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ABSTRACT

Ground water flow through the region south and west of Frenchman Flat, in the Ash Meadows subbasin of the Death Valley ground water flow system, is controlled mostly by the distribution of permeable and impermeable rocks. Geologic structures such as faults are instrumental in arranging the distribution of the aquifer and aquitard rock units. Most permeability is in fractures caused by faulting in carbonate rocks. Large faults are more likely to reach the potentiometric surface about 325 meters below the ground surface and are more likely to effect the flow path than small faults. Thus field work concentrated on identifying large faults, especially where they cut carbonate rocks. Small faults, however, may develop as much permeability as large faults. Faults that are penetrative and are part of an anastomosing fault zone are paricularly important. The overall pattern of faults and joints at the ground surface in the Spotted and Specter Ranges is an indication of the fracture system at the depth of the water table. Most of the faults in these ranges are west-southwest-striking, high-angle faults, 100 to 3500 meters long, with 10 to 300 meters of displacement. Many of them, such as those in the Spotted Range and Rock Valley are left-lateral strike-slip faults that are conjugate to the NW-striking right-lateral faults of the Las Vegas Valley shear zone. These faults control the ground water flow path, which runs west-southwest beneath the Spotted Range, Mercury Valley and the Specter Range.

The Specter Range thrust is a significant geologic structure with respect to ground water flow. This regional thrust fault emplaces siliceous clastic strata into the north central and western parts of the Specter Range. These rocks act as a barrier or aquitard that confines ground water flow to the southern part of the range, directing it southwestward toward springs at Ash Meadows. These siliceous clastic aquitard rocks and overlying Cenozoic deposits probably also block westward flow of ground water in Rock Valley, diverting it southward to the flow path beneath the southern part of the Specter Range.

INTRODUCTION

The Nevada Test Site (NTS) , in the southern Great Basin part of the Basin and Range physiographic province (fig.1), is characterized by internal surface drainage and widely spaced springs fed by water that travels great distances along deep aquifers. The Death Valley ground water flow system (fig. 2), which entirely underlies the NTS, consists of a western series of generally south-flowing aquifers in mostly Tertiary volcanic rocks and an eastern group of southerly flowing aquifers in mostly Paleozoic carbonate rocks. The ground water ultimately reaches Death Valley at the south edge of the ground water flow system. The Frenchman Flat area is in the eastern mostly carbonate flow path of this flow system called the Ash Meadows subbasin of the Death Valley flow system (Laczniak and others, 1996).

The ground water moves down the regional gradient along circuitous routes controlled by water-transmitting properties of the local rocks. The permeability of the rocks is related to primary features such as stratification, grain size, sorting, and cementation, and secondary features such as diagenetic minerals, dissolution, recementation, compaction, brecciation, and fracturing. Fracturing, the most important feature may occur at all scales, from intergranular ruptures to regional faults. Permeability is achieved when cavities or intergranular pores are interconnected or when a continuous feature such as a fault forms a throughgoing path.

The objective of this paper is to evaluate the geologic structures (mostly faults and joints) in the region south and west of Frenchman Flat (fig. 3) as to their impact on the ground water flowing southwestward to Ash Meadows and ultimately Death Valley. The main flow path, controlled by regional hydraulic gradients and locally confined at some depth beneath the potentiometric surface, passes beneath parts of the Spotted Range, Mercury Valley, and part of the Specter Range (Winograd and Thordarson, 1975; Laczniak and others, 1996). The relative influence on the ground water flow of major and minor faults in the area versus the distribution of different rock units is discussed.

Sources of information. This report is based on review of a number of publications on the Nevada Test Site (NTS) region as well as unpublished sources and limited field work carried out in 1997. The main publications used for this summary include: *Summary of hydrogeologic controls on ground-water flow at the Nevada Test Site, Nye County, Nevada* by Laczniak and others, 1996; *Hydrogeologic and hydrochemical framework, south-central Great Basin, Nevada-California, with special reference to the Nevada Test Site* by

Winograd and Thordarson, 1975; *Structural geology of the Specter Range quadrangle, Nevada and its regional significance* by Burchfiel, 1965; *Middle Devonian-Mississippian stratigraphy on and near the Nevada Test Site: implications for hydrocarbon potential* by Trexler and others, 1996; *Tertiary extension north of the Las Vegas Valley shear zone, Sheep and Desert Ranges, Clark County, Nevada* by Guth, 1981; *Preliminary analyses of minor structures and lithologic boundaries for the Frenchman Flat model area* by Grauch and Hudson, 1995; *Digital bedrock geologic map data base of the Beatty 30' X 60' Quadrangle, Nevada by* Carr and others, 1996.; *Regional structural setting of Yucca Mountain, southwestern Nevada, and late Cambrian rates of tectonic activity in part of the southwestern Great Basin, Nevada and California,* Carr, 1984. Unpublished reports include: *Structural relationships of the Pre-Tertiary rocks of the Nevada Test Site region, southern Nevada* by James C. Cole and Patricia H. Cashman; *Characterization of Quaternary faulting within the Cane Spring and Rock Valley fault zones* by Dennis W. O'Leary, Jeffrey A. Coe and James C. Yount; and *Geologic subcrop map of major structures within the pre-Tertiary rocks of the Yucca Flat and Frenchman Flat areas, Nevada Test Site region* by James C. Cole. All references cited in the text are listed in the references section.

Region evaluated. Geologic structures, especially faults, that are shown on various geologic maps of the area south and west of Frenchman Flat (the flow path from Frenchman Flat) make up the main data for this study. Linear features that show on topographic maps, aerial photographs, or satellite photographs and that are probably faults or caused by faults are also considered. Specifically, the area evaluated includes the western part of the Spotted Range directly south of Frenchman Flat, the Red Hills and Mercury Valley west of the Spotted Range, Rock Valley west of the southern part of Frenchman Flat and north of the Red Hills, the Specter Range, Skeleton Hills, and Stripped Hills southwest of Frenchman Flat, and the north end of the Spring Mountains, which merges with, and lies southeast of, the Specter Range (fig.3). Southwest of this area the ground water reaches the Amargosa Desert and surfaces at Ash Meadows before continuing beneath or around the Funeral Mountains into Death Valley. Ground water from west of the Specter Range that comes primarily from the western, mostly volcanic part (Oasis Valley and Amargosa-Furnace Creek Ranch subbasins) of the Death Valley ground water flow system probably does not reach Ash Meadows on its more westerly route to Death Valley (Laczniak and others, 1996).

The stratigraphy, facies, and lithologic character of the Upper Precambrian and Paleozoic rocks in the Death Valley-Nevada Test Site region are considered because of their relevance to the ground water flow path, especially where structures have brought contrasting rock types (carbonate versus siliceous rocks) together.

REGIONAL STRUCTURES

Las Vegas Valley shear zone. The Las Vegas Valley shear zone projects into the southern part of the Spotted Range from the southeast (fig.4). This large crustal structure first described by Longwell in 1960 has about 40 kilometers of right-lateral offset southeast of the Spotted Range and northwest of Las Vegas (Burchfiel, 1965). There is no indication that the Las Vegas Valley shear zone extends west of the Spotted Range. In the Spotted and Specter Ranges tectonism is manifested as southwestward trending structures and southwestward trending topography. This structural and topographic grain was termed an oroflex by Albers (1967) who speculated that it was caused by fault drag near the northwest end of the Las Vegas Valley shear zone. Subsequent geologic and geophysical studies have not borne out the idea of oroclinal bending of structures in the Spotted and Specter Ranges. The southwest-striking structural and topographic features at the north end of the Las Vegas Valley shear zone in the Spotted and Specter Ranges end at the Amargosa Valley. Farther west in the domain of the Walker Lane at Yucca Mountain and Bare Mountain the dominant structures have north to northwest strikes.

In the oroflex model of Albers (1967) dextral drag at the north terminus of the Las Vegas Valley shear zone is expressed in the Spotted and Specter Ranges as southwestward orientation of geologic features including topography, faults, folds and stratigraphic trends in the Paleozoic strata. In the eastern reaches of the Las Vegas Valley shear zone, southeast of the Spotted Range, the bent structures are offset in a right-lateral sense by as much as 40 kilometers (Burchfiel, 1965). No significant right-lateral strike-slip offset can be demonstrated in the western end of the shear zone in the Spotted and Specter Ranges.

The age of the west trending structures in the Spotted and Specter Ranges is open to interpretation. Southeastward, along the Las Vegas Valley shear zone, well- documented offset affects middle to late Tertiary basin-range faults and cuts middle Miocene volcanic rocks. The age of this shearing in the Las Vegas area is bracketed between about 15 and 10 Ma (Bohannon, 1984). There are no rocks of the appropriate age to date the southwest striking structures west of the shear zone in the Spotted and Specter Ranges. Lacking other evidence, it is assumed that the 15 to 10 Ma age of the southeastern part of the shear zone near Las Vegas can be applied to the entire length of the zone, including the southwest striking structures in the Spotted and Specter Ranges.

Walker Lane. The term Walker Lane, Walker line, Walker belt, and Walker Lane belt are names applied to a generally north-northwest-trending linear zone of ranges lying between the Sierra Nevada on the west and northeast trending basin and ranges of the Basin and Range physiographic province on the east. Some descriptions of this belt note strike-slip faulting (mostly right-lateral) as a dynamic tectonic element.

The original description of the belt by Giannella and Callagahn (1934) defined it as a narrow zone of northwest- striking right-lateral rupture typified by the faults that caused the Cedar Mountain earthquake of 1932. The definition of the zone was expanded by Billingsley and Locke in 1939 and 1941 to represent a belt separating regions of contrasting topographic style that runs essentially along the California-Nevada state line south of Reno. It is tens of kilometers wide by this definition. As currently used the term Walker Lane or Walker Lane belt encloses an elongate region of variable topography that owes much of its north-northwest alignment to north-northwest striking strike-slip faults. This broad zone is about 700 kilometers long and 80 to 240 kilometers wide. Stewart (1988) divided this belt into nine tectonic blocks, each with distinctive tectonic style. A somewhat more restrictive Walker Lane belt is that of Carr (1984), whose southwestern boundary is the northwest striking Death Valley-Furnace Creek-Fish Lake Valley fault zone but the northeastern boundary is poorly defined as passing southeast across the Nevada Test Site with no physiographic or geologic definition.

In southern Nevada, including the Nevada Test Site, the eastern boundary of the Walker Lane is difficult to mark because the topography is dominated by Miocene volcanic features, in particular, resurgent collapsed calderas and widespread ash-flow sheets. The Walker Lane can be expanded eastward to include these calderas and eruptive rocks in the Black Mountain and Timber Mountain region or it can be restricted to a belt running west of the calderas (west of the Nevada Test Site). If it is expanded eastward, the Las Vegas Valley shear zone merges into it from the southeast. If it is restricted, there is no obvious connection between the Las Vegas Valley shear zone and the Walker Lane.

In his analysis of the Walker Lane belt, Stewart (1988) proposed an eastern boundary that used the Las Vegas Valley shear zone as the eastern edge of the belt. By this definition the region including Frenchman Flat, the Spotted Range, and the Specter Range are within the Walker Lane belt. Because this expanded Walker Lane belt contains a wide spectrum of geologic features with diverse tectonic styles and trends, Stewart (1988) divided it into a number of structural blocks. One block, called the Spotted Range-Mine Mountain block, is separated from the Spring Mountain block to the south, along Rock Valley. Making Rock Valley a domain boundary between major blocks in the Walker Lane belt suggests that it is a crustal structure of regional significance. However, the stratigraphy and structure of the

Paleozoic rocks north and south of Rock Valley indicate left-lateral offset on the Rock Valley fault is only1.4 to 3.2 kilometers (O'Leary, 1997). Other southwest-striking, left-lateral, strike-slip faults north of Rock Valley near Cane Springs and in the Spotted Range augment the amount of cumulative left-lateral displacement in the region.

Structures between the Walker Lane and the Las Vegas Valley shear zone or, using Stewarts (1988) definition, between blocks in an expanded Walker Lane belt, form the principal paths for ground water flow from Frenchman Flat to the Amargosa Desert. The left-lateral faults in Rock Valley, however, seem to have minimal influence on the flow from Frenchman Flat. There is no evidence that these faults have diverted the ground water along this westerly route into Amargosa Valley. Only along the easternmost parts of the Rock Valley fault zone where it emerges from Frenchman Flat does there seem to be any chance for local westward diversion from its more southwesterly course of some of the ground water (fig. 5). For a short distance at the head of Rock Valley, it is possible that the ground water moves westward. It is more likely, however, that the flow path leads south from Frenchman Flat beneath the Red Hills and joins the main southwesterly trending carbonate rock aquifer beneath the Spotted Range, Mercury Valley, and the Specter Range (fig. 5).

Ground water flowing northward from the north flank of the Spring Mountains joins the flow path of ground water from Frenchman Flat in the area north of Indian Springs along the south edge of the Spotted Range (Winograd and Thordarson, 1968 and 1975; Laczneak and others, 1996). From this point, flow is westward along the main flow path beneath the Spotted Range, southern Mercury Valley, and the Specter Range. This entire route is about three kilometers south of Rock Valley and occupies a lower position on the hydraulic gradient than Rock Valley (Winograd and Thordarson, 1975).

Strike-slip faults. Strike-slip faults are abundant in the southern part of the Spotted Range (Barnes and others, 1982) and are probably more significant in the Specter Range to the west than the most geologic maps suggest (see Burchfiel, 1965, 1966; Frizzell and Shulters, 1990; Hendricks, 1968; Sargent and Stewart, 1971).

The Rock Valley fault zone which extends from the southwest edge of Frenchman Flat and runs westward to the Amargosa Desert, is a well defined series of left-lateral strike-slip faults, some with traces at least several kilometers long. The fault zone underlies a narrow east-northeast striking basin (Rock Valley) that contains as much as 1000 meters of Cenozoic sedimentary rocks. Seismic activity indicates that fault slippage extends to depths as great as 11 kilometers (O'Leary, 1997) and the presence of recemented breccia and injection gouge on some fault surfaces indicates the presence of water in the system at some time in the past. A number of left-lateral faults with southwesterly strikes and as much as 10 kilometers long are mapped in the Spotted Range (Barnes and others, 1982). These faults lie directly above, and are parallel to, the ground water flow path in the area. They undoubtedly produce the major fracturing in the underlying carbonate rocks of this regional aquifer. Other southwest striking left-lateral faults have been mapped in the Specter Range (Burchfiel, 1965) and many of the long, southwest- striking, steeply dipping faults in this range may have left-lateral displacement as well as the dip-slip motion that is shown on most of the geologic maps.

The southwest- striking faults of the Spotted and Specter Ranges and Rock Valley may be part of a zone of faults that are conjugate to the stress field of the Las Vegas Valley shear zone and link it with the Walker Lane. This regional, interrelated fault system serves as an ideal path for ground water where it cuts carbonate rocks that readily form aquifers.

Basin-range faults. Basin range is defined in the *Glossary of Geology,* (Gary and others, 1972), as "a relatively long and narrow mountain range that owes its present elevation and structural form mainly to faulting and tilting of strata and is isolated by alluvium-filled basins or valleys". The term basin-range fault denotes a high-angle normal fault that is responsible for the uplift of an elongate mountain block. In the Basin and Range physiographic province of western United States these structures are generally considered to be late Cenozoic in age. It is emphasized that all late Cenozoic faults in the Basin and Range physiographic province are not basin-range faults.

Throughout the Basin and Range physiographic province springs may occur at range fronts and are clearly associated with basin-range faults. Many springs come up along the fault trace; in places this may be a scarp, but if erosion has removed the scarp, water emerges at the break in slope. Movement on basin-range faults frequently disrupts spring systems, cutting off flow in one place and initiating it in a new place along the fault. Basin-range faults, however, can only be the site of springs if they intersect the ground surface below the elevation of the ground water. The springs along the faults may be artesian if the aquifer's confining cap is breached by fracturing. In many parts of the Nevada Test Site and in particular in the area south and west of Frenchman Flat, these criteria are not met and the few springs that exist are not associated with basin-range faults. In fact, basin and range topography generally is not developed south and west of Frenchman Flat. The Spotted and the Specter Ranges are discontinuous nonlinear blocks without sharply defined boundaries with the surrounding basins. Physiographically they do not resemble horsts and grabens.

Detachment faults. The Spotted and Specter Ranges lie in a region in the southern part of the Great Basin in which great crustal extension has been postulated to have taken place on gently dipping detachment faults in the past 15 million years (Wernicke and others, 1988).

These authors estimate this extension across the entire Great Basin at the latitude of Las Vegas to be on the order of 300 kilometers in a west-northwest direction. The postulated detachment faults separate ductilely deformed rocks below, from brittley fractured rocks above. The rocks above a master detachment fault are thought to be cut by sets of parallel normal faults that steadily flatten with depth, ultimately merging with the detachment surface. Down-dip displacement on these curved, concave-up fault plains presumably causes progressive, potentially extreme, tilting of the fault bounded blocks in the brittle zone. At the crustal level exposed today, the postulated flat detachment fault(s) is not exposed. Its presence at depth is essential, according to Wernicke and his colleagues, to accomodate the inferred great crustal extension. An additional feature of the hypothesized southern Nevada detachment faults is that they tend to reactivate older (Mesozoic) thrust faults (Guth, 1990). Reactivation of Mesozoic low-angle thrust faults in the uppermost part of the earth's crust by late Cenozoic extension, however, seems unlikely if the scale, dimensions, and strength of material (brittle rock) is considered. The possibility that these essentially flat Mesozoic thrust faults in a thin and very widespread plate of brittle rock could direct the renewed fracturing is extremely remote.

It is questionable whether detachment faults underlie the Spotted and Specter Ranges. Moreover, the effect of any detachment fault,if present at all, on the ground water flow path from Frenchman Flat would probably be a second-order phenomenon. Detachment faults would not elevated an aquitard athwart the flow path nor would they increased the thickness of carbonate aquifer units. Such faults might act as horizontal channels for ground water flow if they increased fracture permeability, but there is no reason to expect they would be any more significant in this regard than hundreds of other faults in the region with many orientations and ages.

Thrust faults. Thrust faults have been mapped in the Specter Range and Spotted Range by Sargent and Stewart (1971), Henrichs, (1968), and Barnes and others (1982). In both ranges the faults thrust Cambrian strata on top of younger units. In the Specter Range the younger rocks are Ordovician, Silurian, and Devonian rocks, and in the Spotted Range they are as young as Mississippian. Because of the general similarity in upper and lower plates in the two ranges, it was postulated that the Specter and Spotted Range thrusts are one fault that rides over progressively younger strata from west to east (Barnes and Poole, 1968; Carr, 1984; Snow and Wernicke, 1989, and Caskey and Schweichert, 1992). Careful analysis of the thickness, stratigraphic succession, and location of the stratigraphic units between the Specter Range and the Spotted Range indicates that there are two different thrusts at different structural levels (Cole and Cashman, 1997).

In the western part of the Specter Range the stratigraphic separation between the upper and lower plates is as much as 225 meters; about 1.8 kilometers east in this range, the separation is about half this amount, and further east at the west end of Mercury Valley there is no stratigraphic separation. The upper and lower plates merge eastward as the Specter Range thrust dies out. Eastward across Mercury Valley in the Spotted Range higher stratigraphic levels are encountered because of the general eastward dip of the strata. In the central part of the Spotted Range, Mississippian limestone represents the highest level reached in this succession. In this area, the Spotted Range thrust brings Cambrian rocks on top of the Mississippian and older strata. The Spotted Range thrust, here a klippe comprised of three separate thrust sheets, overrides rocks of the merged upper and lower plates of the Specter Range thrust.

The Spotted Range thrust, representing the highest structural level of the thrusts, and now seen as an isolated klippe at the top of the range, has no effect on the ground water flow from Frenchman Flat. It does not penetrate to the level of the ground water and it does not bring potential aquitards of siliceous clastic rocks that into the area. The lower plate of the Spotted Range thrust is carbonate rock for the upper 3000 or more meters and, as such, acts as an aquifer. West of the Spotted Range beneath Mercury Valley and in the Specter Range it is an aquifer as well. In the Specter Range a new thrust surface develops in the lower plate of the Spotted Range thrust. In the central and western part of this range, the stratigraphic separation between plates of this thrust (the Specter Range thrust) is large as progressively older strata are encountered in the upper plate. In these parts of the Specter Range, siliceous clastic rocks of the Lower and Middle Cambrian Carrara Formation and older units, present at the surface and more common at depth, act as barriers to ground water flow and divert it southward beneath the range (fig.5).

LOCAL STRUCTURES

Faults mapped at the scale of 1:24,000. The characteristics of faulting outlined here are based on evaluation of 1:24,000 scale geologic maps and on field observations by the author. The most detailed geologic maps of the Spotted and Specter Ranges and the Red Hills are at a scale of 1:24,000 (Henricks, 1968, Camp Desert Rock Quadrangle; Sargent and Stewart, 1971, Specter Range NW Quadrangle; Barnes and others, 1982, Mercury Quadrangle). These maps show a variety of faults, most of which are recognized because of stratigraphic offset of Paleozoic units. Some cut other geologic structures that are offset, and some are defined on the basis of linear features seen on topographic maps or aerial photographs. The density and attitude of mapped fault traces are about the same in the three quadrangles; most differences are probably due to the mapping style and philosophy of the different geologists who made the maps. In the Paleozoic bedrock, the number of mapped faults is on the order of 30 to 60 faults in three square kilometers, with the faults ranging between about 100 and 3500 meters in length. Most are about 1000 meters long. These faults range in magnitude from the previously described regional thrust sheets that exhibit thousands of meters of stratigraphic offset and kilometers of transport, to smaller faults with only a few meters of stratigraphic offset. Southwest-striking high-angle faults are the most common local structures mapped. The prevalent faults shown on the 1:24,000 scale maps have offsets that are generally proportional to the length of the fault, short faults have little offset, longer ones greater offset. The amount of offset is about one order of magnitude less than the fault length. A 1000 meter long fault typically has about 100 meters of stratigraphic offset, a 100 meter long fault has 10 meters or less of displacement. The smaller faults probably seldom reach the potentiometric surface several hundred meters beneath most parts of the Spotted and Specter Ranges. For this reason, study of individual small faults in these ranges will probably give little specific information about ground water flow. Their significance, however, is that they offer a clue to the structural framework at the depths where the ground water is. The geometry, general size, and style of the faults mapped at the surface should be similar to those at depth. This is because the stress fields that controlled faults and other structures at the ground surface also controlled those at the levels of the present ground water.The belt of southwest-striking high-angle faults probably extends beneath the Spotted and Specter Ranges to depths on the order of 3500 meters which is well within the saturated zone.

Joints: Joints, like small faults, have limited penetration into the major rock units but their abundance and geometry at the ground surface are indicative of the joint pattern at depth. A major difference between surface and subsurface joints is the width of the joint opening which is strongly influenced by confining pressure that increases with depth. Like small faults, some minor fractures may be effective conduits for ground water, despite their limited structural significance. Permeability does not necessarily develop preferentially along faults with great offset or joints that extend for long distances. Crushing, brecciation, and dilation of a fault or joint can cause a flow path to develop along faults with little motion or along small joints. For this reason, the local fault and joint system is important in its effects on the ground water flow path from Frenchman Flat.

The Paleozoic rocks of the Spotted and Specter Ranges exhibit many joints which are, in general, related to rock type, bedding thickness, and rock texture. In the Nevada Test Site region the joints can be divided into two types; local and throughgoing (P.J. Barosh *in* Winograd and Thordarson, 1975).

Local joints do not cross more than one stratum and they commonly terminate at another joint or fault. The size and number of these joints is controlled by the thickness of a stratum. Grain size and internal laminations play an important roll in joint density and separation, as well. Local joints are less than a few centimeters to a meter long and are usually less than a centimeter wide. In most places there are three sets of local joints and there may be a fourth if bedding-parallel joints are developed. Local joints have consistant trends within their domains or subareas, which in turn are bounded by faults and/or throughgoing joints. The local joints form groups of generally equal-sized polygons within the subareas. Most local joints are perpendicular to bedding. Alteration of primary minerals and precipitation of secondary minerals (mostly calcite and clay) occur along these joints, especially near the ground surface where rain water has percolated to shallow depths.

Throughgoing joints cut the stratigraphic sequence for tens of meters with no change in direction. Most end at faults, which therefore set the limit on their length of as much as several hundred meters. Within sets of two or three throughgoing parallel joints, the adjacent joint surfaces are usually separated by as much as three meters, and multiple intersecting joint sets form a polygonal pattern on the outcrop surface. Most of these joints are perpendicular to bedding. Like local joints, they are filled with secondary calcite and clay at and near the ground surface and locally at depth.

Carbonate rocks at all depths above and below the water table are cut by local and throughgoing joints. In combination with faults, fractures, breccia, and vuggy zones the joints play a role in development of permeability in the carbonate aquifer. Solution of the limestone along joints and faults is a principal means of developing permeability. Because secondary porosity and permeability that develop by solution is mostly a function of soil derived carbon dioxide in the ground water (forming carbonic acid), the depth to the water table and distance from the recharge area are factors that must be considered along with the fault and joint systems in evaluating the Frenchman Flat flow path.

STRATIGRAPHY

Stratified rocks along the flow path south and west of Frenchman Flat are Precambrian and Paleozoic marine strata and upper Tertiary fluvial and, lacustrine deposits. The Tertiary deposits have a large component of volcanic ash. Most of the Specter and Spotted Ranges are comprised of Paleozoic rocks; the upper Tertiary rocks are in and near Rock Valley.

Precambrian and Paleozoic: In the southern part of the Great Basin, more than 10,000 meters of marine strata were deposited in late Precambrian and Paleozoic time (fig. 6). Only about half of this section crops out in the Spotted and Specter Ranges, where the sequence consists mostly of Lower Cambrian through Mississippian rocks. The Lower Cambrian and older rocks do not crop out in the Spotted Range and are only locally present at the surface in the Specter Range. These rocks are siliceous clastic types and represent sediments that were deposited in shallow water on or near the ancient continental shelf. Most of the exposed section of Middle Cambrian through Mississippian strata consists of limestone and dolomite derived from lime muds and bioclastic debris that accumulated on the ancient continental shelf. These Paleozoic carbonate rocks are the primary aquifer, whereas .siliceous clastic rocks form aquitards. Understanding the distribution of these two rock types is fundamental to understanding the ground water flow path from Frenchman Flat.

Spotted Range. The maximum thickness of carbonate strata along the ground water flow path south and west of Frenchman Flat is in the Spotted Range with about 1200 meters of carbonate strata between the range crest and the top of the potentiometric surface and an additional 2000 meters or more beneath the potentiometric surface. The range is comprised of two structural plates of carbonate rocks. The upper plate consists of a klippe of Middle to Upper Cambrian Carrara, Bonanza King, and Nopah Formations, and the lower plate contains rocks as young as the Mississippian limestone of Timpi Canyon and as old as Ordovician Antelope Valley Limestone. The thickness of carbonate strata beneath the oldest limestone exposed in the lower plate (Antelope Valley Limestone) is more than 2300 meters so that carbonate rocks extend more than 2000 meters below the top of the water table. Thus siliceous, clastic rocks of the Lower Cambrian-Precambrian aquitard lie far below the carbonate aquifer in this area and offer no impedence to ground water flow.

Red Hills and Mercury Valley. A few miles west of the Spotted Range, a cluster of low hills called the Red Hills are comprised of Upper Cambrian limestone, dolomite and quartzite of the Nopah Formation, and Ordovician Pogonip Group, Eureka Quartzite, and Ely Springs Dolomite. These rocks are part of the lower-plate structural block of the Spotted Range. Probably at least 2300 meters of Upper and Lower Cambrian limestone underlie these outcrops and the alluvium in Mercury Valley. The water table in Mercury Valley lies high in this sequence of carbonate rocks and about two thousand meters above the top of the siliceous clastic Lower Cambrian and Precambrian aquitard.

Specter Range. The lower structural plate of the Spotted Range and Red Hills also crops out in the eastern part of the Specter Range, where it consists of Upper Cambrian to Devonian carbonate rocks. As in the Red Hills and the Spotted Range, carbonate rocks in the stratigraphic sequence of this thrust plate extend into the subsurface for at least 2300 meters and offer a thick unobstructed potential carbonate aquifer above the siliceous clastic aquitard rocks that are encountered at depth. A few kilometers farther west in the Specter

Range, however, the Specter Range thrust emplaces a second plate of Upper Precambrian to Upper Cambrian rocks on top of the Spotted Range-Red Hills-eastern Specter Range plate. Rocks in this upper plate dip gently eastward so that progressively older and more siliceous clastic rocks crop out toward the west at increasing depth. These siliceous rocks form a barrier, channeling ground water flow in the lower plate aquifer to the southern part of the Specter Range and preventing flow from moving northward into Rock Valley or along Rock Valley.

Cenozoic: Late Oligocene and Miocene terrestrial sedimentary rocks, including fluvial conglomerate, sandstone, and siltstone, and lacustrine claystone and limestone crop out extensively in Rock Valley and along the north edge of the Specter Range. These rocks tend to be either fine grained, or poorly sorted and tuffaceous; in the tuffaceous rocks, glass shards are mostly devitrified or altered to clay and zeolite minerals. Many of the units, especially the conglomerates, are poorly stratified. These Cenozoic strata are divided into the Horse Spring Formation (Oligocene) and rocks of Pavits Spring (Miocene).

The Horse Spring Formation, between 60 and 300 meters thick, mostly consists of fine grained clastic rocks ranging from sandstone to claystone. These rocks are gypsiferous and contain a significant amount of devitrified volcanic ash. Lithographic limestone and subordinate coarser grained limestone comprise about 30 percent of the formation. In general, the Horse Spring Formation is more compacted and lithified than the overlying rocks of Pavits Spring. All the Cenozoic sedimentary rocks are less lithified and recrystalized than the Paleozoic strata on which they unconformably lie.

The rocks of Pavits Spring are a sequence of sedimentary rocks that reach their maximun thickness of as much as 500 meters in the Hampel Wash area in the eastern part of Rock Valley. Comparable thicknesses probably extend westward along the axis of Rock Valley, where the Cenozoic rocks are buried by Quaternary alluvium. The rocks of Pavits Spring are thinner at the margins of Rock Valley and there are only scattered outcrops along the valley margins on the northwest edge of the Spotted Range, the north edge of Mercury Valley, and along the north edge of the Specter Range. Not only do the rocks of Pavits Spring thin abruptly at the edge of Rock Valley, but individual units are discontinuous, lenticular, and intertongue complexly.

These tuffaceous Cenozoic rocks, like some Tertiary tuffs and Quaternary alluvium in other parts of the region, are less permeable than fractured Paleozoic carbonate rocks (Johnston,1968, p.18 and 41). Both the Horse Spring Formation and the rocks of Pavits Spring have most of the characteristics of the "tuff aquitard" as described by Winograd and Thordarson, (1975, p. c118). The low permeability is due to the fine-grained or poorly sorted nature of the sediments and the abundant altered volcanic ash that fills intergranular pore space. The poorly stratified nature of the rocks also limits water flow because there are few throughgoing permeable horizons.

From the ground surface to depths as great as 1000 meters, ground water flow is restricted in Rock Valley by the clastic wedge of relatively impermeable Cenozoic rocks. The thickness of this Cenozoic fill is greater than the depth to the potentiometric surface in Mercury Valley directly south of Rock Valley, and thus the Cenozoic rocks form a barrier to ground water flow northward into Rock Valley. As shown by ground water gradient contours in the Rock Valley-Mercury Valley area, the potentiometric surface slopes southeastward from the north side of Rock Valley to a low beneath Mercury Valley and the southeastern part of the Specter Range (Winograd and Thordarson, 1975; Laczniak and others, 1996). The hydraulic gradient slopes southwest beneath the Specter Range into the Amargosa Desert.

CONCLUSIONS

The role of geologic structure in determining the route of the ground water flow from Frenchman Flat is viewed from two perspectives. First, it is concluded that large geologic structures are instrumental in forming the regional geologic framework through which the ground water flows. These large-scale structures are responsible for the distribution and orientation of bodies of rock on the scale of entire mountain ranges. At a local level, these large-scale structures themselves may or may not have any control on the passage of water. Second, all features such as faults and joints are viewed as possible conduits for ground water flow and perceives the process of fracturing, including shearing and brecciation as important in increasing the transmissivity of a potential aquifer. Small structures, if they are part of an interconnecting network, are as important with respect to fracture permeability as are large, isolated fractures.

In the Spotted and Specter Ranges more than 2000 meters of carbonate rock are present. These rocks extend from the ground surface to the top of the siliceous clastic rocks that are the deep barrier to ground water flow. The top of the water table is more than 300 meters below the surface of Mercury Valley and there is a considerably greater thickness of carbonate rock between the top of the water table and the siliceous clastic aquitard rocks. No high-angle faults are recognized at the land surface in the Spotted Range, Mercury Valley and the Specter Range that have enough vertical displacement to significantly effect the configuration of the deep siliceous clastic aquitard with respect to the flow in the overlying carbonate aquifer. Numerous faults, however, cut the carbonate rocks, forming a network of fractures that creates an extensive aquifer. Many of these faults have a southwesterly strike that tends to direct the ground water in this direction.

Two large thrust faults occur in the area--the Spotted Range thrust and the Specter Range thrust. The former has no effect on ground water flow out of Frenchman Flat because it is essentially "high-and-dry" forming a klippe of carbonate strata at high elevation in the range, and it has not distributed the stratigraphic sequence in the Spotted Range in any way that effects the position of aquifer rocks or confining aquitard rocks. The lower plate of the Spotted Range thrust is composed of water-bearing carbonate strata that extend to depths of thousands of meters below the potentiometric surface.

The Specter Range thrust places upper-plate carbonate rocks and siliceous clastic rocks on lower-plate carbonate rocks in the Specter Range. It is not the same fault as the Spotted Range thrust but represents a separate, tectonically higher, structure. In the eastern part of the Specter Range, at the margin of Mercury Valley, the stratigraphic separation between plates of the Specter Range thrust is not great, less than 200 meters; Cambrian carbonate rocks lie on Cambrian, Ordovician, Silurian, and Devonian carbonate rocks. The stratigraphic separation between the plates increases steadily westward, however, because the fault ramps down-section in that direction. In the central and western part of the Specter Range, subsurface rocks of the upper plate consist almost entirely of Precambrian and Lower Cambrian siliceous clastic types. These rocks form a barrier to ground water flow and channel the ground water in the central and western part of the Specter Range to the southern part of the range and southward toward springs at Ash Meadows about 35 kilometers away.

Regional structural features such as the Las Vegas Valley shear zone the Walker Lane have a second-order influence on the ground water flow in the Ash Meadows subbasin of the Death Valley ground water flow system. The Las Vegas Valley shear zone ends as a right lateral fault zone east of this area and is replaced in the Spotted and Specter Ranges by southwest-striking mostly high-angle faults. Many of these faults have left-lateral displacement and may have formed conjugate to the same stress field as the Las Vegas Valley shear zone. These structures have the same strike as the ground water flow path beneath the Spotted Range, Mercury Valley, and the Specter Range. The flow path trend must be controlled by the southwesterly striking faults where they cut Paleozoic carbonate rocks. These faults facilitate the passage of water through the aquifer.

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Figure 1. Shaded relief map of the western conterminous United States. The Basin and Range physiographic province, the Great Basin (the northern part of the Basin and Range physiographic province), and the Nevada Test Site (NTS) are outlined.

Figure 2. Map of southern Nevada and adjacent parts of California showing the region of the Death Valley ground water flow system. The Tertiary volcanic rock flow path and the Paleozoic carbonate rock flow paths are shown.

Figure 3. Map of southern Nevada and adjacent California showing the location of major topographic features, highways, and populated areas.

Figure 4. Map of southern Nevada showing basins (unshaded) and ranges (shaded) near Frenchman Flat and the Las Vegas Valley shear zone.

Figure 5. Geologic map showing the ground water flow path south and west of Frenchman Flat (broad arrows). The small thin arrows show the direction of the ground water flow that encounters aquitard rocks. Paired heavy arrows show inferred sense of slip on strike-slip faults. . Carbonate rocks are unshaded, siliceous rocks are shaded. Heavy lines are faults. The ground water passes southwestward through carbonate rocks beneath the Spotted Range, Mercury Valley and the Specter Range. This route is controlled in the Specter Range, and probably in Rock Valley by siliceous clastic aquitard rocks in the upper plate of the Specter Range thrust.

Figure 6. Upper Precambrian and Paleozoic stratified rock units in the general area of Frenchman Flat. The name, age, rock type, and average thickness of the unit is shown.

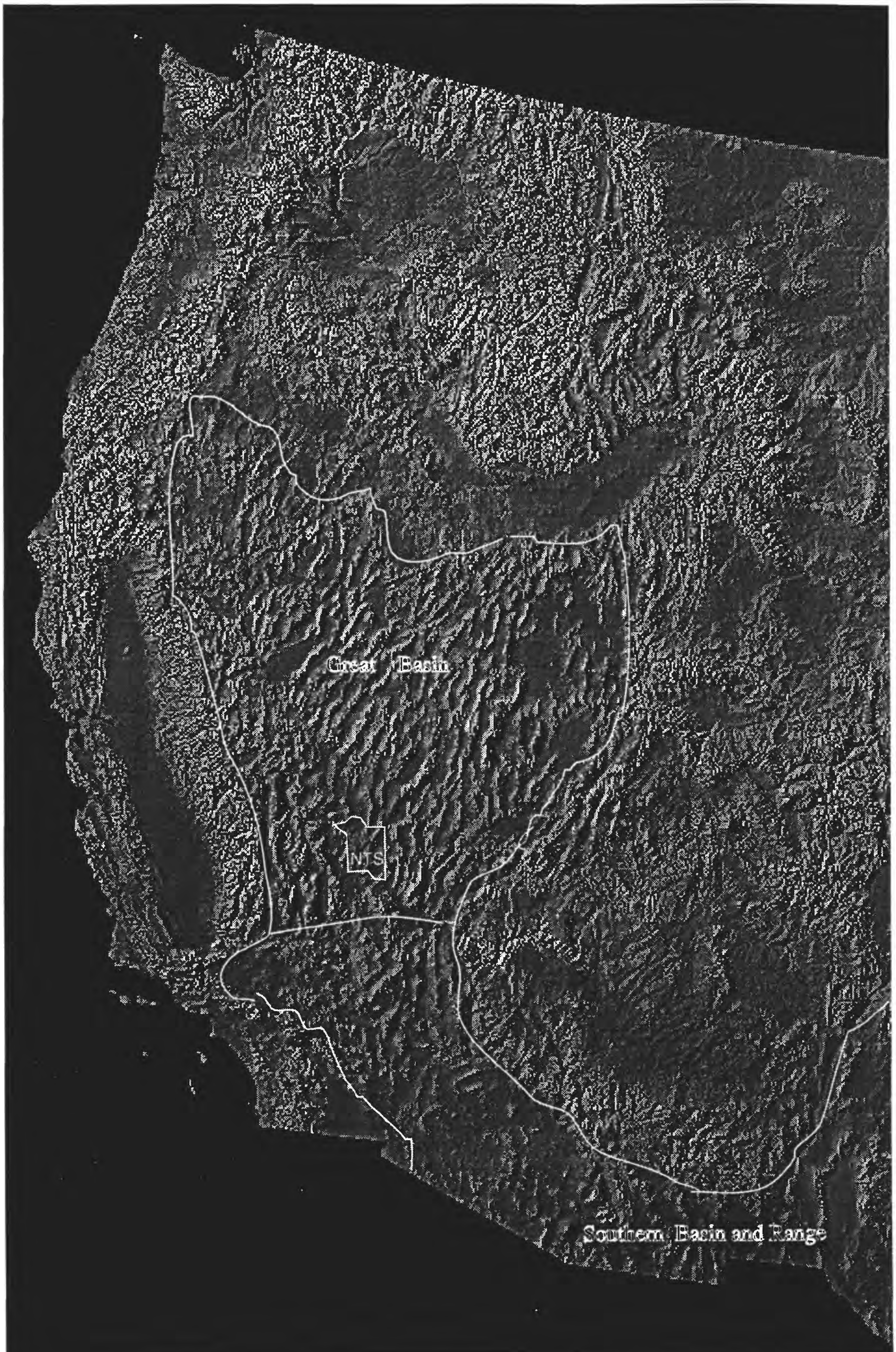

Figure 1

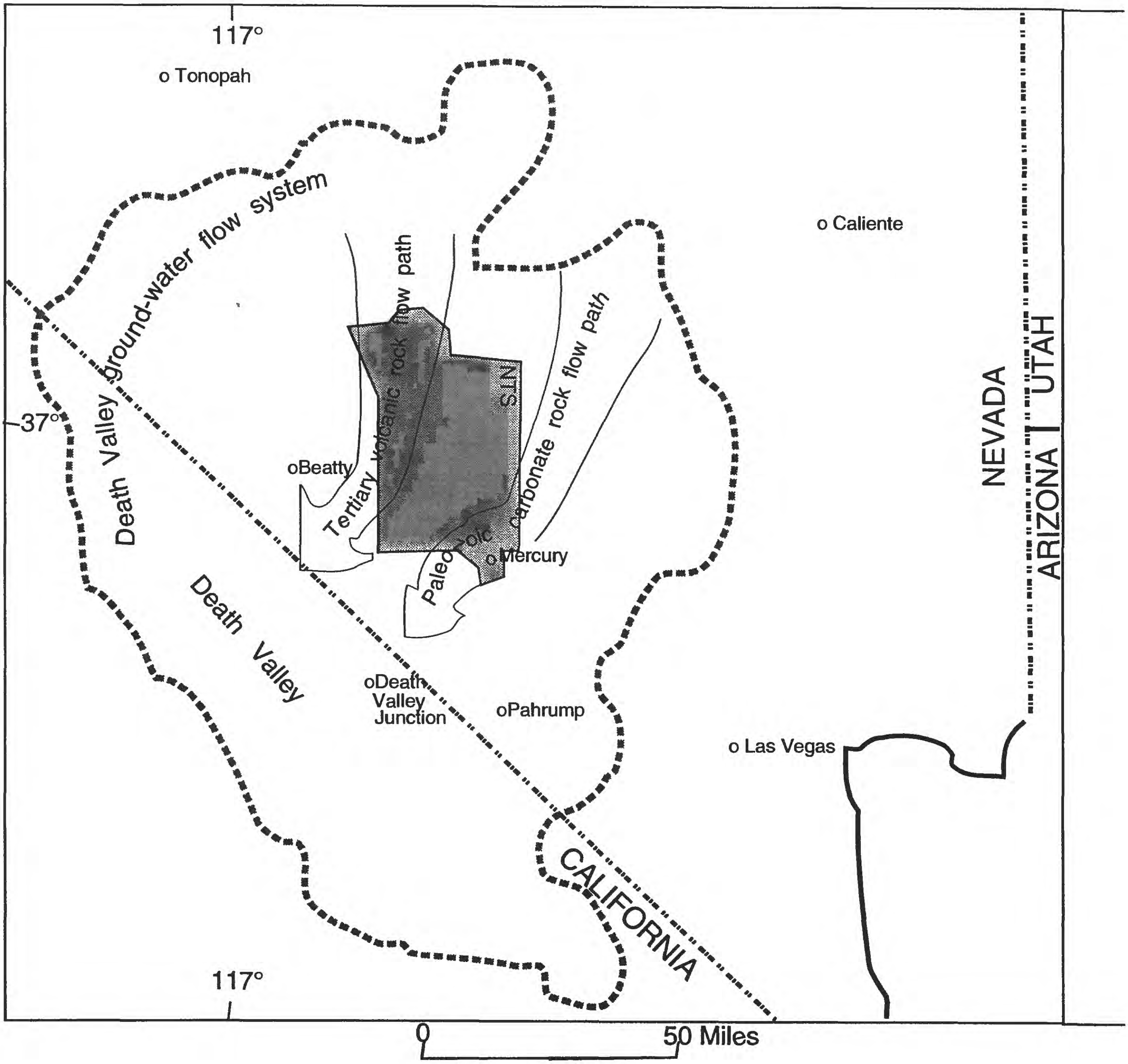
117°
o Tonopah
Death Valley ground-water flow system
o Caliente
Tertiary volcanic rock flow path
carbonate rock flow path
NTS
37°
oBeatty
Death Valley
Paleozoic
o Mercury
Death Valley
oDeath Valley Junction
oPahrump
o Las Vegas
NEVADA
UTAH
ARIZONA
CALIFORNIA
117°
0
50 Miles

Figure 2

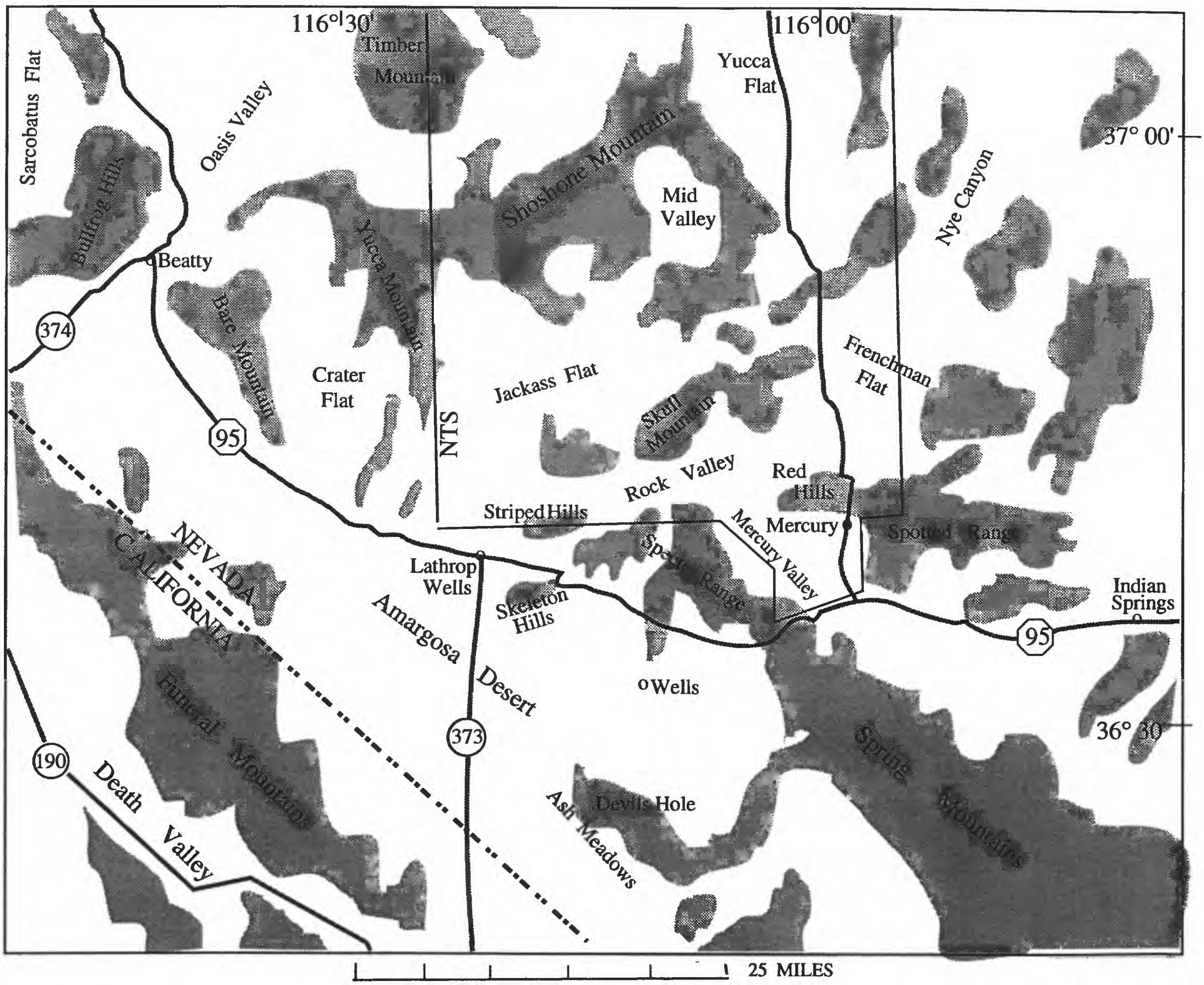
116°30'
116°00'
37° 00'
36° 30'
Sarcobatus Flat
Bullfrog Hills
Oasis Valley
Timber Mountain
Shoshone Mountain
Yucca Flat
Mid Valley
Nye Canyon
Beatty
Bare Mountain
Yucca Mountain
Crater Flat
Jackass Flat
Skull Mountain
Frenchman Flat
NTS
Rock Valley
Red Hills
Striped Hills
Mercury
Spotted Range
Mercury Valley
Specter Range
Lathrop Wells
Skeleton Hills
Amargosa Desert
NEVADA
CALIFORNIA
Indian Springs
Wells
Funeral Mountains
Spring Mountains
Devils Hole
Ash Meadows
Death Valley
374
95
373
190
25 MILES

Figure 3

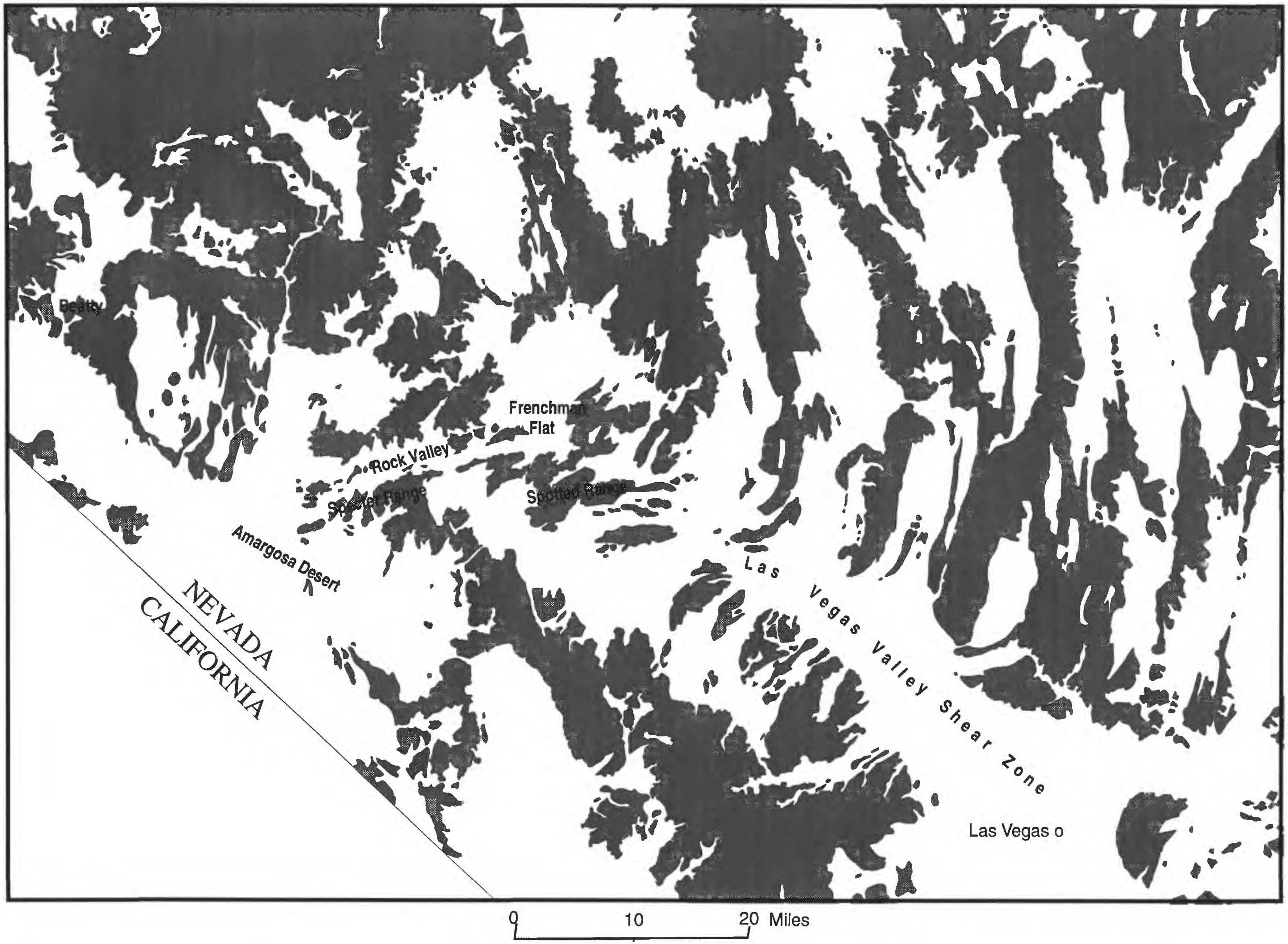
Beatty
Frenchman
Flat
Rock Valley
Specter Range
Spotted Range
Amargosa Desert
NEVADA
CALIFORNIA
Las Vegas Valley Shear Zone
Las Vegas o
0
10
20 Miles

Figure 4

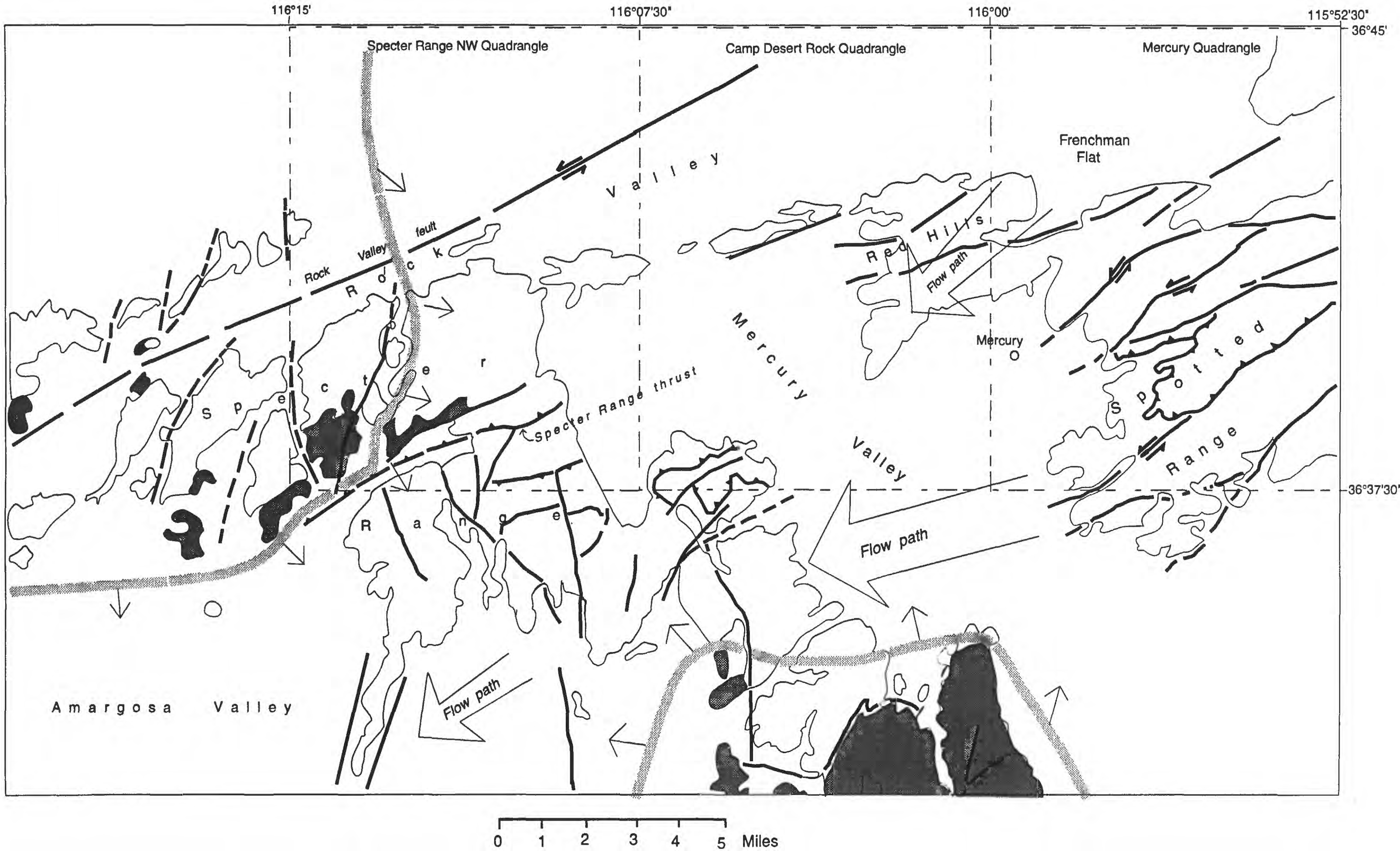
116°15'
116°07'30"
116°00'
115°52'30"
36°45'
36°37'30"
Specter Range NW Quadrangle
Camp Desert Rock Quadrangle
Mercury Quadrangle
Frenchman
Flat
Valley
Rock Valley feult
Red Hills
Flow path
Mercury
Specter
Specter Range thrust
Mercury Valley
Spotted Range
Range
Flow path
Flow path
Amargosa Valley
0 1 2 3 4 5 Miles

Figure 5

25

Mississippian		Limestone of Timpi Canyon	Limestone	400	
		Mercury Limestone	Limestone	250	
		Narrow Canyon Limestone	Limestone	200	
Devonian	Upper	Devils Gate Limestone	Limestone, dolomite, minor quartzite.	>1,380	
	— ? —				
	Middle	Nevada Formation	Dolomite.	>1,525	
Devonian and Silurian		Undifferentiated	Dolomite.	1,415	
Ordovician	Upper	Ely Springs Dolomite	Dolomite.	305	
	Middle	Eureka Quartzite	Quartzite, minor limestone.	340	
	— ? —	Pogonip Group: Antelope Valley Limestone	Limestone and silty limestone.	1,530	
	Lower	Pogonip Group: Ninemile Formation	Claystone and limestone, interbedded.	335	
		Pogonip Group: Goodwin Limestone	Limestone.	>900	Lower carbonate aquifer
Cambrian	Upper	Nopah Formation			
		Smoky Member	Dolomite, limestone.	1,070	
		Halfpint Member	Limestone, dolomite, silty limestone.	715	
		Dunderberg Shale Member	Shale, minor limestone.	225	
	Middle	Bonanza King Formation			
		Banded Mountain Member	Limestone, dolomite, minor siltstone.	2,440	
		Papoose Lake Member	Limestone, dolomite, minor siltstone.	2,160	
		Carrara Formation	Siltstone, limestone, interbedded. Upper 1,050 feet predominantly limestone; lower 950 feet predominantly siltstone.	1,050	
				950	
	Lower	Zabriskie Quartzite	Quartzite.	220	
		Wood Canyon Formation	Quartzite, siltstone, shale, minor dolomite.	2,285	Lower clastic aquitard
Precambrian		Stirling Quartzite	Quartzite, siltstone.	3,400	
		Johnnie Formation	Quartzite, sandstone, siltstone, minor limestone and dolomite.	3,200	

Figure 6