevation; water from Gold Valley is expected to have a stable isotopic signature similar to the recharge area in the Funeral Mountains. Willow spring in Gold Valley has an average discharge between 2.5 to 3.15 L/sec. (40 and 50 gpm). This is about 6% of the discharge of the Furnace Creek springs. Willow Spring water has a deuterium content of –92 units, and an oxygen-18 content of -11.4 units.

Assuming that the local recharge in the Funeral Mountains is similar in isotopic composition to Willow spring water, it requires only 6% Funeral Mountain local recharge water mixed with Ash Meadow spring water to yield water that is the same isotopic composition as water in the Furnace Creek springs.

6.5.3 Ash Meadows Springs

The discharge of the Ash Meadows springs is estimated to be approximately 20.96 x 10^6 m^3 per year (17,000 acre-feet per year). Hunt et al. (1966) hypothesized that ground water is recharged in the Spring Mountains. It then flows westward to the Ash Meadows area then on to Death Valley. The Ash Meadows springs are approximately halfway along the postulated flow path.

Winograd and Thordarson (1975) mapped the regional head in the lower carbonate aquifer. Their map suggests ground-water flow form the northeast side of the Spring Mountains, around the northwest extension of the range, to the Ash Meadows springs. This interpretation differs from that of the Hunt et al. (1966); Hunt et al. suggested a flow path directly west from Pahrump Valley to Ash Meadows.

The major flow path for ground water now appears to be from the north side of the Spring Mountains. This northern flow supplies the bulk of the water to the Ash meadow springs. With this interpretation, it is the combination of ground water from NTS mixed with a larger percent of Spring Mountain derived ground water that supplies the Ash Meadow springs.

One can compare the isotopic data for the Ash Meadows spring water with that from the Furnace Creek springs. One interpretation is that the Furnace Creek regional springs are the result of flow that bypasses the Ash Meadow springs; the Death Valley springs in this interpretation are the down-gradient extension of the Ash Meadows regional flow system. The deuterium/oxygen-18 isotopic composition of the water suggests that there is no significant source of recharge between Ash Meadows and the Furnace Creek area. There is about 48 km (30 miles) of travel distance between Ash Meadows and Death Valley. Local and small local "carbonate" flow systems occur in both the Spring Mountain and Pahrump Valley. These local and small-local flow systems have water with almost no Na+K of Cl+SO4. Water from the Ash Meadows Spring has a major ion content that is typical for a regional carbonate system. However, the water from Ash Meadows has only approximately 50% of the Na+K and Cl+SO4 that is present in the Furnace Creek springs.

The major ions of Na+K, Cl+SO4 increase significantly between Ash Meadows and Furnace Creek, while the stable isotopes are unaffected. One explanation for the increase in major ions is dissolution from the carbonate rock of minerals, principally gypsum, that increases the Na+K, and Cl+SO4 content of the water; Mifflin favors this explanation. Winograd, on the other hand, argues there is little, or no gypsum in the carbonate rocks in this area. He suggests there must be a contribution of other water high in Cl+SO4 along the flow path to the Furnace Creek springs.

The limited hydraulic head data in the area suggests regional flow is from Pahute Mesa to Yucca Flat then southwest to Oasis Valley. To the south the flow is toward the Amargosa Desert, and continuing to the Ash Meadows springs. There is a significant range in the deuterium values from these areas; the variation is 8 to 10 deuterium units. The variation suggests different ages for the waters.

An explanation for the variation in deuterium isotopes is that there is a significant component of old pluvial climate derived recharge in some, if not most, the deeper flow systems both in the larger basin-fill aquifers as well as parts of the regional carbonate flow system. Flow within parts of these systems may be sufficiently slow to still contain water that is more than 12,000 years old.

A mix of deuterium data from young and old water may be misleading in identifying recharge areas for the regional carbonate aquifer. The isotope analyses for the Ash Meadows spring waters may pose such difficulties. The contribution from the Spring Mountain and the Sheep Range contribution may be significantly underestimated. The data suggests that the combined recharge in northeastern portion of Las Vegas Valley had an average deuterium content of -103 units—representing recharge that occurred during an earlier pluvial climate. The data from the local-small springs in the surrounding mountain ranges indicates that the current recharge has a deuterium content no lighter than -96 units. There may be a difference in the deuterium content of -7 units between recharge in an earlier pluvial climate recharge and recharge today.

Thomas et al. (1996) suggested that 40% of Pahranagat Valley water, with an average deuterium content of –109 units, mixes with 60% of Spring Mountain water, with an average deuterium content of -99 units, to yield the observed deuterium content of the Ash Meadow spring water, -103 units. Mifflin suggested that if the average deuterium content of the Spring Mountain recharge is -97 units then a 50/50 mix results. This demonstrates how sensitive the calculations of recharge area are to small changes in isotopic composition. There is no independent evidence for recharge coming from Pahranagat Valley.

The stable isotope data is insufficient to be used exclusively to identify the areas of recharge regional flow systems within the carbonate rocks. In some areas where the water may be quite old the interpretation is made more difficult by the potential shift in deuterium/oxygen-18 composition between the present climate and an older pluvial climate. Mifflin suggests that the regional deuterium data indicate a variation between the current recharge and older pluvial climate recharge of 6 to 7 deuterium units.

6.5.4 Yucca Mountain and Amargosa Desert Basin Fill Recharge

The UE 25-P1 drill-hole at Yucca Mountain was a 1,798 meter (5,900 foot) deep exploratory hole that penetrated 487 meters (1,600 feet) of Paleozoic carbonate rocks underlying the volcanic tuffs. It is the only drill hole at Yucca Mountain to have penetrated the lower carbonate aquifer. The borehole encountered carbonate rock beneath a fault zone believed to have significant displacement.

The hydraulic head measured in the carbonate rock is approximately 18 meters (60 feet) higher than that measured in the overlying volcanic tuff sequence. This indicates that any flow, or leakage, is upward from the carbonate aquifer into the Tertiary volcanic rocks in that area.

The major ion chemistry of the carbonate aquifer water is that of a regional aquifer. The major ion chemistry is similar to that of Texas and Travertine springs in Death Valley, and different than that of the Ash Meadows springs. The Ash Meadows springs are more dilute in the major ions; this may suggest that there is an important different source of recharge for Ash Meadows. Most researchers now agree that much of the water in the springs of Ash meadows is from the Spring Mountains.

The deuterium in the UE 25-P1 carbonate water is -107 units, too light for either Ash Meadows or the Furnace Creek area waters. This indicates that carbonate water from Yucca Mountain must be mixed with water containing heavier deuterium to reach the deuterium values observed in Furnace Creek spring waters.

In conclusion, it is likely that UE 25-P1 carbonate rock water is old, and that it represents a slower zone of flow within the carbonate rock flow system.

The data for wells in the Amargosa Desert is limited. There are 26 wells with gross water chemistries; 20 of these have stable isotope analyses. The average deuterium content is -102 units, and average oxygen-18 content is -13 units. The deuterium ranged from -98 to -105 units, and oxygen-18 from -12.6 to -13.8 units. Both the deuterium and oxygen-18 values are slightly heavier than the Furnace Creek spring waters, but individual analyses overlap the Furnace Creek data.

Claassen (1985) suggested that the Amargosa Desert basin-fill waters came from several sources: 1) carbonate aquifer water, 2) water recharged from surface flows in the Amargosa River and Forty Mile Wash, and 3) water from the volcanic aquifers to the north in the area of NTS. Claassen (1985) recognized the possibility of upward leakage of ground water along the same fault that localizes the Ash Meadow springs. Water from wells in the Amargosa Desert has deuterium and oxygen-18 contents that are similar to the Ash Meadow springs.

6.6 Summary of Conclusions from Geochemical Data Analysis

The water sampled and analyzed from small-local springs in mountain ranges in the vicinity of Death Valley has a major ion signature that groups the waters nicely by mountain range.

By comparing the deuterium content of the large regional springs in the Furnace Creek area with the deuterium content of the small-local springs in the Death Valley area we can constrain the amount of local recharge to the carbonate aquifer in the Funeral Mountains. The amount of local recharge is less than 10% of the regional spring discharge in the Furnace Creek area. This is further evidence that the major springs in the Furnace Creek area discharge from the regional carbonate aquifer.

The question of the ultimate source of recharge for the Death Valley carbonate springs remains partially unanswered. The three possibilities outlined originally by Winograd and Thordarson (1975) remain possibilities. The water can come from recharge in 1) the area of NTS and Yucca Mountain; or 2) the Amargosa Basin fill deposits, or 3) the area to the east that includes the Ash Meadow springs, or some combination of all three. We now know that the local recharge is quite small.

7.0 USGS DEATH VALLEY GROUNDWATER MODEL

Concern about the potential transport of contaminants from both the Nevada Test Site and from Yucca Mountain led to groundwater flow models being proposed for both sites. Different groups within the Department of Energy (DOE) manage these facilities; initially two separate models were under development—one for the Nevada Test Site by IT/GeoTrans and a second for Yucca Mountain by the USGS. This was an obvious duplication of effort; it was decided to merge the two efforts into a single model under the leadership of the USGS.

The groundwater flow model of the area poses unique problems. The area is broken up into mountain ranges and intervening valleys. In addition the area was at the continental margin during much of its geologic history; the facies of many of the stratigraphic units change in the area of the model. While there are outcrops of the rocks in the mountain ranges, there are only a few drill holes in the valleys that penetrate the Paleozoic Carbonate Aquifer. Creating the model is a challenging problem.

As suggested above, there are few drill holes in the area of the Death Valley flow system model that reach the Paleozoic carbonate aquifer beneath the valleys. Outcrops of the various stratigraphic units, including the Paleozoic carbonate rocks occur in the mountain ranges. However, in order to fully populate the model it is necessary to interpret the geology, especially the geology beneath the valleys.

Geologic mapping in the mountain ranges where the rocks are exposed is a more or less straightforward procedure. However, interpreting the geology beneath the valleys is a more subjective endeavor, even when it is guided by regional geophysics. Geologists constructed a series of cross-sections through the area of the model that depicted their interpretation of the geology. There is the further problem that the data must be interpolated from the cross-sections to the model grid; errors in input can occur in this process.

In summary, the USGS Death Valley Regional Flow System Model has the advantage that the laterally discontinuities nature of rocks in the region are accommodated. The model has the disadvantage that it is difficult to extract information of interest. It is our intent to extract form the USGS as much information as possible that pertains to the Carbonate Aquifer. Two groundwater models were developed and used to evaluated flow through the LCA from Yucca to the Southern Funeral Mountains and then through the Funeral Mountains to the major LCA springs in Furnace Creek in DVNP. A description of these model results follows.

7.1 The Paleozoic Carbonate Aquifer

Our particular concern is the Paleozoic Carbonate Aquifer. We extracted from the USGS Death Valley Regional Flow Model the data pertaining to the Paleozoic Carbonate Aquifer. Figure 32 is a distribution map for the carbonate in the model area.

As Figure 32 illustrates, the carbonate rocks are discontinuous across the region. In places they are very thick, reaching more than 5000 m in thickness. A large mass of carbonate rock underlies Yucca Mountain and the Amargosa Valley; this mass extents through the Funeral Mountains to Death Valley.

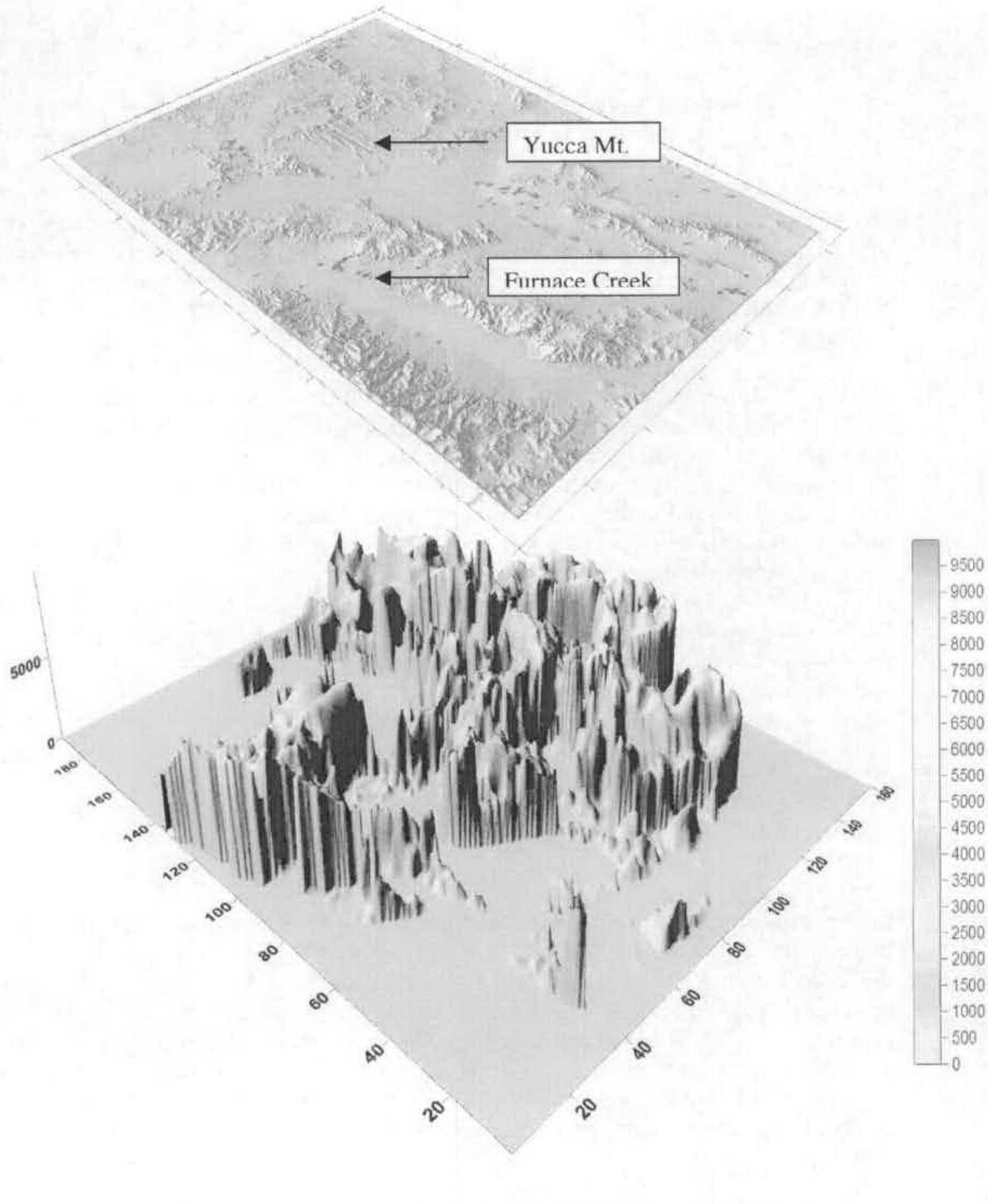


Figure 32. Distribution of Carbonate Rocks in the Death Valley Regional Flow System Model.

Figure 33 is the computed predevelopment potentiometric surface map for the area of the USGS Death Valley Regional Flow System Model; the map also indicates areas of recharge and discharge.

The potentiometric surface shows an area of low gradients over the Amargosa Valley that is bounded by an area of high gradients through the Funeral Mountain Range to the southwest to a discharge area in Death Valley. Within the area of low gradients, discharge occurs at Ash Meadows, and in a smaller amount in Pahrump Valley.

7.2 Amargosa Valley Sub-Region

Our focus is on Yucca Mountain, the Amargosa Valley, and the Funeral Mountains. It is through this area that the Paleozoic carbonate aquifer provides a potential pathway for contaminants to be transported from the Yucca Mountain Repository to the biosphere. We propose to extract the data for the carbonate aquifer, and further to restrict the investigation to a sub-region of the USGS Regional model.

We extracted from the USGS regional model the thickness of the Paleozoic carbonate rock in a sub region. Figure 34 is an isolith map for the Paleozoic carbonate rock within the sub-region. Not all of the sub-region contains carbonate. Beneath the Amargosa Valley the Paleozoic carbonate rock is greater than 5000 m thick. In this area even extensional basin and range faults with large vertical throws would juxtapose carbonate rocks against carbonate rocks across the faults. With such large thickness of carbonate rock one can understand why the aquifer integrates the subsurface flow at depth.

Each hydrogeologist working on the hydrogeology of the Paleozoic Carbonate Aquifer has a somewhat different conceptual image of what forms the interconnected pore space of the aquifer. The brittle carbonate rocks are broken up by the tectonics of the basin and range. Joints and faults in the rock have been enlarged by subsequent dissolution of the rock. Caverns are known to occur—Devils Hole is a good example. The question arises: can one drill anywhere in the carbonate rock terrain and obtain a reasonable good water well—a well producing several hundred gallons a minute or more? At least some old-time Nevada ground-water hydrologists believe this is possible, provided that one drills a "sufficient" thickness of carbonate rock.

Recently the Southern Nevada Water Authority (SNWA) proposed to pump groundwater to the south and east of Ely, Nevada, and pipe it to Las Vegas. Estimates vary for their proposed withdrawal; but they currently talk in terms of 190 million cubic meters annually (150,000 acre-feet). The Nevada State Engineer granted SNWA, with caveats, a permit to pump 73 million cubic meters (60,000 acre-feet) annually from Spring Valley. SNWA's contractor, Durbin & Associates, assembled hydraulic conductivity values for the entire Paleozoic carbonate region as input for a model of Spring Valley (SNWA, 2004). Figure 35 is a cumulative distribution of tramsmissivity taken from the SNWA data.

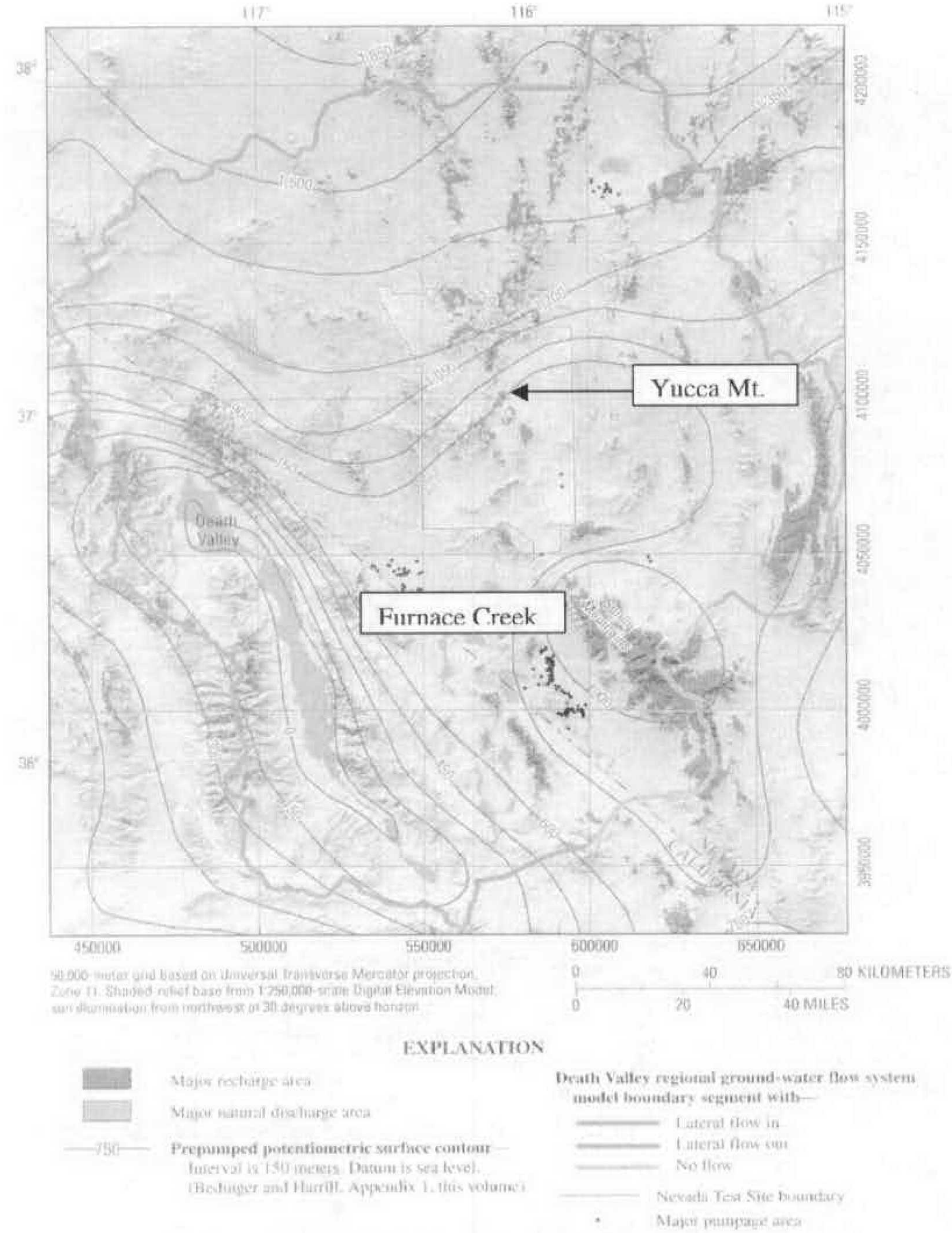


Figure 33. Potentiometric Surface Map for the Area of the U.S.G.S. Death Valley Regional Flow System Model (San Juan, et. al. 2004).

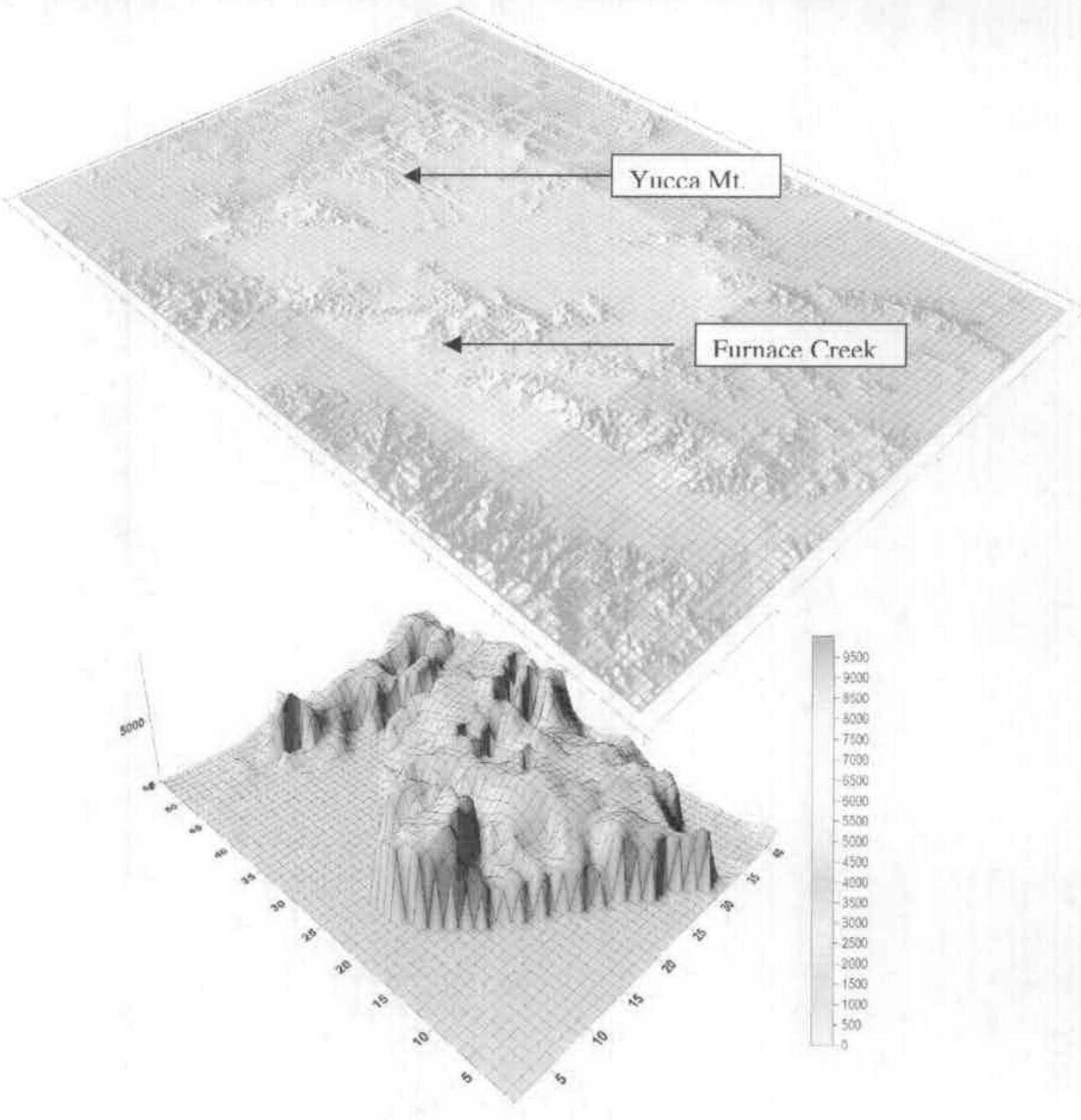


Figure 34. Thickness of the Paleozoic Carbonate Rocks in the Sub-Region.

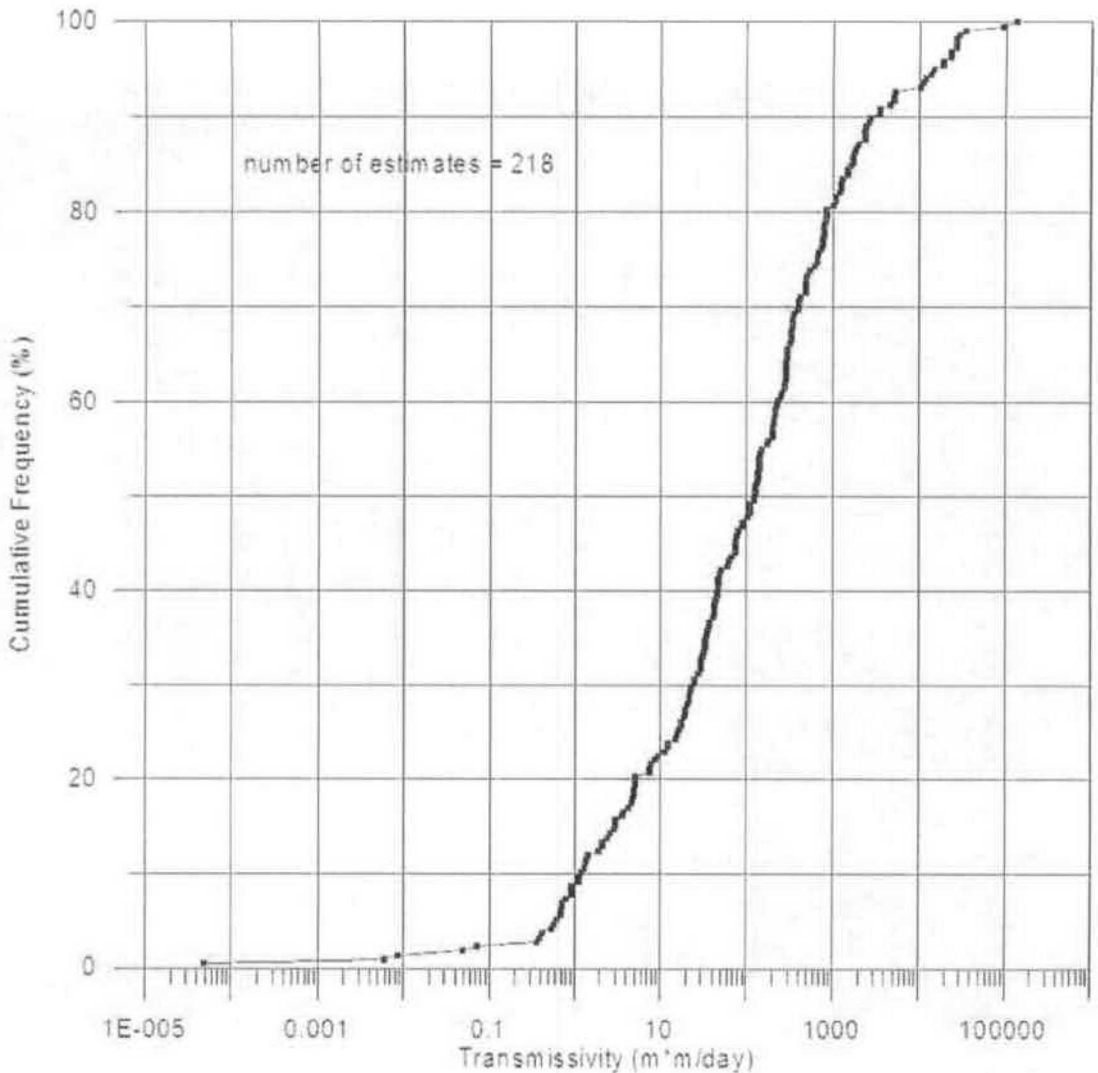


Figure 35. Cumulative Distribution of Transmissivity from SNWA Data (SNWA, 2006).

These data suggest that there is approximately an 85% chance of obtaining a well that yields 0.4 cubic meters per minute with 30 meters of drawdown (100 gpm with 100 feet of drawdown). It also indicates that there is approximately a 10% chance that a well with 30 meters of drawdown will yield approximately 8 cubic meters per minute (2000 gallons per minute with 100 feet of drawdown).

One can calculate a hydraulic conductivity from the transmissivity data. The usual assumption is that the screened interval, or the open-hole section of the portion of the well tested should be divided into the transmissivity to obtain a local estimate of the hydraulic conductivity. Figure 36 is a plot of the hydraulic conductivity, most of which are derived from the transmissivity estimates.

If one compares the ratio of the cumulative distributions you see that the hydraulic conductivity generally represents approximately 30 meters of tested well section. This suggests that there is about an 85% chance that if one drills a sufficiently thick section of Paleozoic carbonate rock one will find a 30 meter, or smaller zone that is sufficiently permeable to yield a good well (defined as more than 100 gpm with 100 feet of drawdown).

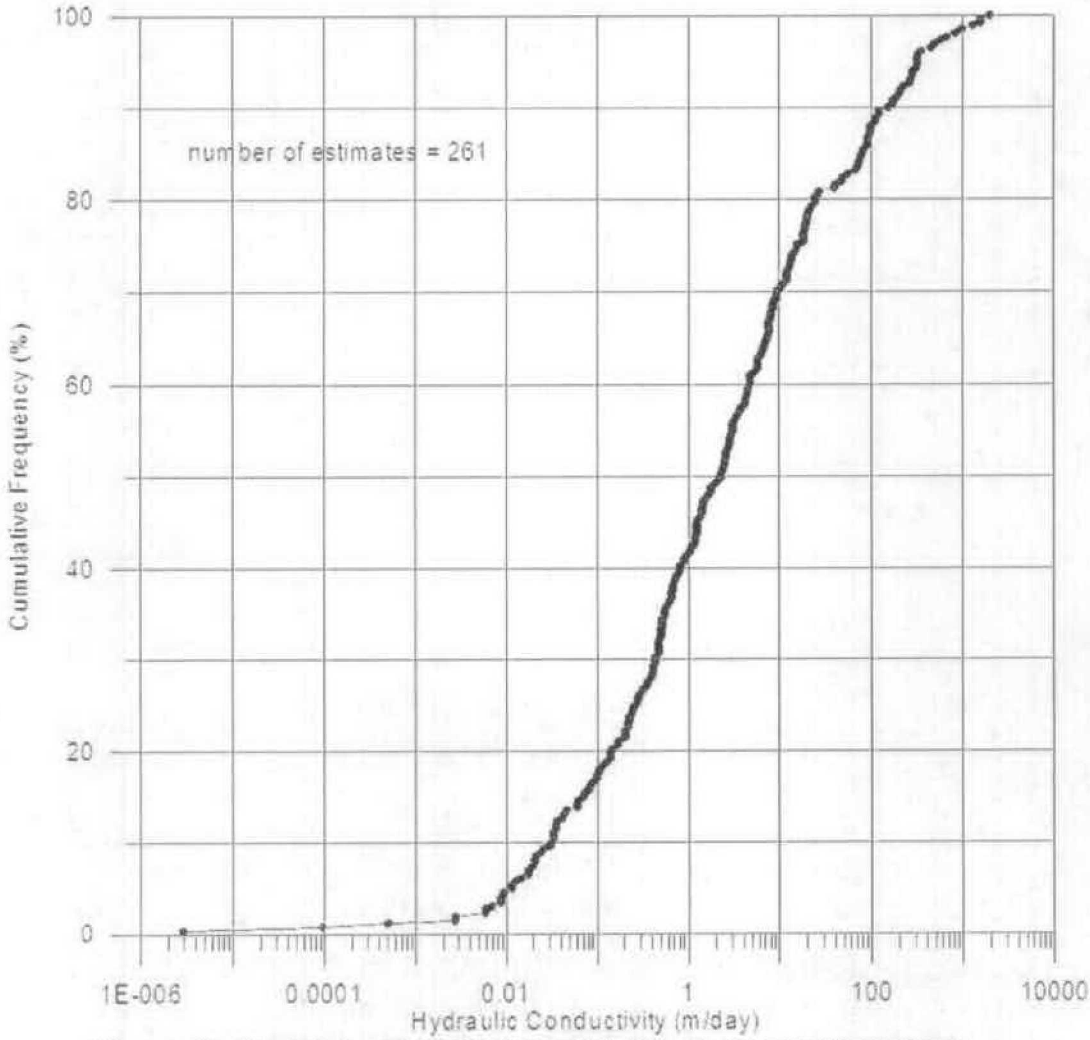


Figure 36. Cumulative Distribution of Hydraulic Conductivity from SNWA Data (SNWA, 2006).

In other words, our simple conceptual model of the hydraulic conductivity in the aquifer is—the aquifer contains permeable zones, maybe 10 meters, or several tens of meters thick, more or less everywhere where the Carbonate rocks are more than several hundred meters thick. The permeability is enhanced where it is associated with recent faulting within the carbonate units. Barriers to flow seem to occur where the carbonate is juxtaposed against less permeable rock. Caves are known in the carbonate rock; for example, Devils Hole is a known cave.

There is some suggestion in the carbonate data that the hydraulic conductivity decreases with depth; however, the data very scattered—noisy. Some workers explain this as due to burial; on the other hand, the temperature rises with depth making the water less viscous, increasing the hydraulic conductivity. Every investigator assumes a depth of burial beneath which the hydraulic conductivity does not decrease further. It seems questionable, given the noisy nature of the data, that correcting the hydraulic conductivity for depth adds much to the precision of the analysis.

The conceptual model may not be all that important when one's concern is only the movement of water. However, when you begin to transport chemical constituents the nature of the conduit for flow becomes all-important—more on the permeability/porosity conceptual model below.

7.3 A Simple Flow Model

One simple way to investigate the system is to assume that the principal pathway for flow is mostly through the Paleozoic Carbonate Aquifer. With this thought in mind one can construct a model for flow through only the carbonate rock; this is a simplistic, first-order approximation for the system; but it does provides insight. The USGS in their RASA study (Prudic et al, 1995) used a two-layer idealized model—this model is even simpler.

In the Ash Madows/Amargosa area the largest amount of recharge comes from the Spring Mountains. The big discharge areas, depicted in Figure 34, are in Ash Meadows, Pahrump Valley, in the area of Shoshone, and in Death Valley. Approximately 75% of the recharge comes from the Spring Mountains.

We created a one layer more of only the Paleozoic Carbonate Aquifer. This is a kind of zero-order model that provides insight into how contaminants might be moved in the carbonate aquifer. In this model the aquifer is decoupled from the overlying Tertiary deposits. Where the Paleozoic carbonate aquifer has been penetrated in the area a good low-permeability confining layer overlies the aquifer. We know that this isolates the aquifer, not totally, but certainly to a great degree. So the simple model is only useful in that it provides an estimate of how contaminants might move. Figure 36 is a computed steady-state potentiometric surface generated from the one layer model. Flow is continuous in the aquifer from the area of Yucca Mountain to the discharge area in Death Valley.

7.4 Potential for Contaminant Travel Through the Carbonate Aquifer

One common way to estimate the time of travel of a chemical constituent is to assume that the constituent moves with the velocity of the water. In groundwater flow the velocity is given by:

$$v = K/\varepsilon \ (fh/fl)$$

where v is the groundwater velocity, K is the hydraulic conductivity, ε is the porosity, and (fh/fl) is the gradient in hydraulic head. The question becomes what is the appropriate porosity to apply to the calculation? This again raises the issue of how one conceives of the connected pore space in the aquifer. There are several investigations that shed some information on this issue.

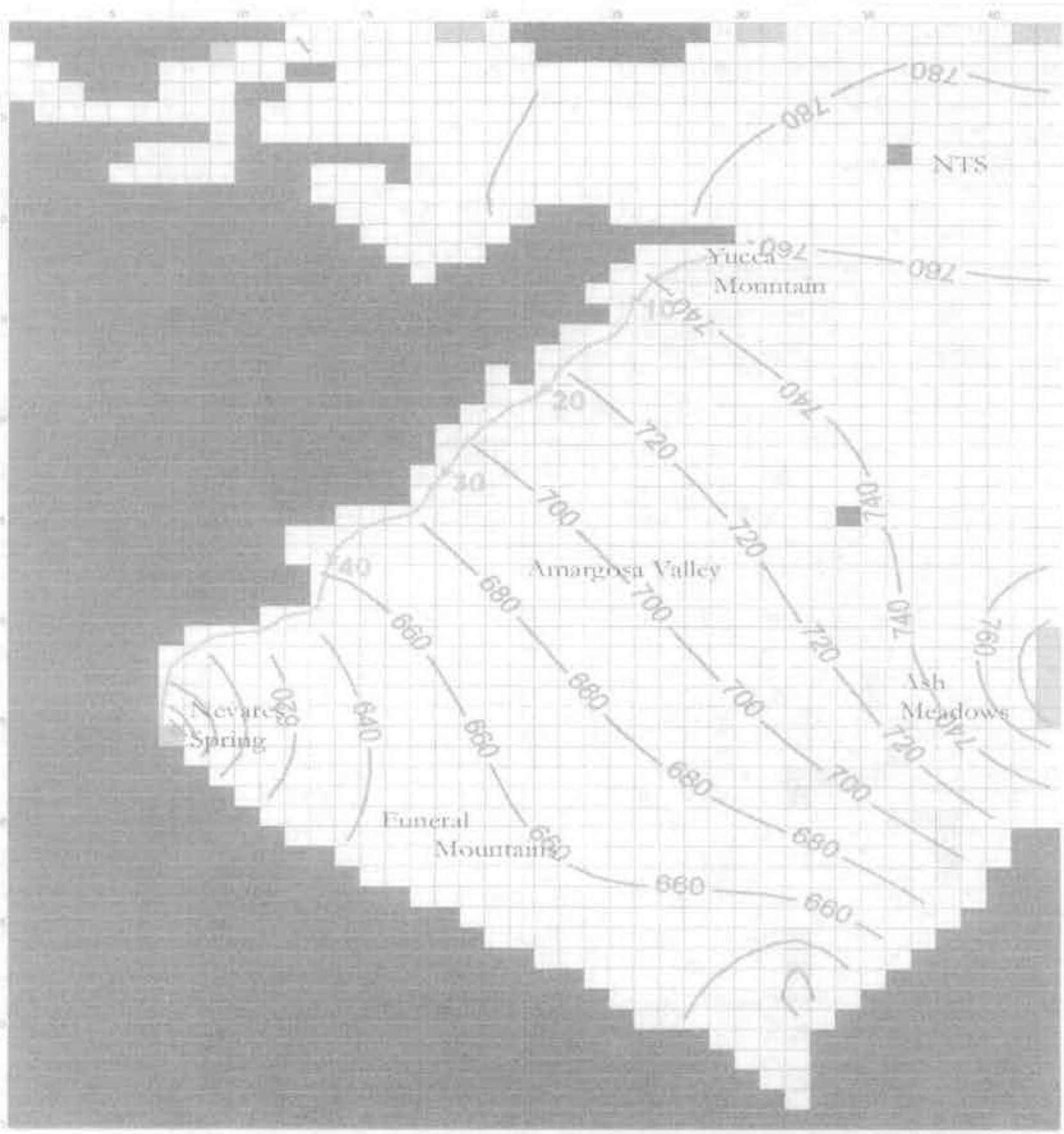


Figure 36. Map of Steady State Hydraulic Head from the One Layer Carbonate Aquifer Model.

The yellow areas are spring discharge areas. The red line is a particle track for a particle introduced in the vicinity of Yucca Mountain that exits in Death Valley—the red numbers are estimates in years of the time of travel for the particle.

Winograd and Pearson (1976) investigated the isotopic content of major springs in the Ash meadows complex. They focused particularly on carbon 14 that varied greatly between individual springs. They concluded that the carbon 14 content of the springs was best explained by what they termed "megascale channeling" within the aquifer.

One hole in the vicinity of Yucca Mountain, UE-25p1, penetrated approximately 500 m of the Paleozoic carbonate aquifer. Galloway and Rojstaczer (1988) studied earth tide signals in the carbonate aquifer. They concluded that the aquifer was well confined, and that the storage coefficient derived from their analysis indicated porosity less than 1%. Craig and Robison (1984) estimated, from a pumping test, that the transissivity of the carbonate aquifer penetrated by the hole was 59 m^2/day; approximately mid-range in the transmissivity distribution (see Figure 4).

The evidence suggests that the porosity one assigns to the carbonate aquifer to estimate the velocity of groundwater flow should be less than 1%. This is consistent with a fractured zone in the thick carbonate sediments that is highly permeable.

The particle pathline, shown on Figure 6, is calculated on the basis of a permeable zone 100 meters thick, with a porosity of 0.1%. With this calculation it takes less than 50 years for the particle to travel though the aquifer from the area beneath Yucca Mountain to Death Valley. If the porosity were 1% the travel time would be 500 years.

7.5 What Protects the Carbonate Aquifer at Yucca Mountain?

Borehole UE-25p1 had a hydraulic head in the Paleozoic Carbonate Aquifer that was 15 m higher than the hydraulic head in the overlying Tertiary volcanic rocks (Bredehoeft, 1997). This higher head has the potential to move groundwater upward from the carbonate into the volcanic sequence of rocks. As long as the head relationship remains as presently observed the carbonate is protected from contamination moving downward from the repository to the carbonate aquifer.

Hydraulic head is one of the more ephemeral of hydrologic conditions. Changes within the groundwater basin can change the hydraulic head. The head is probably most subject to change by development of groundwater for water supply in the Amargosa Valley. The population of southern Nevada is growing rapidly. Local groundwater is looked to for at least a large portion of the water supply. Both the valley fill deposits and the Paleozoic Carbonate Aquifer is the target for development. Groundwater development by lowering the hydraulic head could eliminate the upward hydraulic head gradient as a barrier to contaminate movement into the Carbonate Aquifer at Yucca Mountain.

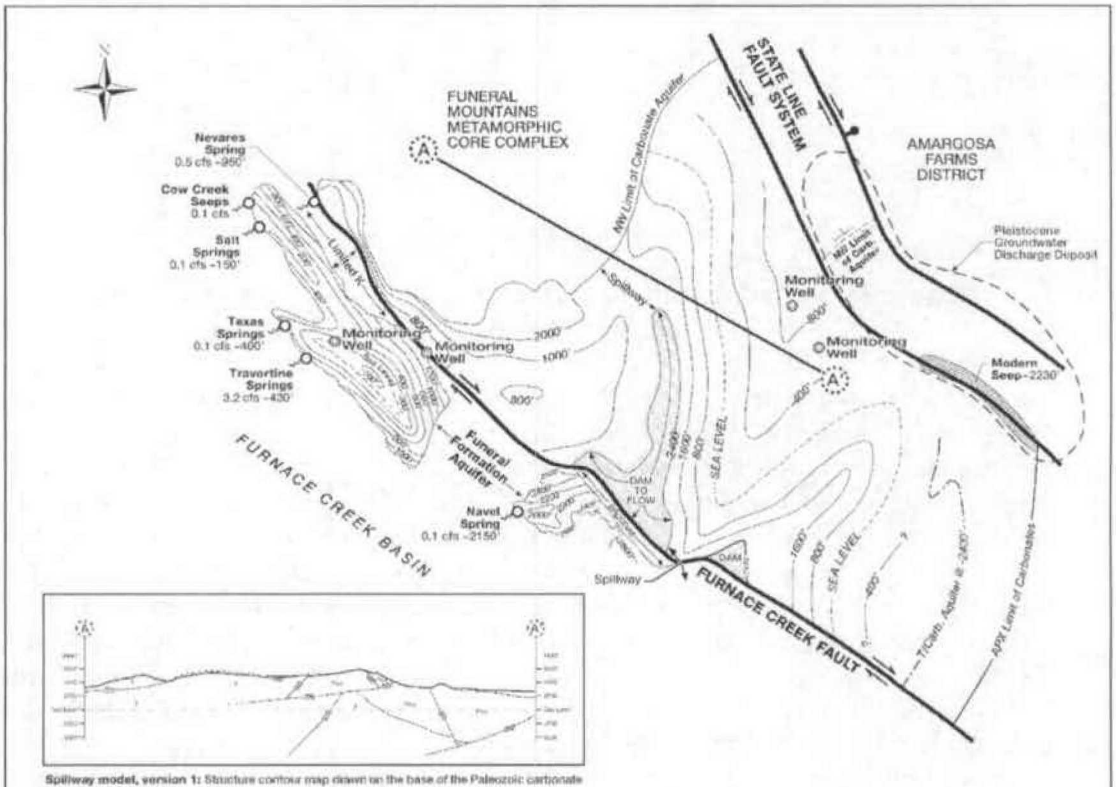
7.6 Southern Funeral Mountain LCA Model

Hydrodynamics developed a groundwater model of the LCA through the Southern Funeral Mountains to determine the feasibility of flow from the Amargosa Valley to the major springs in the Furnace Creek area of DVNP. The development of the model required the characterization of the hydrogeologic units in the study area resulting in a hydrogeologic framework model to define the model boundaries. The model was then calibrated to match know hydraulic head data from the BLM #1 well and spring flow rates. The model is as follows.

7.6.1 Hydrogeologic Units

The rocks of the southern Funeral Mountains and of the two adjacent basins can be divided into five major hydrogeologic units. (1) The lower part of the miogeoclinal section consists largely of siliciclastic sedimentary rocks that are generally very low in permeability except where strongly fractured, as in major fault zones. All of the rocks that underlie the lower siliciclastic part of the miogeoclinal section have a similar hydrologic character. Thus, this lower group of rocks as a whole forms the effective base of the aquifer system. (2) The upper part of the miogeoclinal section is approximately 4 km thick (pre-deformation) and consists dominantly of carbonate rocks—limestone and dolomites, with only few and thin interbedded shale and sandstone formations. A large fraction of the plexus of extensional faults that cut the rocks throughout the study area have throws that exceed the thickness of these generally low permeability interbeds. Hence, these structurally dismembered interbeds have insufficient continuity to effectively interrupt ground-water flow through the dominantly carbonate section, which is a highly permeable, fracture-flow-dominated aquifer. (3) The Carbonate Aquifer is locally capped by 170 m (maximum) section of siltstones and shales of the Perdido Formation. It is questionable whether this formation is anywhere sufficiently continuous enough to form a confining unit by itself. However, the Perdido is overlain by the generally low permeability, lower part of the Cenozoic section. Together the Perdido Formation and the overlying Cenozoic rocks form a confining unit over the Carbonate Aquifer. (4) The Cenozoic section is lithologically very diverse, consisting of basin sediments of numerous types. Most parts of this unit are generally of low permeability, but some thin, highly permeable beds are locally present. On a local scale, some permeable beds in this unit are significant aquifers. However, these permeable beds typically can be traced only over short distances; hence, they probably lack sufficient continuity to have a significant impact on large-scale ground-water flow. The sub-alluvial Cenozoic section as a whole can therefore be treated on a large scale as a confining unit. (5) The capping poorly consolidated alluvium of the Cenozoic section is an excellent aquifer, both in the Furnace Creek basin, where it is called the Funeral Formation, and in the Amargosa Desert basin, where it is unnamed and is widely tapped for agricultural and domestic water supply. In the Amargosa Desert basin, the alluvial water-table aquifer is probably connected only poorly with the underlying Carbonate Aquifer, which is confined under a thick section of Cenozoic lakebeds (mostly claystones and siltstones). In the Furnace Creek basin, however, the alluvial aquifer is juxtaposed against the carbonate aquifer of the southern Funeral Mountains, across the Furnace Creek fault.

The rocks that comprise the Carbonate Aquifer extend above the water table throughout most of the southern Funeral Mountains, and are very well exposed at the surface in the range. Based on unpublished mapping, by Fredrick, of the exposed structure and stratigraphy of these rocks, we have constructed two structure contour maps on the base of the Carbonate Aquifer under the range (Figure 37 and 38). The major uncertainty in this subsurface interpretation is the geometry of the major extensional faults in the subsurface. High-relief surface exposures of all of these faults show that they are strongly listric—they are concave upward because they progressively flatten with depth. They are moderate- to (rarely) high-angle faults in the highest elevation exposures and their dip declines to low-to- (less common) moderate dips with decreasing elevation. An important, unresolved question is whether the high rates of downward flattening observed on the surface continue at depth, or if the rate of flattening declines and these faults approach near-horizontal dips. We present two alternative structure contour maps on the base of the carbonate aquifer: 1) a bounding case that assumes rapid downward flattening of the faults, and 2) another case that assumes much more gradual flattening with depth. The second (gradual flattening) model is our preferred model because the fault geometry appears most reasonable. The rapid flattening model is, however, one we consider a prudent alternative to consider because one of the major extensional faults, in the easternmost part of the southeastern Funeral Mountains, actually shows rapid downward flattening that is this extreme, in local surface exposures.



Spillway model, version 1: Structure contour map drawn on the base of the Paleozoic carbonate aquifer (northeast of the Furnace Creek fault) and the Funeral Formation alluvial aquifer (southwest of the Furnace Creek fault). Note the two spillways in the central part of the southern Funeral Mountains. In this bounding case, the thickness of the aquifer at the spillways is minimized.

Figure 37. Structure contour map of the base of the Carbonate Aquifer formed by the fault planes with shallow dips.

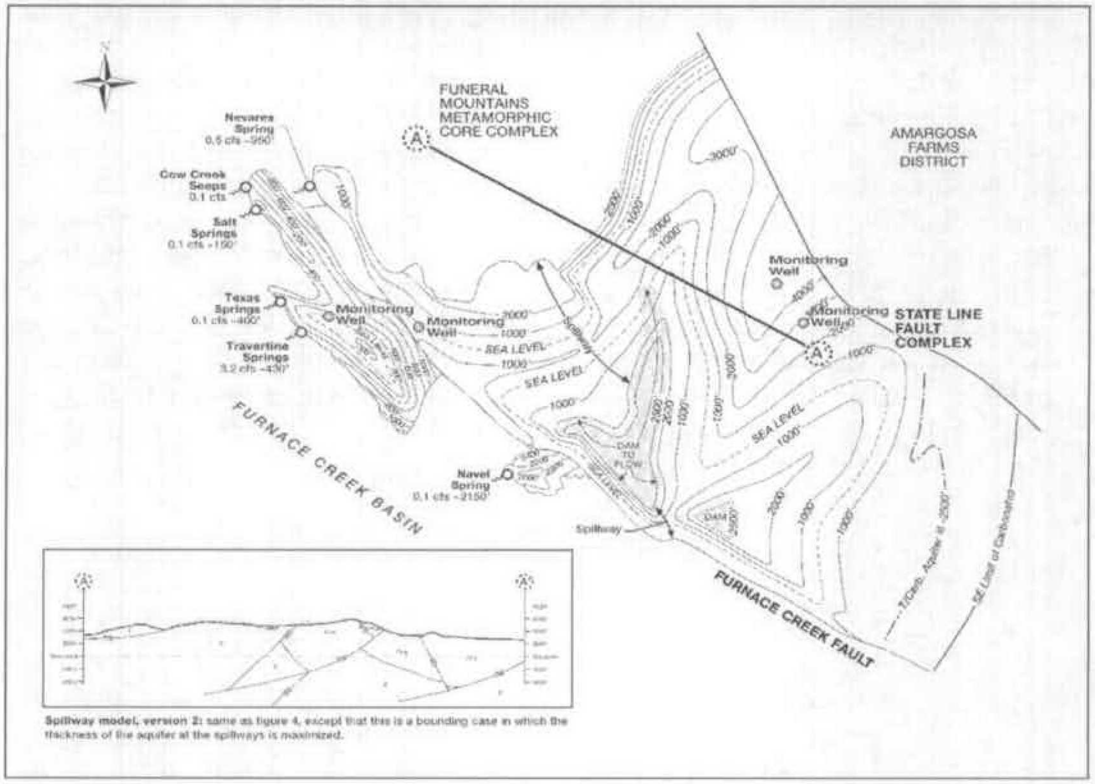


Figure 38. Structure contour map of the base of the Carbonate Aquifer formed by the more steeply dipping fault planes.

In these two map interpretations of the geometry of the carbonate aquifer, those features that are not dependent on the subsurface fault geometry are the same, and are constrained by the exposed structure and stratigraphy. These common features include boundaries of the Carbonate Aquifer: (1) in the northwestern part of the southern Funeral Mountains, where it is truncated by the northwest-dipping Schwaub Peak Thrust and by a number of other contacts to the west, mostly strike-slip faults that are internal to the range, (2) along the southwestern front of the range, where it terminates against the Furnace Creek fault, and (3) near the southeastern limit of the range, where it terminates against the depositionally overlying confining unit formed by the combination of the Perdido Formation and the overlying basal Tertiary section. Additionally, three isolated bedrock outcrops immediately north of the Funeral Mountains, exposed between strands of the Stateline fault, show that the Schwaub Peak Thrust, the northwest limit of the Carbonate Aquifer, is offset approximately 15 km in a right-lateral sense across the southernmost strand of the Stateline fault. There are additional, but smaller right-lateral offsets of the aquifer boundary across other strands of the Stateline fault, in the southern part of the Amargosa Desert basin. However, as pointed out above, there are very few data to constrain the geometry of the Carbonate Aquifer under this Amargosa basin.

A final element of the two-aquifer maps (Figures 37 and 38) is the geometry of the Funeral Formation aquifer within the Furnace Creek basin. This formation is an important part of the hydrologic system because all but one of the Furnace Creek springs issue from the Funeral Formation, rather than from the Carbonate Aquifer. Nevares spring is the only spring that issues directly from the Carbonate. The outline of the Funeral Formation is largely a function of erosion, except along the fault along the southwest range-front of the Funeral Mountains. At the southeastern limit of the larger mass of the Funeral Formation there is a northeast-striking normal fault within the Furnace Creek basin called the cross-basin fault (McAllister, 1970). Northeast-southwest contractional folding controls the base of the Funeral Formation, which occurred in the Furnace Creek basin mainly between 4 and 2 Ma; this folding is still feebly active today.

On a regional scale, the Paleozoic Carbonate Aquifer extends northeastward at least as far as the east-central border of Nevada. The grouping of springs at Furnace Creek is only one of several discharge areas that lie near to, or at the southern termination of this huge ground-water flow system. Flow in the regional carbonate aquifer is generally to the southwest, and the springs in Death Valley are located at the ultimate southwestward termination of the system. The Funeral Formation provides a very short continuation of the flow system beyond the limit of the Carbonate Aquifer. Where that formation is Furnace Creek Formation is erosionally truncated, there are no adjacent permeable rocks to accept the groundwater, so it discharges onto the surface at the lowest-elevation points along the southwest boundary (Figures. 2 and 3).

From the southernmost part of the Amargosa Desert basin to the lowest-elevation spring in Furnace Creek, the water-table elevation drops by approximately1800 feet. This large decline in head has a straightforward relationship to the geometry of the base of the Carbonate Aquifer under the Funeral Mountains. Under part of the axis of this range, the base of the aquifer is structurally uplifted (Figures 2 and 3). However, there are two areas within this range where the base of the aquifer is lower than the water-table elevation in the southernmost part of the Amargosa Desert basin—our recent BLM #1 well had a hydraulic head in the Carbonate Aquifer of 2180 ft. The uplift under the axis of the range plays a key role in restricting groundwater flow through the Funeral Mountains.

Two lines of evidence support the interbasin flow model under the southeastern Funeral Mountains: 1) the flow from the springs in Furnace Creek is about an order of magnitude higher than the estimated recharge to the Furnace Creek basin and the adjacent southern Funeral Mountains, and 2) the chemistry and isotopic signature of the water that issues from these springs provides evidence that the Carbonate Aquifer under the southern Amargosa Desert basin is the source of the spring water (Winograd and Thordarson, 1975; Mifflin, 1968). Nonetheless, local recharge to the Funeral Mountains probably does contribute approximately 10% of the flow of the Furnace Creek springs.

7.6.2 Groundwater Flow Through the Funeral Mountains.
Given the maps of the base of the Carbonate Aquifer, Figures 37 and 38, it is feasible to attempt to model the groundwater flow through the Funeral Mountains. The model needs constraints, and boundary conditions. It was our intent to keep the model as simple as possible; we are attempting to test the feasibility of groundwater flow through the Funeral Mountains.

One constraint on the model is the quantity of the discharge from the springs in the Furnace Creek area of Death Valley. Obtaining a good estimate of the discharge is not as easy as it first appears. There have been several attempts to estimate the total spring flow (Table 6). The spring flow is a problem to measure because in many instances the spring orifice is not well defined; much of the water flows out in the nearby alluvium. The earliest was by Pistrang and Kunkel (1964). Terry Fisk, of the National Park Service made measurements in 2001 and 2003 (personal communication). We attempted to reconcile the measurements (Table 6).

Table 6. Estimates of the discharge (cubic feet per second—cfs) of the Furnace Creek springs.

Springs	Pistrang & Kunkel	Fisk	Our Estimate
Texas	0.8	0.98	1.0
Travertine	3.6	3.09	3.2
Nevares	0.6	0.32	0.5
Cow Creek	0.1	0.10	0.1
Navel			0.1
Salt			0.1
Total			**5.0**

With these data we can set boundary conditions on the model and constrain the flow. The map of the base—Figures 37 and 38 establishes the extent of the aquifer through the Funeral Mountains.

The hydraulic head in the southern Amargosa Desert basin on the northeast flank of the Funeral Mountain is known. BLM #1 has a hydraulic head in the Carbonate Aquifer of approximately 2180 ft. in elevation. There is an area along the Amargosa River indicated in Figure 2 that is perpetually wet; phreatopyhtes are extensive in this area. This appears to be an area of groundwater discharge that overlies the Stateline fault in this area. The area has a ground elevation just above 2200 ft. A hydraulic head of 220 feet in this area of the Carbonate Aquifer is consistent with the elevations of the Ash Meadows springs, Devils Hole, and our BLM #1 head.

The groundwater flow model was created using MODFLOW. As suggested above, the extent of the aquifer was dictated by the geologic mapping of the base of the aquifer—Figures 37 and 38; we use a 1/4 x 1/4 mile square grid to represent the aquifer. The model aquifer includes both the Carbonates in the Funeral Mountains and the adjoining Furnace Creek deposits.

The springs are represented in the model as *drains*. Each drain has an associated elevation. The computed hydraulic head is depicted in Figure 39.

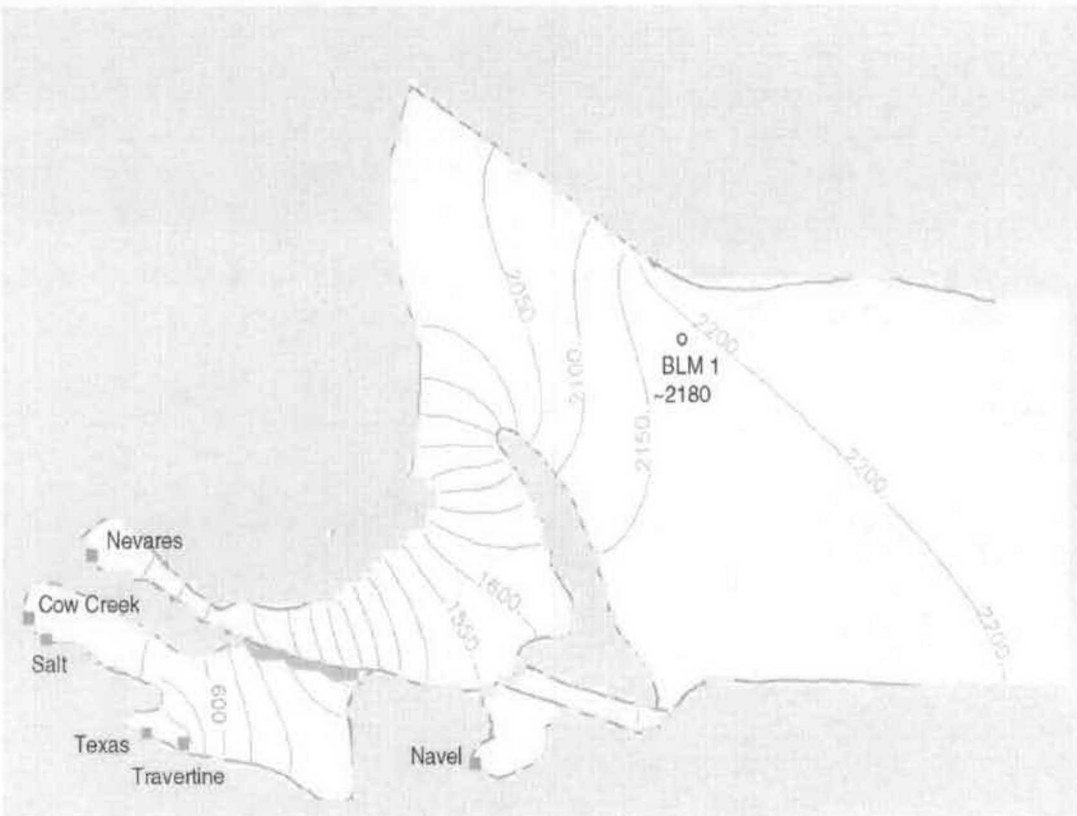


Figure 39. Computed Hydraulic Head in Carbonate Aquifer.

The model as depicted in Figure 39 reproduces the discharge of the various springs quite well (Table 7)

Table 7. Computed discharge of the Furnace Creek springs.

Springs	Approximate Elevation (Feet)	Estimated Flow (Cfs)	Model Computed Flow (Cfs)
Navel	2150	0.10	0.11
Nevares	950	0.50	0.47
Travertine	430	3.20	3.26
Texas	400	1.00	0.89
Cow Seeps	150	0.10	0.08
Salt	150	0.10	0.08
Total		**5.00**	**4.89**

The model needs further discussion. We specified a single transmissivity throughout the entire active groundwater domain of the model. The total flow through the system is sensitive to the transmissivity—the best value was 0.022 ft^2/sec.

One hydraulic problem posed by the model is how to force groundwater flow northwestward in the finger of carbonate rock that extends out to Nevares spring. Nevares is approximately 500 ft higher in elevation than Travertine and Texas springs. The model requires a flow barrier to force flow out to Nevares spring; we simulated this barrier along the Furnace Creek fault zone. The model projects a high head drop across the fault—500 to 600 ft.

The model results are consistent with either of the maps of the base of the aquifer—Figures 37 or 38. In the case of the shallower dipping fault plane (Figure 2) the model projects approximately 300 feet of aquifer saturation through the critical area—designated as the spillway on Figure 37. One could calculate an aquifer permeability using the model transmissivity. In the case of shallow fault plane the critical thickness is 300 ft; in the steeply dipping case the thickness is approximately 1000 ft. The viscosity of water at 20^0C is one-centipoise; at 50^0C the viscosity is 0.55 centipoises. Temperature alone makes almost a factor of two differences in permeability. If we assume a saturated aquifer thickness of 300 ft, and water of 50^0C temperature, then the calculated permeability is 1.2×10^{-13} m^2. This compares favorably with the permeability for the Carbonate Aquifer used in the DOE saturated model for Yucca Mountain. Since the aquifer is dominated by fractures it seems more reasonable to treat the system with a single transmissivity.

Modeling the spring discharge is also somewhat problematic. The drain function in MODFLOW requires that one specify both 1) an elevation (which is straightforward), and 2) a resistance to flow (that is not so straightforward). By adjusting the additional resistance in the drain function one can effectively adjust the spring discharge—one can use various rationales to justify this additional resistance in the drain function. It seemed to us that the flow to the principal springs, especially Nevares, and Travertine, should be controlled by the transmissivity of the aquifer. We made the resistance to flow in the drain function sufficiently large that it had no impact to the flow to these springs. We did use the additional resistance in the drain function to adjust the flow to the other springs.

8.0 Summary and Conclusions

The Paleozoic Carbonate Aquifer in the Death Valley flow system has been the site of intensive investigation since the 1950s. Conventional wisdom, that has become doctrinaire, has the Carbonate Aquifer integrating the ground water flow in the area. The investigations have intensified as the U.S. has embarked on building a nuclear repository at Yucca Mountain. One of the more ambitious of the projects has been the construction of the USGS Death Valley Regional Ground-Water Flow Model.

The intent of our investigations is to create a homogeneous picture of the Paleozoic Carbonate Aquifer. From a coherent view of the Carbonate Aquifer, we constructed a very simple model in an effort to estimate potential contaminant movement through the carbonate aquifer.

Any model of contaminant transport through the carbonate aquifer depends heavily upon how one pictures the connected pore space in the carbonate rocks. Our conceptual model is of a thick carbonate sequence that contains a zone ten to several tens of meters thick where the rocks are fractured and provide a permeable pathway for flow. The information suggests that everywhere there is a reasonable thickness of carbonate rock one can obtain good water well, provided he/she drills a sufficient thickness of the rock. One can enhance his/her chances of getting a really good well by going to places where recent tectonics movements in the region have further disturbed the carbonate rocks.

BLM #1 did reach our objective—the Carbonate Aquifer in the Amargosa Desert basin. This deep drilling has established a Carbonate Aquifer water level in our first drill hole BLM #1—approximately 2280 ft. in elevation. BLM #1 was completed, as the only know LCA monitoring well south of Yucca Mountain.

BLM #1A was completed as a Tertary aquifer monitoring well adjacent to BLM #1. The head and temperature difference between BLM #1A and #1 indicate an up-ward gradient in the LCA.

Our second deep hole in the Amargosa Desert basin, BLM #2, was drilled and cased to a depth of 2700 ft. in the lower section of the Titus Canyon Formation just above the Carbonate Aquifer. The borehole was deepened to 3340 feet below ground surface, and is still in the lower section of the Titus Canyon Formation. The hole can be drilled deeper when the budget allows.

Geologic mapping in the Funeral Mountains has provided two possible contour maps for the base of the Carbonate Aquifer in the range. Geophysical surveys through the Amargosa and Southern Funeral Mountains have provided insight into the subsurface structural geology of the LCA in the study area.

The water sampled and analyzed from small-local springs in mountain ranges in the vicinity of Death Valley has a major ion signature that groups the waters nicely by mountain range.

By comparing the deuterium content of the large regional springs in the Furnace Creek area with the deuterium content of the small-local springs in the Death Valley area we can constrain the amount of local recharge to the carbonate aquifer in the Funeral Mountains. The amount of local recharge is less than 10% of the regional spring discharge in the Furnace Creek area. This is further evidence that the major springs in the Furnace Creek area discharge from the regional carbonate aquifer.

The question of the ultimate source of recharge for the Death Valley carbonate springs remains partially unanswered. The three possibilities outlined originally by Winograd and Thordarson (1975) remain possibilities. The water can come from recharge in 1) the area of NTS and Yucca Mountain; or 2) the Amargosa Basin fill deposits, or 3) the area to the east that includes the Ash Meadow springs, or some combination of all three. We now know that the local recharge is quite small.

We have created a MODFLOW groundwater flow model that is consistent with the available data and recreates the flow through the Funeral Mountains. The flow model reproduces the spring flow rather well. The model suggests that either interpretation of the base of the Carbonate Aquifer is feasible. The model is very sensitive to the transmissivity of the aquifer; our best value for transmissivity is 0.022 ft^2/sec.

Finally with this model in mind transport through the Carbonate Aquifer from a location beneath the site of the Yucca Mountain Repository to the biosphere in Death Valley will be relatively rapid. Our calculation with a permeable zone 100 m thick and porosity of 0.1% indicates a transit time of less than 50 years; if the porosity is of the order of 1% the time is of the order of 500 years.

The bottom line is that the Paleozoic Carbonate Aquifer is a good pathway for contamination to the biosphere. Every effort should be made to keep contaminants out of the carbonate aquifer.

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Inyo County
Yucca Mountain Repository Assessment Office

Licensing Support Network (LSN)

You have reached Inyo County's Licensing Support Network (LSN). This page, partially completed, contains Inyo County's datasets pertaining to the proposed high-level nuclear waste repository at Yucca Mountain. The LSN is a distributed collection of documents pertaining to the Yucca Mountain Project. It can be reached at http://lsnnet.gov/

"The LSN provides a single place where the parties and potential parties to the licensing hearing can search for documents from any/all of those collections in a uniform way."

Transportation Studies:

- Inyo County Transportation Risk Assessment Project, Transportation, Scenario Estimation
  - Task 2 Transportation Scenario Estimation (13,933 kb)
  - Task 3 Transportation Data (834 kb)
  - Task 4 Risk Estimates for Inyo County (1717 kb)
  - Task 5 Identification of Mitigation Strategies and Measures (309 KB)

link

Groundwater Studies:

- YEAR ONE PROJECT REPORT: Death Valley Lower Carbonate Aquifer Monitoring Program: Wells down gradient of the proposed Yucca Mountain Nuclear waste repository (large 49MB pdf) Prepared by Inyo County Yucca Mountain Repository Assessment Office through a US Department of Energy Cooperative Agreement: DE-FC28-06RW12368
- Death Valley Regional Groundwater Monitoring Program - DE-FC08-02RW12162 This is a large document (70,261 Kb) imbedded with lots of graphics and will be slow to download.
- Death Valley Regional Groundwater Monitoring Program - DE-FC08-02RW12162 This is a much smaller and easier to upload document (73 Kb) that does not include any graphics.
- BLM No. 1 Well Caliper Borehole Volumes Table (741 Kb)
- BLM No. 1 Well Deviation Survey Table (388 Kb)
- BLM No. 1 Well Electric Log Gamma-Ray Table (722 Kb)
- BLM No. 1 Well Sonic Velocity Variable Density Table (1,537 Kb)
- BLM No. 1 Well Temperature Gamma-Ray Table (690 Kb)
- BLM No. 2 Well Electric Log Gamma-Ray Table (912 Kb)
- BLM No. 2 Well Sonic Velocity Variable Density Table (2,489 Kb)
- The Lower Carbonate Aquifer as a Barrier to Radionuclide Transport (15,682 Kb) This paper was presented at the 2005 Devils Hole Workshop by Bredehoeft, Fridrich, and King.

- Death Valley Springs Geochemical Investigation Yucca Mountain Nuclear Repository, Inyo County Oversight-1998, Hydrodynamics, March 1999 (92 kb)
- Hydrodynamics Presentation to Inyo County Board of Supervisors, Feb 26, 2007 (6777 kb)
- Paper: THE LOWER CARBONATE AQUIFER AS A BARRIER TO RADIONUCLIDE TRANSPORT, Presentation by John Bredehoeft, The Hydrodynamics Group; Chris Fridrich, U.S. Geological Survey; and Michael King, The Hydrodynamics Group, LLC at the Waste Management Conference, February 27- March 3, 2005, Tucson, AZ (359 kb)
- Presentation: THE LOWER CARBONATE AQUIFER AS A BARRIER TO RADIONUCLIDE TRANSPORT, Presentation by John Bredehoeft, The Hydrodynamics Group; Chris Fridrich, U.S. Geological Survey; and Michael King, The Hydrodynamics Group, LLC at the Waste Management Conference, February 27- March 3, 2005, Tucson, AZ (4222 kb)

Healing Ourselves and Mother Earth (HOME):

These reports are provided as a courtesy to HOME, a research and public education nonprofit group based in Tecopa, CA. These reports have not been endorsed by the County of Inyo.

- Hazardous Materials Transportation on CA Routes 127 and 178 with in the Southern Inyo Fire District - HOME Sept 2006 (3400 Kb)
- The Yucca Mountain Legacy Project, Phase I: Groundwater Contaminant Baseline Data for the Yucca Mountain Region. Report prepared for HOME by: Jennifer Olaranna Viereck, Ex. Director; John Hadder, Project Chemist; George Rice, Project Hydrologist May 2006 (7700 kb)