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-FC08-02RW12162
FINAL PROJECT REPORT
PREPARED BY INYO COUNTY YUCCA MOUNTAIN
REPOSITORY ASSESSMENT OFFICE

Inyo County completed U.S. Department of Energy Cooperative Agreement No. DE-FC08-02RW12162.
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 radionuclides 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, geophysical surveys, and geological mapping of the Southern Funeral Mountain Range. The culmination of this research was a numerical ground water model of the Southern Funeral Mountain Range demonstrating the potential of a hydraulic connection between the LCA and the major springs in the Furnace Creek area of Death Valley.

Abstract
Inyo County has participated in oversight activities associated with the Yucca Mountain Nuclear Waste Repository since 1987. The overall goal of these studies are the evaluation of far-field issues related to potential transport, by ground water, of radionuclides into Inyo County, including Death Valley, and the evaluation of a connection between the Lower Carbonate Aquifer (LCA) and the biosphere. Our oversight and completed Cooperative Agreement research, and a number of other investigators research indicate that there is groundwater flow between the alluvial and carbonate aquifers both at Yucca Mountain and in Inyo County. In addition to the potential of radionuclide transport through the LCA, Czarnecki (1997), with the

U.S. Geological Survey, research indicate potential radionuclide transport through the shallower Tertiary-age aquifer materials with ultimate discharge into the Franklin Lake Playa in Inyo County.
The specific purpose of this Cooperative Agreement drilling program was to acquire geological, subsurface geology, and hydrologic data to:

1. Establish the existence of inter-basin flow between the Amargosa Basin and Death Valley

Basin,
2. Characterize groundwater flow paths in the LCA through Southern Funeral Mountain Range,
and
3. Evaluate the hydraulic connection between the Yucca Mountain repository and the major
springs in Death Valley through the LCA.
The hydraulic characterization of the LCA is of critical interest to Inyo County and the U.S. Department of
Energy because:

1. The upward gradient in the LCA at Yucca Mountain provides a natural barrier to radionuclide
transport,
2. The LCA is a necessary habitat resource for the endangered Devil's Hole pup fish, and
3. The LCA is the primary water supply and source of water to the major springs in Death Valley
National Park.

The surface geology of the Southern Funeral Mountain Range area was initially mapped by the U.S.
Geological Survey to develop both a geological and hydrological framework model of the Southern Funeral
Mountain range. Gravity, magnetic, and Time Domain Electromagnetic (TEM) surveys were then
conducted on both the Eastside and Westside of the Southern Funeral Mountain Range. The results of the
geophysical surveys combined with the geological framework model were used to site exploratory
monitoring wells with a high potential of penetrating the LCA.

Project funding levels allowed the drilling of Inyo-BLM#1, Inyo-BLM#2, and Travertine #2 wells. The
Inyo-BLM#1 well penetrated the LCA at a depth of approximately 2,400 feet below ground surface. The
Inyo-BLM#2 was cased in the lower section of the Tertiary-age sequence of rock approximately 1,500
above the LCA. The well was cased to allow reentry. The Travertine #2 well was drilled to an approximate
depth of 1,300 feet below ground surface about 1,200 feet up gradient from the Travertine Spring complex.
The well was completed in multiple zones to allow water level monitoring in a lower permeable zone and
in the upper water table aquifer.

A numerical ground water model of the LCA through the Southern Funeral Mountain range was developed
to demonstrate the hydraulic connection between the Amargosa Valley area and the major springs in the
Furnace Creek Ranch area of Death Valley National Park. The model indicates potential flow through
spillways in LCA through the Southern Funeral Mountain Range. A second numerical ground water model
of the water table aquifer system at the Texas and Travertine Spring complexes was developed. The model
was specific to simulating the potential effect of water production wells in this area on spring flows. The
model indicates impacts on spring flow will be less then significant.

1.0 Introduction

Yucca Mountain is the site of the only proposed high-level nuclear repository in the United States. The repository was designed using the philosophy of multiple barriers, both engineered and natural, each of which impede the movement of contaminants. The proposed repository will be in the unsaturated zone above the water table in Tertiary tuffaceous rocks. The principal transporting mechanism for radionuclides is moving groundwater. The primary potential radionuclide transport path would be through the Tertiary-age tuffaceous aquifer system through Amargosa Valley terminating at Franklin Lake Playa in Inyo County. Underlying the repository at a depth of approximately 4250 ft (1.3 km) is an extensive Carbonate Aquifer known to be highly permeable. Only one drill hole at Yucca Mountain has been drilled into the Carbonate Aquifer—hole UE-25p1. This hole encountered the Paleozoic Carbonates at a depth of 4256 ft (1300 m).

Up until the 1960s the conventional wisdom in Nevada was that individual basins contained separate and distinct groundwater systems. Winograd, working at the Nevada Test Site in the early 1960s, hypothesized, based on the chemistry of groundwater, that Paleozoic Carbonate rocks that underlie both eastern and southern Nevada integrated the groundwater flow into a much larger system, or systems, than those suggested by the overlying topographic basins. Winograd's prime examples were the major springs in Death Valley that he postulated were the discharge from the underlying Paleozoic Carbonates. Winograd was slow to publish his ideas; however, other investigators quickly adopted his hypothesis (Mifflin, 1968; Winograd and Thordardson, 1975). The idea that the deep groundwater systems in southern and eastern Nevada are integrated through the Carbonate Aquifer is now generally accepted doctrine.

The principal data used to determine the origin of spring discharge in the area of the Amargosa Desert basin are the chemistry of the groundwater. The Carbonate Aquifer groundwater has a distinct chemical signature. The major springs in the Furnace Creek area of Death Valley have the distinct carbonate water chemistry. The groundwater recharges that supply the springs of Death Valley are thought to be principally in an area north of Yucca Mountain. The groundwater is believed to flow southward through the Carbonate Aquifer beneath Yucca Mountain, beneath the Amargosa Valley, and then through the Funeral Mountains to finally discharge in the springs in Death Valley.

Usually groundwater flow paths are based upon hydraulic head data that indicates the hydraulic gradient; however in the case of Amargosa Valley/Funeral Mountain/Death Valley Carbonate Aquifer system there

are very few boreholes on which to base hydraulic head information. The UE-25p1 hole, mentioned above,
reached the Carbonate Aquifer beneath Yucca Mountain at a depth of 4256 ft. The hydraulic head data
from the hole showed that the head in the Carbonate was 65 ft (20 m) higher than the head in the overlying
Tertiary Tuffs. The temperature of the groundwater in the deep Carbonate was high–approximately 540C
(Sass et al., 1988). Bredehoeft (1997) commented on the higher head in the Carbonate Aquifer:

This is a favorable condition for the proposed repository. The upward potential for flow from the
deep Carbonate Aquifer protects it from the downward movement of contaminants…. Nothing
should be done either: 1) through construction of the repository, or 2) through ground-water
development to reduce heads in the Carbonate Aquifer; the higher heads protect the Carbonate
Aquifer.

There are few other boreholes that penetrate the Carbonate Aquifer in the Amargosa Valley flow system.
Nye County drilled a series of early warning holes in the vicinity of the community of Amargosa Valley to
the south of Yucca Mountain. One of the Nye County wells is believed to have penetrated the Paleozoic
Carbonate rocks. The heads in the deepest portion of this well were higher than those usually encountered
in the Tertiary Tuffs in the area. The groundwater and head in this well is thought to reflect the Carbonate
Aquifer. Other wells encountered groundwater with a carbonate chemical signature.

One wildcat oil well is reported to have reached the Paleozoic Carbonates in Amargosa Valley. This well
was plugged and abandoned without hydraulic head measurements or water samples taken from the
Carbonate Aquifer. Devils Hole in the Amargosa Valley is a water-filled cave in the Paleozoic Carbonate
Aquifer. We have a good water level record for Devils Hole. Nearby Devils Hole are the Ash Meadow
springs that discharge from the Carbonate Aquifer.

The Carbonate Aquifer has the potential of providing a conduit for radionuclide transport away from Yucca
Mountain. However, the head higher in the Carbonate Aquifer than in the Tertiary Tuffs provides a barrier
to the movement of contaminants from the Tertiary Tuffs downward to the Carbonate Aquifer; the gradient
in head is upward not downward. The higher hydraulic head in the Carbonate Aquifer in the vicinity of
Yucca Mountain could be reduced by groundwater development in the Amargosa Valley. A rapidly
growing population in Las Vegas and Pahrump Valley are seeking sources of water; local groundwater in
the highly permeable Carbonate Aquifer is an obvious source of great interest. Were contaminants to enter
the Carbonate Aquifer in the vicinity of Yucca Mountain they would be transported through the aquifer to
the springs in Death Valley.

Inyo through a Cooperative Grant program funding by the US Department of Energy has been conducting

research to prove groundwater movement through the Paleozoic Carbonates from the Amargosa Valley
through the Southern Funerals to the major spring in Death Valley. Our recent study culminated in a
MODFLOW groundwater model that is supported by our current program of: 1) monitoring well drilling in
the Southern Funeral Mountains (Inyo BLM #1 and #2, and Travertine Well No. 2), 2) surface and
subsurface geologic mapping in the area, and 3) geophysical surveys.

2.0 Problem Statement
Inyo County's primary concern for high-level nuclear waste disposal at the Yucca Mountain repository is
the far-field issues related to potential transport, by ground water, of radionuclides into Inyo County,
including Franklin Lake Playa and Death Valley, and the potential connection between the Upper Tertiary-
age aquifer system and the Lower Carbonate Aquifer (LCA) to the biosphere. The relationship between
carbonate spring waters in Death Valley (within Inyo County) and the groundwater flowing under Yucca
Mountain has yet to be conclusively demonstrated. In addition, the "peak-dose" time frame, radionuclides
from the proposed repository will reach Franklin Lake Playa, where they may be released to the
environment through wind transport. Ground-water flow velocity along Fortymile Wash is estimated to be
about 4 meters per year and decreases to about 1 meter per year or less in the alluvium because of much
larger porosity. A transit time from the repository to Franklin Lake Playa may be 50,000 to 100,000 years.

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3.0 Evidence For Inter-basin Groundwater Flow between the Alluvial and Carbonate Aquifers at Yucca Mountain and in Inyo County
The evidence that the alluvial and the LCA are linked at Yucca Mountain and in Inyo County is threefold:

1 The geochemistry of the spring water from a number springs in the Death Valley Groundwater
Basin is similar to the groundwater in the Lower Carbonate Aquifer;

2. The structural geology of the southern Funeral Mountain Range suggests a continuous Lower
Carbonate Aquifer through the range; and
3. Numerical groundwater modeling tends to corroborate flow through the Lower Carbonate
Aquifer to the Death Valley Groundwater Basin.
A discussion of the results of Inyo County research is provided below. The discussion provides evidence
for groundwater flow between the alluvial and LCA at Yucca Mountain and Inyo County.

3.1 Geological Framework of the Southern Funeral Mountain Range
A general geologic map of the Furnace Creek and adjoining parts of the Amargosa Desert basins is
provided in Figure 1. Copies of surface geology maps of the Southern Funeral Mountain range are
provided in Attachment A (Fredrick, et. al., 2003). The Funeral Mountains uplift is bounded by two

regional-scale right-lateral strike-slip faults. Strands of the Furnace Creek fault have a northwestward horizontal offset; the offset increases to the northwest and reaches a maximum of 80 km of offset to the northwest of the study area. The furnace Creek fault forms the southwest front of the range and abuts

against the Furnace Creek basin.
Figure 1. Geologic Map of the Southern Funeral Mountains and Adjoining Areas.

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In contrast, the major southernmost strand of the Stateline fault system is located 2 to 4 km to the northeast of the irregular northeastern flank of the range; the Stateline fault has approximately a 25 km offset. The Stateline fault underlies the active channel of the Amargosa River in the area. The jagged northeastern range-front itself is controlled by several different features, including: 1) three large west-to northwest-dipping extensional faults that crop-out within the range, 2) a network of smaller faults that are peripheral to, and related to the Stateline fault system, and 3) a number of east to southeast-facing, dip slopes of the extensionally tilted fault blocks that comprise the range.

The internal structure of the southern Funeral Mountains includes the extensional faults, noted above, as well as two large thrust faults–the Cleary and Schwaub Peak Thrusts. The extensional faults formed mainly during the 12 to 7 Ma extensional episode of basin and range tectonics in which the mountain range was formed. These dates are based on dated tephras in tectonic sediments deposited and preserved associated with these faults within the range (Fridrich and Miggins, unpub. data). The 25 to 40-degree east to southeast-tilted structural blocks between the major extensional faults are shattered by a plexus of closely spaced, smaller extensional faults, that strike in a wide range of directions, and that form a continuous fracture network that bridges between the major extensional fault zones. Thrust faults formed during the older Mesozoic Sevier Orogeny, and several large folds are present in the range, adjacent to these thrusts. The thrust faults and the related folds are cut and tilted by the much younger extensional faults.

The rocks exposed in the Funeral Mountains include an 8 km thick late Proterozoic to late Paleozoic section of miogeoclinal sedimentary rocks that were deposited when this region was part of the western continental margin and slope of North America that was covered by the eastern edge of the Pacific Ocean.
The miogeoclinal sediments overlie an older rock section of sedimentary rocks (now medium-grade metasedimentary rocks) of the Pahrump Group; this Group was deposited during premonitory rifting related to the initial formation of the Pacific Ocean. The Pahrump Group rocks, in turn, overlie 1.7 Ga old crystalline basement rocks, mostly high-metamorphic-grade gneisses and schists.

Cenozoic (Oligocene to
Quaternary) sediments overlie the Paleozoic miogeoclinal rocks. The rock sequence includes sediments
formed before, during, and after the basin-range tectonic extension that formed the mountain range.

The Amargosa Desert basin is a composite of several extensional and strike-slip basins, and is floored by
the same miogeoclinal rocks that compose most of the Funeral Mountains. In contrast, the much shallower
Furnace Creek basin, to the southwest of the funeral Range, is thought by most workers to be the footwall
basin of the Amargosa detachment fault, in which the Cenozoic basin-fill sediments largely overlie the
rocks that predate the miogeoclinal section. In the detachment-fault interpretation, the miogeoclinal section
was mostly in the upper plate of the detachment, and was transported approximately 80 km northwestward,
on the detachment fault, and is now exposed as the Panamint and Cottonwood Ranges (Stewart, 1983).
Thus the Cenozoic fill of this basin was deposited directly onto the largely metamorphic lower plate of the
detachment fault. Even those workers who disagree with the detachment-fault interpretation agree that the
miogeoclinal section is almost completely absent under the Furnace Creek Basin; they ascribe that absence
to erosion, rather than to detachment faulting (e.g., Wright and others, 1999). Exposures in the Black
Mountains, on the south side of the narrow Furnace Creek basins, show that the miogeoclinal rocks are
absent under the Tertiary basin fill, except as small isolated scraps, most of which are blocks of tectonic
breccias.

3.2 Southern Funeral Mountain Geophysical Program
In 2002, we conducted gravity, magnetic and TEM surveys along the east side of the Funeral Mountains near
Bat Mountain and Death Valley Junction. Figure 2 shows the location of the survey areas. A total of 22 miles of
gravity data was collected using station spacing between 250 and 1,000 feet. The data was used to construct
maps of the top of the bedrock surface under a portion of the Amargosa Valley, and to select preliminary
locations for four LCA monitoring wells. The data from the Death Valley Junction area was used to map the
position of the Funeral Mountain Fault on the west side of Bat Mountain. The Death Valley Junction survey
was conducted in support of a National Park Service ground water monitoring program.

Bat Mountain
Area
FY2000 Program

Scale: 1" = 12.5 miles

FY2002/2003 Program

Figure 2. Map Showing the Location of Geophysical Surveys on the West and East Sides of the Southern
Funeral Mountain Range.

The Bat Mountain data indicates the elevation of the bedrock surface varies by several thousand feet over
lateral distances of a few thousand feet. Given the cost of drilling to these depths, we determined that additional
geophysical work was warranted to refine the shape of the bedrock surface and to locate sites where monitoring
wells would penetrate the LCA at cost effective depths. An additional 37 miles of gravity and magnetic data
were collected in 2003 to accomplish these goals.

In February of 2004, we conducted 40 Time Domain Electromagnetic Induction (TEM) soundings and 76
gravity measurements along two profile lines from the Funeral Mountains to the saltpan. This data was
used to supplement 73 gravity stations collected in the Furnace Creek area in 2003. In addition, we
conducted high-resolution electrical resistivity surveys in the Furnace Creek Wash and on the Nevares
spring mound. This data was used to provide a more accurate estimate of the ground water discharge to the
saltpan through the alluvial fan deposits.

3.3 Southern Funeral Mountain Well Program
Project funding levels allowed the drilling of Inyo-BLM#1, Inyo-BLM#2, and Travertine #2 wells. The
Inyo-BLM#1 well penetrated the LCA at a depth of approximately 2,400 feet below ground surface (Figure
3). The Inyo-BLM#2 was cased in the lower section of the Tertiary-age sequence of rock approximately
1,500 above the LCA (Figure 3). The well was cased to allow reentry. The Travertine #2 well was drilled
to an approximate depth of 1,300 feet below ground surface about 1,200 feet up gradient of the Travertine
Spring complex (Figure 4). The well was completed in multiple zones to allow water level monitoring in a
lower permeable zone, and in the upper water table aquifer. Geophysical logs from Inyo-BLM#1, Inyo-
BLM#2, and Travertine #2 wells are provided on a DVD disc in Attachment B.

Figure 3. Geological and Geophysical Logs of Inyo-BLM#1 and #2 Wells.

Figure 4. Geological and Geophysical Log of Travertine #2 Well.

The first hole, Inyo-BLM#1, was difficult to drill with washouts and sloughing material in the Amargosa
Desert Basin sequence of sediments. Casing was placed in the hole from the surface to a depth of 2129 ft;
the casing facilitated the deeper drilling. Once the hole reached total depth, and the drilling was completed,

the hole partially filled with caving to the bottom of the casing. No geophysical logs could be gotten in the bottom portion of the hole. The water level stabilized at a depth of 103 ft below ground surface. This suggested that the hydraulic head in the Carbonate Aquifer is approximately 2180 ft.; this is estimated since we do not currently have an accurate elevation for the site. A water level was obtained in the Amargosa Valley sediments during the drilling; however, the observations during drilling suggested that there were not large differences in hydraulic head between the Carbonate Aquifer and the overlying sediments. The water from the 2550-foot zone had a temperature of 52OC–similar to the temperature of the Carbonate Aquifer water in UE-25p1 at Yucca Mountain.

Inyo-BLM#1 and #2 wells encountered complex subsurface geological structures. A geological profile from Pyramid Mountain to Inyo-BLM#1 illustrates the complex nature of the subsurface geology (Figure 5). Subsurface conditions at Inyo-BLM #1 indicate steeply dipping rock units that are brecciaed and highly broken up by faulting.

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Figure 5. Geological Profile Through An Eastern Portion of the Southern Funeral Mountain Range.

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3.4 Hydrologic Framework of Southern Funeral Mountain Range
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 (predeformation) 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. 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 (Figure 6 and 7). 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.

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Figure 6. Structure contour map of the base of the Carbonate Aquifer formed by the fault planes with shallow dips.

Figure 7. Structure contour map of the base of the Carbonate Aquifer formed by the more steeply dipping fault planes.

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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. The structure was
known to be complex based on the regional geologic framework and the presence of an outcrop of
Paleozoic Carbonate rock that forms a small mound projecting above the valley fill sediments
approximately 1.5 miles north of Pyramid Peak. The structural context of this outcrop was unknown and
speculations included a detached block of carbonate placed on top of the valley fill by a gravity slide.
However, as pointed out above, there are very few data to constrain the geometry of the Carbonate Aquifer
under this Amargosa basin.
Our gravity line model, illustrated in Section A-A' (Figure 5), shows the carbonate aquifer extending into
the basin from the Bat Mountain and Pyramid Peak fault blocks with a basin filled with Tertiary and
Quaternary units. The gravity data supports the general structure shown on the eastern third of the geologic
cross-sections shown on Figures 6 and 7. Figure 8 is a map of the bedrock surface beneath the Amargosa
Valley adjacent to the Southern Funeral Mountains constructed from modeled gravity

profiles. The
interpreted bedrock surface shows the Bat Mountain and Pyramid Peak fault blocks project a short distance
into the Amargosa Valley. Monitoring well Inyo-BLM#1 is positioned above a projection of the Bat
Mountain Fault block. Both mountain blocks are truncated by steep dips approximately one half mile north
of the outcrops. Several steep-sided bedrock knobs project into the valley fill about 1 mile north of the
mountain block outcrops. Vertical relief on the bedrock knobs is believed to be on the order of about 6,000
feet over distances of about one half mile.

The bedrock knobs appear to be fragments of the mountain block faults of the Funeral Mountains sheared
off by strike slip faults related to the State Line Fault system. The State Line Fault system is a right lateral
fault. The gravity data suggests that the fault system represents a fault zone with numerous fault splays
accommodating the lateral motion of the fault as indicated on Figure 8. While it is not possible to
determine the relative motion of the individual fault splays, in keeping with the general right lateral motion,
it is reasonable to assume that the bedrock knobs represent blocks that have experienced less overall
displacement than the mountain blocks on the west side of the fault system. As a result, these blocks are
likely to be positioned southward from the mountain blocks from which they originated. Inyo-BLM#2
appears to be sited on a fragment of the Pyramid Peak fault block. The mound of Paleozoic carbonate
bedrock projecting above the valley fill may be a piece of the Schwaub Peak fault block.

The gravity data clearly shows the complexity of the bedrock surface in the Amargosa Valley.
Understanding this complexity is important when siting monitoring wells as missing the bedrock knobs
could result in thousands of feet of extra drilling. However, from a regional flow or groundwater modeling
perspective, the small-scale structure of the bedrock surface may not be significant as the Carbonate
Aquifer is heavily faulted and very permeable. It is unlikely that the faulting inferred from the gravity data
is forming any hydraulic barriers to groundwater flow.

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Figure 8. Depth to Top of Carbonate Aquifer Map From Gravity Data in the Southern Funeral Mountain Range.
A final element of the two-aquifer maps (Figures 6 and 7) 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.
3.5 Hydrologic Framework of Furnace Creek Ranch Area-West Side of Southern Funeral Mountain Range
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 (Figure 9). 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
-116.54 -116.52 -116.5 -116.48 -116.46 -116.44
Longitude
36.4
36.42
36.44
36.46
36.48
Latitude
BLM-1
BLM-2
Ogle-1
SL-1
150
650
1150
1650
2150
2650
3150
3650
4150
4650
5150
DEPTH TO TOP OF CARBONATE AQUIFER MAP FROM GRAVITY DATA
SOUTHERN FUNERAL MOUNTAINS
Depth to Bedrock
Elevation - Ft, MSL
Proposed well location
Gravity station

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 (Figure 10).

Figure 9. Map Showing Regional Groundwater Flow Paths and Discharge Areas.

3.5.1 Travertine and Texas Spring Area
Time Domain Electromagnetic Induction (TEM) soundings were collected in 2000 at the Travertine, Texas,
Nevares, and Grapevine Springs in Death Valley, California. Figure 10 shows the

location of the
geophysical surveys. The soundings identified hydrogeologic controls influencing the location of the
springs, and determined the subsurface extent of the Paleozoic carbonates exposed in the Funeral and
Grapevine Mountains (Jansen et al., 2003). Geological mapping and TEM data appears to have identified
faults in close proximity to the springs at Texas, Travertine and Nevares Springs (Figure 11). At Texas and
Travertine Springs, the interpreted faults are present along a synclinal structure along the West Side of the
Funeral Mountains. The position of Travertine, Texas, and several other springs appears to be controlled by
a fault along the western limb of the syncline. Nevares Spring appears to be controlled by the Furnace
Creek fault adjacent to the Funeral Mountain block. The presence of these faults is confirmed by seismic
and magnetic data (Machette et al., 2000, Blakely et al, 2000). Geophysical surveys conducted on the
western side of the Funeral Mountains have confirmed this interpretation of the geologic controls on the
discharge points for the Carbonate Aquifer.

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Figure 10. Furnace Creek Area Image Showing the Location of Geophysical Surveys.

Seismic Line DV3
Figure 11. Geology Map of Furnace Creek Area of Death Valley
Showing Structural Control of Major Springs.

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This interpretation is supported by seismic reflection data collected by Machette (2000) (Figure 12) and the
Hydrodynamics Group. The reflection data shows truncations of reflectors coincident with the Echo
Canyon Thrust Fault. The position of the faults appears to correlate to the linear trend of Travertine Spring,
Texas Spring, and several other springs in the area. We have added arrows to indicate positions where we
have inferred faults.

Uninterpreted processed seismic-reflection profile DV-3. Depths are relative to the surface at the eastern end of the line.
C is point of intersection with profile DV-2. Source: Machette et al, 2000, with modification to show Inferred Faults.

Interred Fault
Figure 12. Seismic-reflection Profile DV-3

The soundings also detected three geo-electric layers. The upper layer is approximately 200 to 300 feet
thick and has relatively high resistivity, indicating it probably consists of coarser grained units. The second
layer has an intermediate resistivity on the eastern and central part of the profile, but the resistivity drops to

values indicative of fine-grained sediment near the western end of the line. This layer probably represents saturated valley fill sediment with intermediate or mixed grain size on the eastern and central portion of the line with an apparently abrupt change to fine grained sediment on the western end of the line. The deepest layer has relatively high resistivity, and dips from the outcrop of Paleozoic carbonate units in the Funeral Mountains into the Texas Springs syncline. This unit may represent the Paleozoic carbonate rock dipping along the plane of the Furnace Creek Fault.

A geological profile that corresponds to Machette's 2000 reflection survey through the Travertine Spring complex is provided in Figure 13. The profile was developed from geological and geophysical well logs from the U.S. Geological Survey Travertine #1 well, the Travertine #2 well, and four monitoring wells constructed by the National Park Service. This profile illustrated a water table aquifer system confined to

the upper 250 feet of material. The profile also further illustrates the function of the Texas Syncline Thrust Fault in creating the Travertine spring complex.

Figure 13. Geological and Geophysical Profiles Through the Travertine Spring Complex.

A modeled profile of the Texas Gravity Line (Figure 14) indicates that the Paleozoic carbonate units dip relatively smoothly from the start of the line into the basin, but rises as part of the bedrock saddle under Furnace Creek Ranch about 1.5 miles west of the start of the line. The gravity data indicates that the bedrock drops steeply into the Death Valley Basin south of the bedrock high under Furnace Creek Ranch and north into the Furnace Creek Wash. A smaller bedrock high is present approximately one mile west of the east end of the line. This bedrock high begins within a few hundred feet of the position of the Echo Canyon Thrust mapped by Machette (2000). This suggests that the Echo Canyon Thrust Fault may involve the bedrock below the valley fill sediments and is likely to offset the entire sequence of the fan complex.
The presence of an apparent extension of the fault into the bedrock suggests the possibility that at least a portion of the spring flow may be traveling up the Echo Canyon Thrust from the bedrock.

3.5.2 Echo Canyon and Furnace Creek Fault Area
A gravity survey and a total of 49 TEM soundings were conducted along Echo Canyon Road and in the area around Texas, Travertine and Nevares Springs. The purpose of the gravity survey was to map the carbonate bedrock surface across the Furnace Creek Fault. The purpose of the TEM soundings were to map the relative grain size of the valley fill deposits in the upper 1,000 to 1,500 feet of the alluvial fan deposits

adjacent to the Southern Funeral Mountains.

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Figure 14. Modeled Profile of the Texas Gravity Survey Line.

A modeled profile of the Echo Canyon Gravity Line, Figure 15, indicates that the Paleozoic carbonate units
project outward into the basin for about 1.4 miles with a slope of about 40 degrees, then drops steeply to a
depth of about 9,000 feet below sea level. The bedrock surface rises toward the Black Mountains at the
west end of the line. The relatively shallow dip of the bedrock surface at the mountain front is contrary to
prior expectations, which assumed that the Furnace Creek Fault was nearly vertical and the dip of the
bedrock would also be nearly vertical. Upon closer observation, the shear zone of the Furnace Creek Fault
can be seen at the western front of the Southern Funeral Mountains along Echo Canyon Road. The fault
trace dips at approximately 40 degrees at this exposure. The projection of the bedrock surface into the
valley fill sediments provides an opportunity to complete a well in the Carbonate Aquifer with a well
without having to drill from protected wilderness or without having to transport a drill rig into Echo
Canyon at considerable expense and with serious disruption of a scenic area.

A geo-electrical profile line was also constructed from six TEM soundings along the Echo Canyon road
(Figure 16). The location of these soundings in relationship to local geological structure features is shown
on Figure 10. The geo-electrical section suggests that the Travertine and Texas Springs complexes emerge
at facies changes from coarse grained to fine grained sediments at the Echo Canyon Thrust Fault along the
western limb of the Texas Springs syncline.

This geo-electrical profile further indicates that the upper coarse-grained layer is much thinner than in the
area above Texas and Travertine springs (Figure 16). An apparently continuous finer-grained unit is
present below the upper layer. This layer may impede the flow of groundwater through the alluvial fan
deposits, forcing the water flowing up along the Furnace Creek Fault to the surface much closer to the
mountain front.

3.5.3 Nevares Spring Area
The Nevares spring surfaces a short distance west of the Funeral Mountains near the Furnace Creek Fault.
Four deep TEM soundings were collected along Cow Creek Road to determine the grain size of the valley
fill units down to a depth of about 1,500 feet (Figure 17).

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Figure 15. Modeled Profile of the Echo Canyon Gravity Survey Line.

Figure 16. A Geo-electric Profile Along the Echo Canyon Road Generated from TEM Survey Data.

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Figure 17. Map Showing Location of TEM Surveys Through Nevares Spring.

The TEM data detected a high resistivity layer at the east end of the line (Figure 18). This layer is
interpreted as Paleozoic carbonate bedrock dipping fairly gradually approximately one half mile into the
basin from the mountain front. The data indicates the bedrock surface dips steeply into the basin between
soundings TEM8 and TM9, which is less than 1,000 feet west of the Nevares spring mound. This suggests
the spring is located close to the Furnace Creek Fault.

A modeled profile of the Nevares Gravity Line, shown in Figure 19, indicates that the Paleozoic carbonate
units project outward into the basin for about one mile with a slope of about 40 degrees, then drops steeply
to a depth of about 8,000 feet below sea level under the salt pan of the Death Valley Basin. The bedrock
surface appears to be fairly smooth with no significant mounds or offsets superimposed on the general
slope into the basin.

Figure 18. Geo-electric Profile Through Nevares Spring.

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Figure 19. Modeled Profile of the Nevares Spring Gravity Survey Line.

A high-resolution resistivity survey line was run across the Nevares spring mound to provide a more
detailed picture of the structure of the mound complex (Figure 20). The high resistivity area (red colors) at
the northeast end of the line represents the portion of the mound that is unsaturated and consists of dry,
high resistivity travertine deposits. A shallow low resistivity zone (blue colors) is present near the center
and southwestern end of the line. This is interpreted as the saturated portion of the spring mound. The low
resistivity zone appears to dip steeply to the southwest near the eastern edge of the zone of saturation. We
interpret this structure as a saturated fault or fracture zone that is feeding the spring mound from some
deeper source of water.

Figure 20. High-resolution Resistivity Survey Across the Nevares Spring Mound.

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3.5.4 Furnace Creek Ranch Area

Twenty high-resolution TEM soundings were run from above the Texas spring line to the saltpan north of
Furnace Creek Ranch, as previously discussed (Figure14). The soundings were run using a smaller
transmitter coil and denser station interval to focus on the upper 200 feet of material. The high-resolution
data showed a higher degree of variability in the upper units than the deep TEM soundings along the Echo
Canyon line. However, the high-resolution TEM profile confirmed that the upper coarse-grained unit was
significantly thinner below the spring line and that the middle layer was predominantly fine-grained below
the springs.

Five gravity profile lines were conducted across the Furnace Creek alluvial fan south of the Furnace Creek
Ranch Area (Figure 21). Figure 21 is a projection of the bedrock surface from the Southern Funeral
Mountains under the Furnace Creek Ranch area as interpreted from the gravity data. Furnace Creek Ranch
appears to sit on a bedrock high associated with a subsurface projection of the northern terminus of the
Black Mountains. The Furnace Creek Wash and the Death Valley Basin are expressed as deep structural
lows on either side of the high. The Southern Funeral Mountains form a large bedrock high on the eastern
side of the projection.

Figure 21. Projection of Bedrock Surface Below Furnace Creek Ranch Alluvial Fan Area.

4.0 Groundwater Flow Through the Southern Funeral Mountain Range

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.

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 6 and 7). 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 Inyo-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.

Given the maps of the base of the Carbonate Aquifer, Figures 6 and 7, it is feasible to attempt to model the
groundwater flow through the Funeral Mountains. We developed two numerical groundwater flow models
of the Southern Funeral Mountain Range to evaluate the potential of flow through this mountain block.
The first model was includes the complete southern portion of the Funeral Mountains. The second model is
confined to the Texas and Travertine spring areas of Death Valley National Park. The development and
results of these two models are provided below.

4.1 Southern Funeral Mountain Range Numerical Groundwater Model
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 1. 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, Table 1 (personal communication). We attempted to reconcile the
measurements.

Table 1. 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 6 and 7 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. Inyo-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 6 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 Inyo-BLM#1 head.

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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 6 and 7; 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 22.

Figure 22. Computed Hydraulic Head in Carbonate Aquifer.

The model as depicted in Figure 22 reproduces the discharge of the various springs quite well, as shown in
Table 2.

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Table 2. Computed Discharge of the Furnace Creek Springs.

Springs Approximate Estimated Model Computed
Elevation (Feet) Flow (Cfs) 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 ft2/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 2 or 3. In the case of the shallower dipping fault plane (Figure 6) the model projects approximately 300 feet of aquifer saturation through the critical area-designated as the spillway on Figure 2. 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 200C is one-centipoise; at 500C 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 500C temperature, then the calculated permeability is 1.2 x 10-13 m2. 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.

4.2 Groundwater Flow Through the Travertine and Texas Spring Complex
The alluvial portion of the Travertine and Texas spring aquifer complex is contained in two synclines that are situated to the southwest of the Furnace Creek Fault-they are shown best on Figure 11. The synclines appear to be thrust to the southwest. Fridrick attempted to contour the base of the alluvial aquifer in Figure

6. Figure 23 is a detailed tectonic map of the area of in the vicinity of Texas and Travertine springs; it shows the locations of the recent test wells.
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Figure 23. Tectonic map in the vicinity of the Texas and Travertine springs; the map shows the location of recent test wells.

Figure 13 contains two cross-sections through the area shown of Figure 23. The test drilling indicated that the most permeable sediments are relatively shallow, above a depth of 250 feet.

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A numerical groundwater flow model of the Texas and Travertine spring complex was developed from exploratory monitoring well logs, geophysical surveys in the study area, and from a 72-hour pumping test. The geological framework of the Texas and Travertine spring complex was presented in Section 3.5.1 and

3.5.2 of this report. Our analysis of the 72-hour pumping test is provided below.
4.2.1 Travertine Well #1 72-Hour Pumping Test Analysis
A 72-hour pumping test was conducted, in May 2005, in a well in the vicinity of Travertine and Texas springs–shown on Figure 23. The purpose of a pumping test was to determine the hydrologic properties of the aquifer–transmissivity, and storativity. Once these properties were determined, they where used to estimate the impact that pumping will have upon the system.

Figure 24 shows a log-log plot of drawdown observed during the pumping test in one of the observation wells–TSS-MW-2.

Figure 24. Plot of drawdown in observation well TSS-MW-2 during the 72-hour pumping test in May 2005.

The analysis of pumping test data involves fitting a theoretical model to the observed data. In the past this was done manually, now there are computer programs to assist one in the analysis. AQTESOLVE (2002) is one of the more widely used programs for pumping test analysis. There are two theories that best fit our test results–1) Moench (1993), and Moench (1996); and 2) Neuman (1974). Figure 25 is the pumping test drawdown data from observation well, TSS-MW-1, fit to the Neuman (1974) theoretical drawdown curve, using AQTESOLVE (2002). The fit to the Neuman theoretical curve is rather good. From the fit to the theoretical model we determine the aquifer properties.

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Figure 25. Fit of the 72-hour pumping test drawdown data to the Neuman (1974) theoretical curve using AQTESOLVE (2002).

The results of the pumping test analysis are summarized in Table 3:

Table 3. Summary of Pumping Test Results

Well	Transmissivity--ft2/d		Specific Yield	
	Neuman	Moench	Neuman	Moench
TSS-MW-1	5,980	6,260	0.24	0.27
TSS-MW-2	15,400	16,360	0.04	0.03
TSS-Well-2s	5,890	5,020	0.03	0.20
Average	9,090	9,215	0.10	0.17

The pumping test drawdown data, as illustrated by Figures 7 and 8, demonstrate what hydrologists refer to as delayed yield responses. These are typical of water table aquifers–aquifers in which the productive zone extends to the land surface.

The pumping test results indicate that the alluvial aquifer has a transmissivity of approximately 0.1 ft2/sec
(~9,000 ft2/d). It is approximately one-half (50%) of the transmissivity estimated for the Paleozoic
Carbonate rocks that underlies the Funeral Mountains. This also indicates that our regional model
calculations for the alluvial portion of the aquifer, shown above in Figures 3 and 4, are wrong and need to
be revised with new information from the pumping test.

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4.2.2 Travertine and Texas Spring Complex Groundwater Flow Model
In order to assess the local impacts of pumping we created a digital aquifer model of the alluvial part of the
aquifer using the U.S. Geological Survey (USGS) computer program MODFLOW. The first task is to map
the alluvial aquifer on a local base map. Figure 26 is a map of Fridrick's structure contour map on the base
of the alluvial aquifer overlain on the local topography.

Figure 26. Structure contour map of the base of the alluvial aquifer overlain on the topography.
The extent of the alluvial aquifer is shown.

The next step in the modeling is to place a finite difference grid over the area of interest. Figure 27 shows
our finite difference grid imposed upon the aquifer. The grid cells are 500 by 500 feet. The grid is oriented
parallel to the Furnace Creek Fault approximately in a northwest-southeast orientation. This orientation
minimizes the number of inactive cells in the model and facilitates the numerical computations.

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Figure 27. Topographic map with the alluvial aquifer and the model grid superimposed.

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The active portion of the model is shown on Figure 28.

Figure 28. The active portion of the model. Recharge occurs along the Furnace Creek Fault in the dark
blue cells. The springs occur along the southeast edge of the model in the four orange colored cells.

We first input recharge, equally distributed along the Furnace Creek Fault where the fault adjoins the
alluvial aquifer tc the northeast–indicated by the dark blue cells in Figure 28. We then use the model to

compute a steady-state flow condition without pumping–groundwater discharges in the principal springs.
We have data that constrains the model:

• we have estimates of flow for the four springs that discharge from the alluvial aquifer,
• we also know the spring elevations, and
• we have a non-pumping water level for the cluster of wells.

The point of the steady-state model is to best fit the observed data. Figure 29 is our best-fit, steady-state
model. It was virtually impossible to match the elevation of the Cow Creek and Salt springs and the
Travertine and Texas springs with a continuous aquifer, even with an aquifer in which there were very
large changes in permeability between the two spring areas. The modeling suggests that there is a barrier to
flow between the two areas. We have arbitrarily introduced a flow barrier in the finger of alluvial
sediments that extends to the northwest–the barrier is obvious on Figure 12.

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Figure 29. Calculated steady-state water table in the alluvial aquifer prior to pumping.
The cells that have spring discharge are shown in orange

We now introduce the pumping into the model. We simulated the impact of pumping a 12" diameter well
in approximately the location of the well that was pumped for the pumping test. We assume that this well
was properly constructed and developed so that the well losses are minimized. (The well used for the
pumping during the test had very large losses caused by the state of the well itself–a very inefficient well.)
We simulated pumping the well at 1.0 cfs (448 gpm) indefinitely. Figure 30 shows the calculated water
table caused by pumping the well continuously, indefinitely–steady-state water table.

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Figure 30. Calculated water table produced after pumping a well at the indicated location at 1 cfs indefinitely.

The drawdown caused by the pumping is small so that there is very little change between Figures 29 and

30. Figure 31 is a map of the calculated drawdown caused by pumping the well.
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Figure 31. Calculated steady-state drawdown caused by pumping the well at the indicated
location at a rate of 1 cfs indefinitely.

The calculated drawdown in the model cell that contains the well is 9.65 feet. This translates to a steady-state drawdown in a 12-inch diameter, efficient well of 19.2 feet

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The computed drawdown is approximately 0.5 ft in vicinity of the Travertine springs. Table 4 summarizes
our results for the flow from the springs associated with the alluvial aquifer.

Table 4. Summary of calculated results for the springs associated with the alluvial aquifer.

Spring	Measured	Steady-state	Pumping
Cow Creek	0.1	0.08	0.08
Salt	0.1	0.12	0.12
Texas	1.0	1.27	1.05
Travertine	3.2	2.93	2.16

The modeling suggests a smaller impact from the pumping on Texas spring even though it is the closest
spring to the well and has almost 4 feet of calculated drawdown. Springs are simulated in the model by
specifying both the spring elevation and a hydraulic conductivity; the hydraulic conductivity presumably
represents the hydraulics of the spring orifice. Travertine and Texas springs are difficult to reproduce in
the model with their 30-foot difference in elevation–Travertine is 30 feet higher than Texas. One-way to
make the model fit is to introduce a lower hydraulic conductivity for the spring orifice at Texas spring; this
is what was done. Whether this lower hydraulic conductivity for Texas spring is real is problematical.
There may be a larger impact on Texas spring than the modeling suggests. Making the impact larger at
Texas would reduce the impact at Travertine by an equal amount.

As indicated above, the amount of drawdown in the pumping well is modest. Our best estimate is that the
pumping well will have a steady state drawdown of just over 19 feet (~19.2 ft). This assumes that the
pumping well has good well efficiency–gravel packed, properly developed by the driller, etc.

5.0 Summary and Conclusions Concerning the LCA
Inyo County successfully completed U.S. Department of Energy Cooperative Agreement No. DE-FC0802RW12162 within the allow budget. The program met the overall goal of these studies to evaluation
issues related to potential transport, by ground water, of radionuclides into Inyo County, including Death
Valley, and the evaluation of a connection between the Lower Carbonate Aquifer (LCA) and the biosphere.
The program was partially successful in establishing the relationship between carbonate spring waters in
Death Valley (within Inyo County) and the groundwater flowing under Yucca Mountain. The program was
also partially successful in:

1. Establish the existence of inter-basin flow between the Amargosa Basin and Death Valley
Basin,
2. Characterize groundwater flow paths in the LCA through Southern Funeral Mountain

Range,
and
3. Establish the hydraulic connection between the Yucca Mountain repository site to the major
springs in Death Valley through the LCA.
Geologic mapping in the Funeral Mountains provided two possible contour maps for the base of the
Carbonate Aquifer in the range. Each geological framework model illustrates the existence of hydraulic
flow paths in the LCA through the Southern Funeral Mountain Range. It also indicated a barrier to
groundwater flow in the LCA system. Groundwater flow paths appear to be confined to "spillways"
through the mountain block.

Inyo-BLM#1 did reach our objective–the Carbonate Aquifer in the Amargosa Desert basin, but funding
constrains prevented the completion of the well as a LCA monitoring well. This deep drilling has
established a Carbonate Aquifer water level in our first drill hole
Inyo-BLM#1–approximately 2280 ft. in
elevation.

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Our second deep hole in the Amargosa Desert basin, Inyo-BLM#2, was drilled and cased to a depth of
2700 ft. in the lower section of the Amargosa Formation just above the Carbonate Aquifer. The hole can be
drilled deeper when the budget allows.

Our Southern Funeral Mountain numerical groundwater flow model provides the strongest evidence of a
hydraulic connection between the carbonate spring waters in Death Valley (within Inyo County) and the
groundwater flowing under Yucca Mountain. Our MODFLOW groundwater flow model is consistent with
the available data and recreates the flow through the Southern 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 ft2/sec.

The 72-hour pumping test results indicate that the alluvial aquifer has a transmissivity of approximately 0.1
ft2/sec (~9,000 ft2/d), and a specific yield of approximately 0.2. This suggests that the alluvial portion of
the aquifer is a reasonably permeable, water table aquifer. The transmissivity is approximately one-half the
transmissivity we estimated, using our regional MODFLOW model, for the Paleozoic Carbonate part of
aquifer that underlies the Funeral Mountains.

Our model of the alluvial portion of the aquifer system indicates that the local aquifer can easily sustain a
well pumping 1 cfs (448 gpm). The pumping well will have a drawdown of just over 19 feet. Texas and
Travertine springs will undergo a reduction in discharge equal to the pumping–1 cfs. Since our estimate

of the combined flow of the springs is 4.2 cfs before pumping, the reduction in combined flow will be less than 25%.

The modeling suggests that the larger impact will be on Travertine spring where the reduction in flow, attributable to the pumping, might be as large as 26%; the modeling further suggests that the flow of Texas spring will be reduced by 17%. There are problems associated with the procedure for representing springs in MODFLOW. Texas spring is closer to the pumping well; there may be a larger impact at Texas spring, even though the model does not suggest it. Any further reduction in the flow of Texas spring will be compensated by a comparable increase in the flow of Travertine spring.

6.0 Recommendations

Project funding constraints prevented the completion of the total proposed Cooperative Agreement program to drill and complete five monitoring wells in the LCA in the Southern Funeral Mountain Range area. Inyo-BLM#1 penetrated the LCA, but funding constrains prevented the completion of the well as a LCA monitoring well. The pump testing and water chemistry sampling of this well would provide critical data on the LCA. Inyo-BLM#2 well was cased approximately 1,500 feet above the contact of the LCA. The deepening and completion of this well would also provide critical data on the LCA. In addition, geologic constraints, coupled with hydrologic characterization of the flow-system, penetrated by additional deep LCA wells would provide new information that will allow one to further:

1. evaluate regional groundwater flow through the southern Funeral Mountains,
2. establish structural controls on flow-paths and discharge areas, and
3. evaluate potential zones of mixing between deep, regional Lower Carbonate Aquifer

groundwater and that derived locally from shallow groundwater systems to the northeast.

The U.S. Department of Energy models of the Yucca Mountain area represent a reasonable interpretation of the geology of the area; however, they are based on limited data on the groundwater hydrology of the Death Valley system. Major data gaps exist in:

1. Drilling data in the LCA,
2. Groundwater discharge measurements in Death Valley,
3. Surface and groundwater inflow data into Death Valley from the Amargosa River,
4. Infiltration measurements in mountains that adjoin Death Valley,

5. Direct data on the source of springs in Death Valley,
6. Water level monitoring data,
7. Hydraulic parameters of the associated aquifers, and
8. Information on hydraulic boundary conditions in Death Valley.

For the USGS Death Valley Groundwater Basin regional model and the U.S. Department of Energy Yucca Mountain System Performance model to be improved these major data gaps need to be filled. Both models are used to estimate the travel time of radionuclides from Yucca Mountain through the LCA.

The U.S. Environmental Protection Agency recently modified its dose criteria for the Yucca Mountain
Project. The effect of this modification is to effective increase the critical study period to approximately
one million years. At this time frame, groundwater transport from Yucca Mountain into Inyo County is
likely. Thus the further hydraulic analysis of the Southern Funeral Mountain Range, and the Franklin Lake
Playa areas would be critical to the U.S. Department of Energy Yucca Mountain System Performance
model.

Work Plan: We recommend the following work plan:

1. Evaluate relevant existing hydrochemical and isotopic data for ground water (Yucca Mountain,
Crater Flat, Amargosa Desert (east and west), Ash Meadows, Franklin Lake Playa).
2. Installation of up to 10 nested monitoring wells in the Franklin Lake Playa to an approximate
depth of 200 feet below ground surface.
3. Sample relevant wells to characterize the noble gas budget of the Yucca Mountain flow system.
4. Conduct high-precision analyses of noble gas contents of sampled wells.
5. Develop a numerical groundwater flow of the Tertiary-age aquifer system.
6. Establish end-member water compositions and develop a hydrochemical model to determine the
degree and extent of mixing, dilution, or burial of the contaminant plume as it moves from Yucca
Mountain to Franklin Lake Playa.
7. Summarize the results of the study and estimate dose for the possible scenarios.

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