Case No. 84739

IN THE SUPREME COURT OF THE STATE OF NEVADA

ADAM SULLIVAN, P.E., NEVADA STATE ENGINEER, et al.

Appellants,

vs.

LINCOLN COUNTY WATER DISTRICT, et al.

<u>JOINT APPENDIX</u>

VOLUME 35 OF 49

Distribution of Carbonate-Rock Aquifers and the Potential for Their Development, Southern Nevada and Adjacent Parts of California, Arizona, and Utah

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 91-4146

Prepared in cooperation with the
STATE OF NEVADA,
LAS VEGAS VALLEY WATER DISTRICT, and
the CITY OF NORTH LAS VEGAS

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By Michael D. Dettinger, James R. Harrill, and Dwight L. Schmidt,
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Carson City, Nevada
1995

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
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Denver, CO 80225-0046

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TABLES—Continued

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
acre	0.4047	square hectometer
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year
cubic foot (ft^3)	0.02832	cubic meter
cubic mile (mi^3)	4.168	cubic kilometer
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot squared per day (ft^2)	0.09290	meter squared per day
gallon per minute (gal/min)	0.06309	liter per second
gallon per minute per foot [(gal/min)ft]	0.2070	liter per second per meter
inch (in.)	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

Temperature: Degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) by using the formula °F = [1.8(°C)]+32. Degrees Fahrenheit can be converted to degrees Celsius by using the formula °C = 0.556(°F-32).

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929, formerly called "Sea-Level Datum of 1929"), which is derived from a general adjustment of the first-order leveling networks of the United States and Canada.

Distribution of Carbonate-Rock Aquifers and the Potential for Their Development, Southern Nevada and Adjacent Parts of California, Arizona, and Utah

By Michael D. Dettinger, James R. Harrill, *and* Dwight L. Schmidt, U.S. Geological Survey, *and* John W. Hess, Desert Research Institute

ABSTRACT

In 1985, the State of Nevada entered into a cooperative effort with the U.S. Department of the Interior to study and test the State's carbonate-rock aquifers. The work was funded by several agencies and done by the U.S. Geological Survey, the Desert Research Institute, and the Bureau of Reclamation. The studies were focused on southern Nevada, mostly north of Las Vegas and south of Pioche and Tonopah, and were intended to address the following basic concerns:

- Where is water potentially available in the aquifers?
- How much water potentially can be withdrawn from aquifers?
- What effects might result from development of the aquifers?

Several types of basic hydrologic data were collected in eastern and southern Nevada, including measurements of (1) precipitation at high-altitude sites; (2) discharge at representative springs; (3) water levels in wells open to the carbonate-rock aquifers; and (4) meteorological conditions used to estimate evapotranspiration rates by native plants. Geology was mapped in an area of about 1,800 square miles north of Las Vegas and centered on the Sheep Range, emphasizing carbonate rocks and younger sediments. Surface geophysical measurements were made to estimate thicknesses of basin-fill aquifers overlying the carbonate-rock aquifers and to locate faults deep beneath land surface. Water samples were collected and analyzed to characterize ground-water quality, to delineate flow paths, to update water budgets, and to identify flow and mixing rates in six parts of southern Nevada, including the Spring Mountains, Las Vegas Valley, the Ash Meadows area, and the Muddy River Springs area. Nine wells were drilled (a total of about 4,500 feet in basin fill and 5,500 feet in carbonate rocks) and two abandoned wells in key locations were rehabilitated. Borehole-geophysical logs were collected from selected depth intervals in all these wells and in four wells drilled during the MX-missile siting investigation. The aquifers were tested at three of the new wells and at three of the MX wells during 1985-88 to determine transmissivity. Results from reports of drill-stem tests in 13 petroleum-exploration wells and aquifer tests at 33 other wells in the carbonate-rock aquifers of Nevada were compiled. Finally, these results were synthesized to answer the three basic concerns listed above.

The carbonate rocks of southern Nevada were deposited as layers of ancient marine sediment that cumulatively were as much as 40,000 feet thick. The carbonate-rock layers—because of their brittleness and tendency to dissolve into flowing water—are believed to be the principal water-bearing (or aquifer) zones within these ancient sediments.

Although the carbonate rocks were deposited as widespread layers, geologic forces subsequently deformed the rocks into innumerable blocks and folded rock masses of all sizes.

Because of this deformation, rocks of widely differing geologic age are intermingled, and the distribution of rocks that constitute aquifers is greatly complicated. Also, as a result of the action of those forces, much of southern Nevada is underlain by areas where the carbonate rocks remain only as isolated blocks. In contrast, the central third of southern Nevada is underlain by north-south corridors of thick, laterally continuous carbonate rocks. North of Las Vegas, within the central corridor, two areas are underlain by thick and relatively continuous carbonate rocks that are connected to a similarly thick carbonate-rock mass farther north. The thick carbonate rocks probably contain the principal conduits for regional flow from east-central Nevada into southern Nevada, with the flow ultimately discharging at Ash Meadows and Death Valley, and at the Muddy River Springs. Farther south, the thick carbonate rocks underlie the Spring Mountains-Pahrump Valley area. Water flowing through these rocks at this latitude is derived mostly from recharging snowmelt in the Spring Mountains, which flows radially away to discharge near Tecopa, in Pahrump Valley, at Indian Springs, and (in the past) at Las Vegas Springs.

Some zones within the central corridor are highly transmissive, and the present study developed the hypothesis that these zones function as large-scale drains, collecting water from less transmissive rock that underlies most of the study area. The drains probably conduct much of the flow that discharges at large regional springs. The present study also hypotheses that such zones stay highly transmissive only if large volumes of water continue to flow through them. Otherwise, openings in the rock gradually close and the rock reconsolidates. The practical implication of these hypotheses is that wells that tap conduits of concentrated regional flow probably will be most productive.

Natural recharge in the mountains of southern Nevada has been estimated to total about 140,000 acre-feet annually, of which about 110,000 acre-feet is from within the central corridor of thick carbonate-rock aquifers. In addition to ground-water recharge in southern Nevada, geochemical balances computed in the present study indicate that another 21,000 acre-feet per year is supplied to southern Nevada by inflow through carbonate-rock aquifers from east-central Nevada.

Discharge at regional springs and by flow out of the study area through carbonate rocks that extend into California totals about 77,000 acre-feet from carbonate-rock aquifers of the central corridor. The remaining water either leaks upward into the basin fill or directly recharges the basin fill, and ultimately discharges at local springs, playas, meadows, and streams. Previous studies have estimated that the natural discharge from basin-fill aquifers in the central corridor is about 50,000 acre-feet per year. A review of aquifer conditions within and along the boundaries of the central corridor indicates that only along the California border are the carbonate-rock aquifers continuous enough to transmit large quantities of water to areas where its discharge at land surface could have been overlooked in this study.

The perennial yield of the carbonate-rock aquifers cannot exceed the total flow through them. However, part of this flow discharges by leaking into adjacent basin-fill aquifers. The perennial yield of the carbonate-rock aquifers of southern Nevada, as a result, is defined in terms of the remainder of the total flow, which is no more than the combined rates of discharge at regional springs in southern Nevada and at discharge areas in the Death Valley region (total, about 77,000 acre-feet per year).

The other component of the carbonate-rock water resources is the large volume of water stored in the rocks. Because of the areal extent and great thickness of the carbonate rocks in the central corridor, the total volume of rock is enormous. Assuming that about 0.01 cubic foot of recoverable water is stored in each cubic foot of aquifer, the total quantity of water stored in the carbonate rocks south of Pioche and Tonopah would be on the order of 800 million acre-feet. For practical purposes, not all this water can be extracted. However, if an average of 100 feet of the aquifer's thickness could be dewatered, the central corridor could yield a volume of stored water on the order of 6 million acre-feet; once depleted, however, that resource would be replenished only by the equivalent of decades or centuries of recharge.

Ultimately, long-term development of the carbonate-rock aquifers would result in depletion of stored water, or in the capture of water that otherwise would discharge from the aquifers of southern Nevada and vicinity, or both. Possible effects of developing the carbonate-rock aquifers include declining water levels, decreasing springflow rates, drying up of some streams, playas, and meadows, and changing water quality.

Sustained effects within the carbonate-rock aquifers resulting from development of those aquifers have not been observed to date (1989). Hydraulic calculations indicate that water-level declines in extensive, unconfined carbonate-rock aquifers commonly would be less than 70 feet at distances beyond 1 mile from a production well after 10 years of pumping at 1,000 gallons per minute. In a confined part of the aquifer, calculated water-level declines of similar magnitude would spread as far as 10 miles from the pumped well. These calculations are, however, based on many idealized simplifying assumptions. Currently (1989), data that allow a realistic representation of the complexities of the aquifers are not available; however, several previous studies have included computer models that provide insight into the problems of prediction. Regardless of whether the effect of pumping near Devils Hole is being modeled or whether regional flow toward Death Valley is being simulated, the geologic complexity of southern Nevada has been shown to be hydrologically important. This requires (1) that detailed aquifer descriptions be available before accurate site-specific predictions can be made and, probably, (2) that those predictions be based on effective use of sophisticated computer models.

The potential for adverse effects in adjacent aquifers resulting from development of the carbonate-rock aquifers is another concern. Historical experience with such conditions is available at two areas in southern Nevada that have undergone development of basin-fill aquifers adjacent to carbonate-rock aquifers: Ash Meadows and Muddy River Springs. At Ash Meadows, direct connections between pumping from basin-fill aquifers and water-level declines in the carbonate rocks were demonstrated. Around the Muddy River Springs, in contrast, development of basin-fill aquifers has resulted in minimal changes in water levels of the carbonate-rock aquifers. The difference between responses at these areas probably could not have been predicted before the aquifers were pumped and early effects observed.

The effects of depletion of stored water and capture of water that otherwise would discharge from the aquifers would depend on site-specific conditions around areas where the water is withdrawn. Confidence in predictions of the potential effects of development of the carbonate-rock aquifers will remain limited until observations become available that document changes as the aquifers respond locally to long-term pumping stresses.

INTRODUCTION

Rocks that formed from ancient marine sediments underlie much of a 50,000 mi^2 area of southern and eastern Nevada referred to as the carbonate-rock province (fig. 1) that also extends into western Utah, eastern California, and southeastern Idaho. These rocks are dominated by limestone and dolomite, two common carbonate-rock types, and are commonly associated with large springs, most with discharges greater than 1,000 gal/min. Several wells drilled into fractured zones in these carbonate rocks have been pumped at high rates with little water-level decline. The large area underlain by the rocks, together with their demonstrated capacity to transmit large volumes of ground water, has long indicated that the carbonate rocks of Nevada comprise aquifer systems of regional scale and significance. A problem exists in that although some data could indicate a favorable potential for development, the current (1989) understanding of the distribution and hydrologic properties of these rocks and of the regional-scale aquifers that they form is not adequate to determine their overall potential for development and the probable effects of development. This information is needed to support wise development and management of the State's water resources and to ensure optimum utilization of the carbonate aquifers as a significant component of the overall resource.

Nevada is the most arid State in the Nation, and faces rapid population growth and increasing demands for water. These increasing demands have sparked considerable interest in the largely unexplored carbonate-rock aquifers as a future water supply. Historic sources of water—surface water (streams and lakes) and ground water in localized sand-and-gravel aquifers—are used or appropriated nearly to (and in some valleys, beyond) their estimated sustainable yield in many areas, and thus, without stricter resource management or new sources of water, expectations of continued growth in some parts of Nevada may be limited.

The State of Nevada passed Senate Bill 277 in 1985 and entered into a cooperative effort with the Federal Government for the study and testing of the carbonate-rock aquifers of eastern and southern Nevada. The overall study plan (U.S. Department of the Interior, 1985, p. 4 and 9) called for a 10-year program to systematically study the 50,000 mi^2 of Nevada underlain by the carbonate-rock province. The southern part was studied during the first 3 years of the program and the results of that effort are the topic of this report.

Funds supplied by the State, the Las Vegas Valley Water District, and the City of North Las Vegas were matched by Federal funds supplied by the U.S. Geological Survey and the Bureau of Reclamation. Technical work has been done by a study team consisting of personnel from the U.S. Geological Survey, the Desert Research Institute, and the Bureau of Reclamation.

Purpose and Scope

Each 3-year study proposed in the overall program is designed to address the following three questions:

1. Where is water potentially available in the aquifers?
2. How much water potentially can be withdrawn from the aquifers?
3. What effects might result from development of the aquifers?

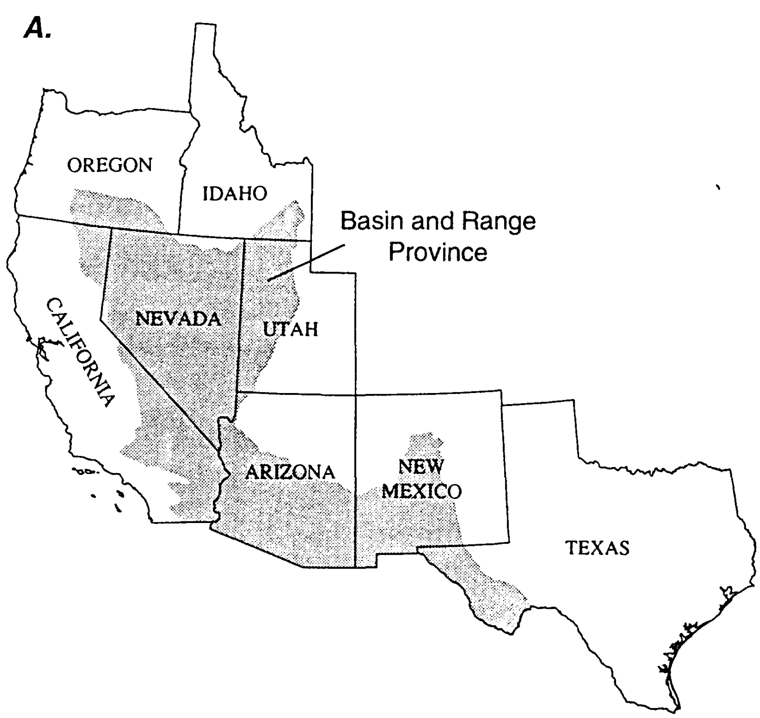
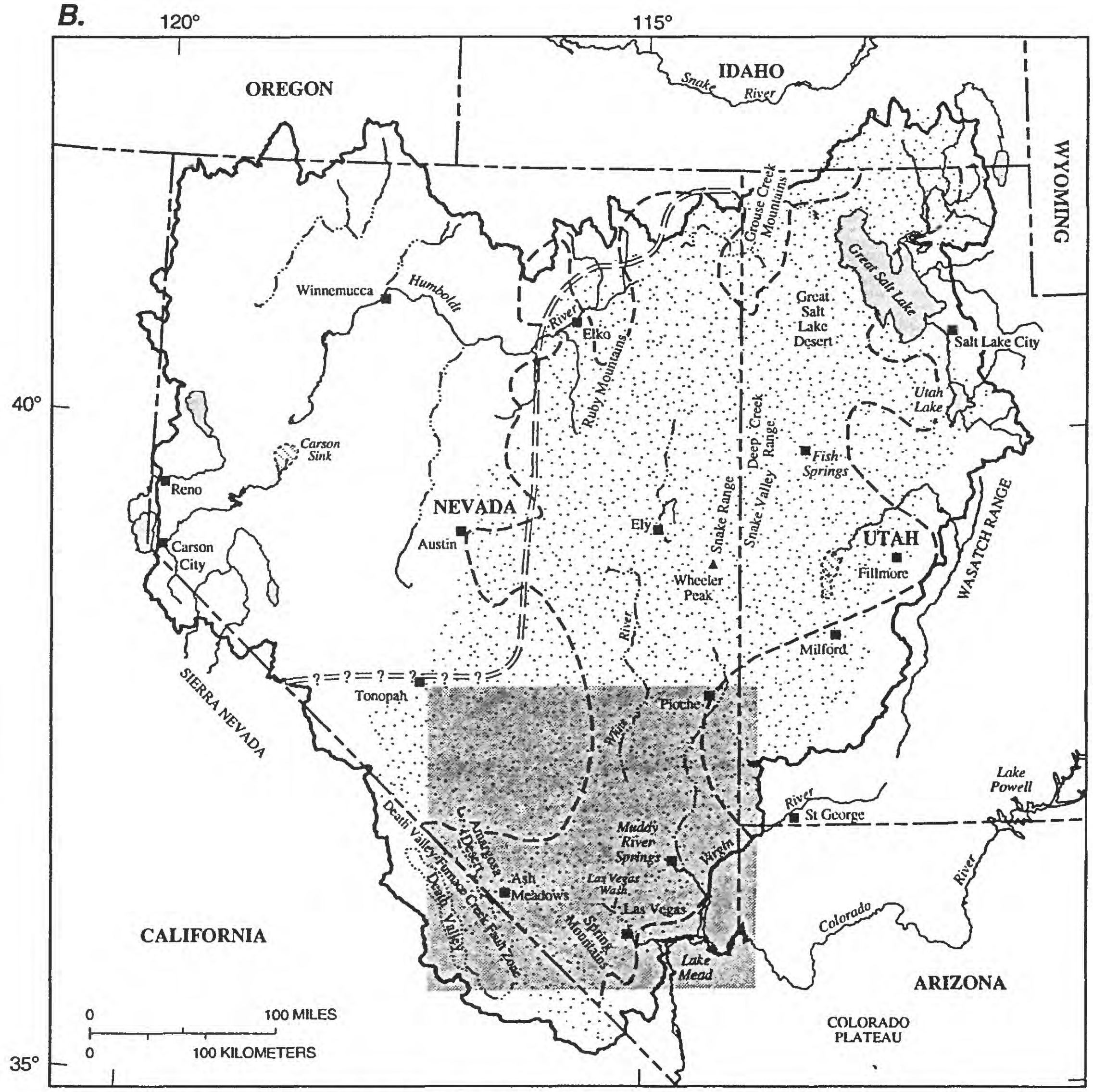


Figure 1. Location and general extent of (*A*) Basin and Range Province, and (*B*) Great Basin and carbonate-rock province. Figure 1*A* modified from Bedinger and others (1983); figure 1*B* modified from Harrill and others (1983, fig. 8).

B.



Base modified from U.S. Geological Survey digital data, 1:100,000 and 1:250,000
Albers Equal-Area Conic projection
Standard parallels 29°30' and 45°30', central meridian -114°

EXPLANATION

Study area

Carbonate-rock province as used in this study — From Thomas and others (1986, sheet 2)

Boundary of Great Basin Regional Aquifer-System Analysis (RASA) study area

Approximate boundary of carbonate-rock province of Mifflin and Hess (1979) — Within province, at least 80 percent of measured sections are composed of more than 50 percent carbonate rock

=?== **Approximate boundary of Roberts overthrust belt** — Queried where uncertain

Note: Lakes and rivers dashed where ephemeral

Figure 1. Continued

The purpose of this report is to summarize results of specific activities and studies in southern Nevada during the first 3-year study (1985-88). Regional-scale analyses have been made to improve understanding of the carbonate-rock aquifers at a large scale and to provide information applicable to specific areas. Detailed studies and analyses have been made in specific areas chosen for their relevance to the development of carbonate-rock aquifers to meet water demands in Las Vegas Valley, as well as for extending conclusions to all parts of southern Nevada. This report is intended to answer the three basic questions presented above as they apply in general in southern Nevada, within the limits of our current (1989) understanding. The scope includes summary of the findings of specific studies done in support of this project and incorporating the results into an overall regional synthesis for southern Nevada.

Activities summarized in this report extend to areas as far north as about 40°N. latitude, but are generally focused in southern Nevada, south of 38°N. latitude (that is south of Pioche, Tonopah, and vicinity). The studies and conclusions include areas of Utah and Arizona west of the Beaver Dam and Virgin Mountains and areas in California in and around Death Valley. Plate 1 shows the southern Nevada study area and many locations discussed later in this report.

Related Publications

This report is one of a number of products resulting from this study. A brief summary of findings (Dettinger, 1989b) presents the overall results of the study for the non-technical reader. Data and analysis that support the more detailed summary presented in this report are in 20 reports that were prepared as part of the overall program for the study and testing of carbonate-rock aquifers in eastern and southern Nevada. These reports are listed in the References Cited section of Dettinger (1989b) in bold type. The Bureau of Reclamation evaluated the relative economic feasibility of several alternative sources of water, including carbonate-rock aquifers, to supply water to meet peak demands for Las Vegas in the near future (Bureau of Reclamation, 1988).

Acknowledgments

Many more people contributed to the present studies during 1985-88 and to this summary report than could be listed as authors. Michael E. Campana, Ronald L. Hershey, Brad F. Lyles, W. Alan McKay, R. Eric Noack, and Karl F. Pohlman—from the Desert Research Institute in Las Vegas and Reno—contributed activity summaries and short sections of the text. Gary Dixon of the U.S. Geological Survey, Geologic Division, in Las Vegas contributed to planning and development of the document. David L. Berger, Lori A. Carpenter, Michael J. Johnson, Kathryn C. Kilroy, Donald H. Schaefer, and James M. Thomas—all from the U.S. Geological Survey, Nevada District Office in Carson City—contributed figures, activity summaries, and short sections of the text.

GENERAL HYDROGEOLOGY

This section presents general background information describing the carbonate-rock aquifers and how water flows through them. These basic concepts are intended to serve as a foundation for understanding much of the rest of the report.

Geologic Setting

The regional geologic setting of southern Nevada can be referenced to three overlapping provinces (shown in fig. 1): the Basin and Range Province, the Great Basin "province," and the carbonate-rock province. The Basin and Range Province is a physiographic and structural province characterized by numerous north-south trending mountain ranges separated by intervening basins. This structure and topography is the result of stretching or extension of the region at various times during the past 30 million years. The Great Basin is a region characterized by internal drainage in which no surface water flows to the ocean. Much of southern Nevada fits this hydrologic description with the exception of those basins draining to the Colorado River. The carbonate-rock province is more informally defined (see fig. 1 for more details on how its boundaries have been described), but is generally described as that part of the Basin and Range Province in which ground-water flow is predominantly or strongly influenced by carbonate-rock aquifers of Paleozoic age.

The carbonate rocks that underlie much of eastern and southern Nevada are dense and brittle sedimentary rocks deposited in the shallow ocean off the west coast of the North American continent during the Paleozoic Era, between 200 and 500 million years ago, when western Utah was the west coast. These rocks are predominantly limestones and dolomites that are somewhat soluble in water. These two rock types contain an ion composed of carbon and oxygen, the carbonate ion; hence the name carbonate rocks. Other, noncarbonate sedimentary rocks—rocks that do not contain a large proportion of carbonate ions—were deposited also and today occur as subordinate layers, major sequences, and interfingering zones within the layers of carbonate rock. These noncarbonate rocks commonly are either quartzite or shale, and are lithified sand, clay, or silt. The carbonate and noncarbonate rocks were deposited in layers that totaled more than 30,000 ft thick in some areas and record temporal and spatial variations in the depositional environment from dry-land erosional surfaces to tidal flat conditions and conditions at the edge of the continental shelf (Stewart, 1980, p. 5). Figure 2 shows the sequence of rock types in an idealized Paleozoic-rock column beneath the Sheep Range (north of Las Vegas, pl. 1) and is typical of Paleozoic rocks beneath southern Nevada. See Stewart (1980, p. 16-54) for a technical overview of the sedimentary rocks deposited during this time period; a less technical history of the deposition is presented by Fiero (1986, p. 79-96). The history of these rocks subsequent to their deposition also is presented in these references.

The carbonate rocks today underlie most of the area beneath southern Nevada north of Jean (pl. 1) and eastern Nevada east of Tonopah, Austin, and Elko (fig. 1). The rocks extend beneath much of the western third of Utah, into southeastern Idaho, and south to at least Death Valley in California. The rocks originally exhibited relatively small spatial variations in thickness at local scales but, regionally, the thicknesses ranged from 4,000 ft near the present-day Muddy Mountains to 17,000 ft near the present-day Sheep Range and 25,000 ft near the Nevada Test Site (fig. 3). These thicknesses vary directly with distance from the ancestral continental coast line (located mostly in western Arizona and Utah at various times during the Paleozoic Era), and an ancestral Antler highland in central Nevada that eroded to contribute thick layers of noncarbonate rock in some places (for example, the Nevada Test Site) during the middle Paleozoic (Stewart, 1980, p. 42). The carbonate-rock section thinned eastward toward the ancient coast line, and thickened westward toward the deep edge of the ancestral continental shelf or, by middle Paleozoic time, on approaching the central Nevada highland. The mixture of carbonate and noncarbonate rocks in the Paleozoic rocks varies only slightly with distance from these boundaries and, except in the Nevada Test Site area, is about 90 percent carbonate rock and 10 percent noncarbonate rock.

The Paleozoic carbonate rocks were deposited on thick layers of older (lower Cambrian and late Precambrian age) noncarbonate clastic sediments that in turn were deposited on a complex mixture of metamorphic and igneous rocks of well over a billion years old (Precambrian age). After deposition of the Paleozoic carbonate rocks, carbonate and noncarbonate sedimentary rocks of Mesozoic age were deposited on top of the carbonate rocks (fig. 3) under both marine and continental conditions. Layered volcanic rocks (which are noncarbonate) of Cenozoic age in turn were deposited on the Mesozoic rocks as a result of volcanic activity in the region, and in some areas plutonic rocks were intruded into the pre-existing rocks. The present-day outcrops of all these various rock types are shown on plate 1.

Since deposition, the carbonate and noncarbonate rocks have been greatly deformed and, as a result, have been thickened during thrusting, compressional deformation, thinned during extension, tensional deformation, and juxtaposed against each other during both deformations. In the carbonate-rock province, Paleozoic carbonate rocks either comprise or underlie most of the ranges and lie beneath the basin fill in many basins. Figure 4 shows, in generalized form, the geometric relations of rocks that lie beneath southern Nevada. The carbonate-rock aquifers extend to great depths but also are commonly present near the surface in mountain ranges. A single continuous "layer" of carbonate rocks may underlie several basins (as shown in fig. 4) and because of this can link ground-water flow systems over large distances. Basin-fill aquifers in a given basin may or may not be in hydraulic contact with the underlying carbonate rocks. The degree of contact depends primarily on the vertical hydraulic conductivity of the deeper basin fill.

SYSTEM	GROUP, FORMATION, MEMBER	THICKNESS, IN FEET	DESCRIPTION
Mississippian	Indian Springs Formation	100	Rusty shale, very poorly exposed
Mississippian	Joana Limestone	820	Dark gray crinodal limestone, with prominent cherty zone
Mississippian	Pilot Shale	50	Shaly limestone, with thin basal quartzite and bedded chert
Devonian	Devils Gate Limestone	1,440	Limestone, dark gray to blue gray; upper middle part with interbedded clean quartzite; lower middle part with abundant stromataphorids; thin silty dolomite at base
Devonian	Nevada Formation: Upper Member	640	Dolomite, laminated, dark to light gray
Devonian	Nevada Formation: Oxyoke Canyon Sandstone-Beacon Peak Dolomite	160	Sandstone, sandy dolomite, cherty dolomite, and silty dolomite
Silurian	Laketown Dolomite	980	Dolomite, light gray, thin bedded, with some chert
Ordovician	Ely Springs Dolomite	460	Dolomite, black, massive
Ordovician	Eureka Quartzite	160	Quartzite, mostly white and vitreous, with minor dolomite
Ordovician	Antelope Valley Limestone: Aysees Member	910	Silty, light gray dolomite in upper part; massive, dark gray dolomite in lower part
Ordovician	Antelope Valley Limestone: Ranger Mountains Member	420	Silty, crepe-weathering limestone and dolomite
Ordovician	Antelope Valley Limestone: Paiute Ridge Member	590	Silty dolomite and minor limestone
Ordovician	Lower Pogonip Group Undifferentiated	1,060	Light gray dolomite, cherty, with interformational conglomerate; silty dolomite at base
Cambrian	Nopah Formation: Upper Member	890	Black and white massive dolomite
Cambrian	Nopah Formation: Dunderberg Shale	100	Shale and shaly limestone
Cambrian	Bonanza King Formation: Banded Mountain Member	1,340	Dolomite and limestone, color-banded, mottled, laminated, ledge-forming; silty limestone at base
Cambrian	Bonanza King Formation: Papoose Lake Member	1,610	Dolomite and limestone, mottled, burrowed, laminated
Cambrian	Carrara Formation	870	Interbedded shale and limestone
Precambrian	Wood Canyon Formation	660	Dark colored siltstone and quartzite
Precambrian	Stirling Quartzite	?	Light colored quartzite and conglomerate

EXPLANATION

- **Dolomite**—Other patterns are superimposed where noncarbonate minerals and layers are present
- **Limestone**—Other patterns are superimposed where noncarbonate minerals and layers are present
- **Shaly or silty rock**
- **Quartzite**
- **Cherty interbeds**
- **Conglomerate interbeds**

Figure 2. Paleozoic-rock section as exposed in Sheep Range (modified from Guth, 1980, pl. 3). Rocks shown range from latest Precambrian (older than 570 million years) through Mississippian (about 330 million years old).

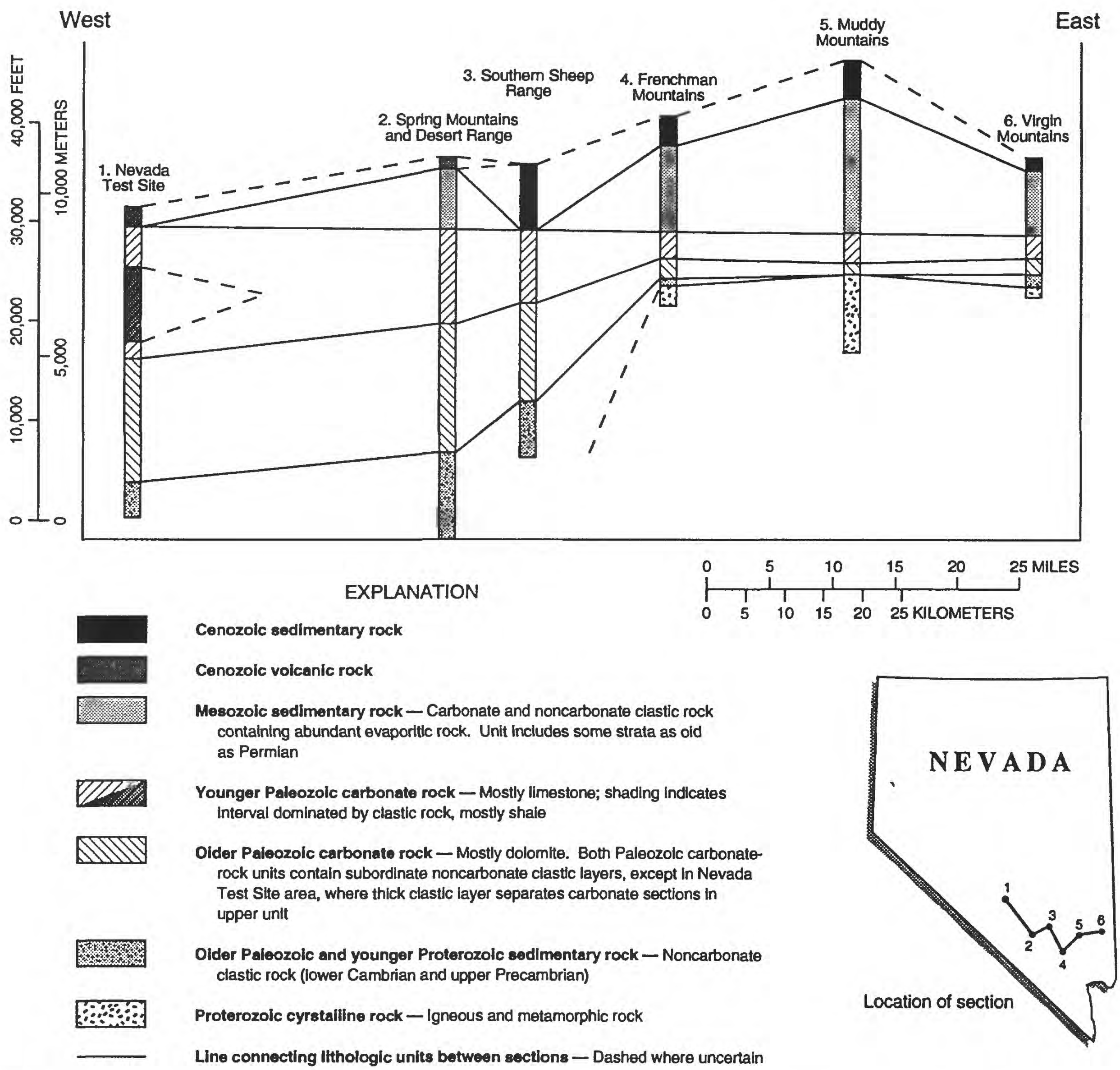


Figure 3. Stratigraphic sections showing thickness of Paleozoic carbonate rocks, overlying Mesozoic and Cenozoic rocks, and underlying Precambrian rocks beneath southern Nevada at a latitude of about 36°30′ north. Depositional thickness is shown without regard to subsequent deformation. Sources of stratigraphic data are: section 1, Tschanz and Pampeyan (1970); sections 2, 5, 6, and 7, Longwell and others (1965); section 3, Guth (1986); and section 4, Langenheim and others (1962). Index map shows location of section.

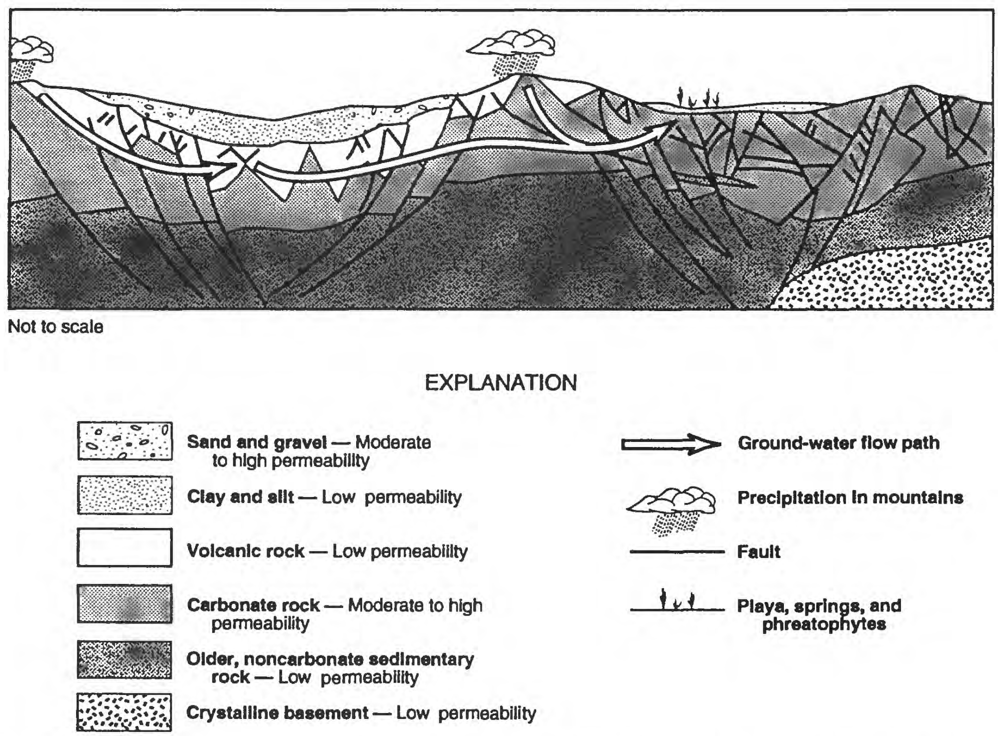


Figure 4. Schematic hydrogeologic section across basins and ranges of southern Nevada, showing hypothetical subsurface configuration of aquifers and rocks of low permeability. (Modified from Anderson and others, 1983, fig. 10.)

Deformation of the Carbonate Rocks

The carbonate rocks having depositional thicknesses as great as 30,000 ft have been deformed subsequent to their deposition, by compressional forces and by tensional forces. Beginning about 100 million or possibly as early as 200 million years ago, continental-scale forces compressed the rocks eastward against the North American continent. These forces mostly ceased about 70 million years ago (Stewart, 1980, p. 79), but while active, thick sections of the rocks were folded and thrusted over adjacent sections. The deformation created large, overlapping folds and thrusts in the previously flat-lying rocks, and in many places these repeated sections of carbonate rock remain today. For example, in parts of southern Nevada, a deep drill hole might intercept older carbonate rocks above a thrust fault and intercept younger carbonate rocks below the fault (Armstrong, 1968). Thus, the original thickness of the carbonate rocks in places was doubled by such compressional deformation.

More recently, at various times during the past 30 million years, the entire region underlying present-day Nevada was extended or pulled apart, by tensional forces. In southern Nevada, extension stretched the region between the Sierra Nevada and the Colorado Plateau by possibly more than 150 mi overall (Wernicke, Snow, and Walker, 1988, p. 256). The stretching was accommodated along both low and high-angle normal faults as well as along nearly vertical strike-slip faults (Stewart, 1980, p. 110-116). The sedimentary rocks were extended along numerous faults that transported large blocks of rock over long distances and rotated blocks of rocks to various angles. As a result, the mountain ranges were raised and tilted and the basins were depressed and filled with erosional debris from the adjacent raised ranges to give the region its characteristic Basin-and-Range topography (see fig. 1; Hamilton and Myers, 1966; Wernicke and others, 1984).

Extension of the carbonate rocks served to reverse the thickening process induced by the compressional forces by dramatic structural thinning and disruption of most of the rocks. In some areas, brittle, broken carbonate-rock layers were virtually pulled apart above deep, ductally extended crystalline rocks of Precambrian age (Wright and others, 1981; Wernicke and others, 1984, p. 488; Wernicke and others, 1985, pl. 2; Hamilton, 1988; Wernicke, Walker, and Hodges, 1988). In other areas, the carbonate rocks were removed entirely from the lower noncarbonate part of

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the full rock section leaving only isolated blocks of carbonate rock. In still other areas, the thick layers of the Paleozoic rock section were pulled along and deformed but remained largely intact above lower layers of carbonate rocks and the noncarbonate, Precambrian sedimentary rocks (Wernicke and others, 1984, p. 490 and fig. 9; Guth, 1988). In all these examples, depending on the juxtaposition of carbonate and noncarbonate rocks, the thinned and deformed rocks might function as barriers to flow or might function as extensive and continuous aquifers.

During much of the time when extension of the Basin and Range Province was taking place, volcanism was active in parts of the province (Stewart, 1980, p. 98-104). On all sides of the carbonate-rock province in southern Nevada, thick, expansive layers of volcanic rocks were deposited and in part remain today. Some volcanic rocks are permeable and constitute aquifers, whereas others are less permeable and constitute aquitards (Winograd, 1971). North of the study area and beneath the Nevada Test Site, these rocks constitute important local aquifers (Fiero, 1968; Blankennagel and Weir, 1973). Within the study area, however, volcanic rocks are generally not continuous or thick enough to form regional aquifers comparable to the carbonate-rock aquifers.

As a result of these various forces, the originally flat-lying carbonate rocks are today complexly deformed and faulted into blocks and folds wherein rocks of all ages may be intermingled. The previous depositional "layer cake" structure of the sedimentary rocks has been transformed into a complex mixture of carbonate and noncarbonate rocks that separate and underlie basins partly filled with unconsolidated sediments, and the original stratigraphic thicknesses of the rocks commonly have been greatly modified to their present-day thicknesses.

Avenues for Ground-Water Flow Through the Carbonate Rocks

The carbonate rocks are generally dense and brittle, and, where unbroken, are nearly impermeable. The unbroken carbonate rocks impede ground-water flow—because after deposition they consolidated under the great weight of sediments deposited on top of them and because, as a result, most of the original spaces between the grains or crystals making up the rocks have been compacted or sealed by cementation and recrystallization processes.

Most carbonate rocks of southern and eastern Nevada have been fractured, brecciated, and otherwise broken during the complex deformational history of the area (Hess and Mifflin, 1978, p. 16). Because the carbonate rocks are dense and brittle, many openings caused by extensional deformation are clean, smooth fractures or joints. Most of the noncarbonate sedimentary rocks, when deformed, will break into well-graded fragments (as for quartzite) that reconsolidate into impervious rock or will yield ductally (as for shale) and, in either example, will not result in significant openings through which water can flow. Some openings (fractures) that form in carbonate rocks can be excellent paths for ground-water flow. Carbonate rocks containing many fractures and interbreccia openings are commonly much more permeable than they would be if unbroken.

In addition to being brittle and subject to fracturing, the carbonate rocks have the special property of being relatively more soluble in water than most other rock types. Consequently, under the right geochemical conditions, they will dissolve when in contact with water. This is why in many parts of the world limestone terranes are riddled with caves and sink holes (Fairbridge, 1968, p. 582). The rock that once filled these large and extensive openings has simply been dissolved by water flowing through the openings. In Nevada, geochemical conditions that allow dissolution of the carbonate rocks are not common and therefore these landforms and openings are present only locally. The amount of rock that can be dissolved prior to the water becoming saturated depends on conditions that add acid to the water and make it corrosive in the rocks. The most important limiting conditions are probably the small volumes of water (relative to more humid settings) flowing through the rocks and the relatively small quantity of acid produced by the thin soils and vegetation in the ground-water recharge areas in Nevada (Fairbridge, 1968, p. 582; Winograd and Thordarson, 1975, p. C115). Both of these conditions are attributable to the aridity of the State. The relatively small quantity of water flowing through the rocks means that less water is available to dissolve the rock. As a consequence, water becomes "saturated" with carbonate ions after flowing only a short distance through the aquifers. Once saturated the water does not dissolve more rock until geochemical conditions change such that the water becomes undersaturated with respect to carbonate ions.

Regardless of these limiting conditions, some carbonate rocks of Nevada are slowly dissolved and carried away by ground water flowing through fractures. The dissolution widens the openings and allows even more water to flow through the rocks, increasing the overall permeability of the rock masses (Kemmerly, 1986). Although some dissolution occurs along fracture faces, unmodified fractures and joints are more common than solution-enlarged fractures in southern Nevada. This suggests that the dissolution process contributes to creation of large-scale permeability, but probably is not as important as simple, sustained fracturing of the rocks (Winograd and Thordarson, 1975, p. C1; Alan M. Preissler, Dwight L. Schmidt, and Gary L. Dixon, U.S. Geological Survey, written communs., 1986-87).

Hydraulic Properties of the Carbonate Rocks

Winograd and Thordarson (1975, p. C17) report that carbonate rocks in 13 cores collected at the Nevada Test Site had matrix porosities ranging from 0.4 to 12.4 percent of the total bulk rock volume, with a median value of 5.5 percent. These values are in the range suggested by borehole geophysical logs obtained during the present study (Berger, 1992). Only about 20 percent of the matrix porosity is interconnected and "effective" in allowing throughflow of water (Winograd and Thordarson, 1975, p. C17).

While most ground-water flow through the carbonate rocks of southern Nevada is assumed to be through fractures and solution openings, the amount of water actually stored in these openings is uncertain. Small, open fractures and joints generally constitute less than 1 percent of the total volume of rock (Winograd and Thordarson, 1975, p. C18; Alan M. Preissler, U.S. Geological Survey, written commun., 1987), which is less than the effective porosity of the rock matrix reported by Winograd and Thordarson (1975, p. C17). Large fractures and joints are likely to be even less common than smaller ones, and, although highly permeable, only comprise a very small volume of the aquifers. Even though water moves more easily through large open fractures near and along major fault zones, most of the water stored in the carbonate rocks is in the extensive volumes of less fractured rock between major fault zones. This water moves slowly, if at all, because of low matrix hydraulic conductivities and would be yielded to wells at only moderate rates.

The hydraulic conductivity is a measure of the capacity of a rock to allow water to move through it and is directly proportional to its permeability. Winograd and Thordarson (1975, p. C17) report that matrix or primary hydraulic conductivities of carbonate rocks in those same 13 cores range from 0.000003 to 0.01 ft/d. The median value was 0.00001 ft/d. To provide an example of how low this median conductivity is, and how impermeable the rocks are, methods described by Skibitzke (1963, p. 293-297) predict that a 12-in. diameter well that extends 500 ft beneath the water table in a water-saturated mass of unfractured carbonate rocks that is suddenly bailed dry would take more than 17 years to refill to within 1 ft of the undisturbed (static) water level.

As a result of fractures, and to an unknown extent because some of these openings have been enlarged by dissolution, the hydraulic conductivities determined in field-scale aquifer tests are much larger than reported matrix conductivities. Available measurements of hydraulic conductivity from aquifer tests at 39 carbonate-rock wells in southern and eastern Nevada are listed in table 1 with locations shown in figure 5. Of these tests, 33 are reported results and 6 are from tests made as part of this study. Another source of estimates are specialized hydraulic tests called "drill-stem tests" commonly done in oil-test wells. For completeness, table 2 is included here; it summarizes results from 13 such wells in carbonate rocks. These results were assessed for their usefulness in defining the properties of deeper parts of the aquifers (as part of the present studies and as reported in McKay and Kepper, 1988), but, at present (1989), unresolved differences have been noted between the "population" of aquifer properties determined by drill-stem tests as opposed to aquifer tests in water wells. These differences are discussed in more detail in a later section of this report, but the drill-stem test results are not included in the following statistical description of aquifer properties.

Hydraulic conductivities of the fractured rocks range from 0.01 to 940 ft/d and have a median value of 4.5 ft/d (table 1). The number of wells at which various orders-of-magnitudes of hydraulic conductivity were measured is shown in figure 5. Of the wells in table 1, the median value of hydraulic conductivities is the same as at a well near Mercury, Nev.—Army Well 1. This median hydraulic conductivity also is comparable to that of basin-fill aquifers composed predominantly of sand. Hydraulic conductivities for the most productive carbonate-aquifer wells are comparable to those for clean gravels (described by Bear, 1979, table 4-1).

Table 1. Construction data and aquifer-test results for wells in carbonate-rock aquifers and noncarbonate (clastic) rocks of Nevada

Site designation: Local name or USGS identification, preceded by: MX, constructed for studies of MX Missile-Siting Water Resources Program; NCAP, constructed for present study; NTS, constructed for studies associated with Nevada Test Site (but not necessarily located there); Prv., privately constructed.
Age: p∊, Precambrian; ∊, Cambrian; ∊O, Cambrian-Ordovician; O, Ordovician; S, Silurian; D, Devonian; M, Mississippian; IP, Pennsylvanian; pIP, Permian-Pennsylvanian.
Rock-unit name: LS, limestone.
Lithology: C, predominantly noncarbonate clastics; D, predominantly dolomite; L, predominantly limestone. Multiple abbreviations are listed in order of predominance.
[--, no data available; <, less than]

		Degrees, minutes, seconds		Rocks tested			Well construction			
							Depth (feet below land surface)			
Site No.	Site designation	Latitude	Longitude	Age	Rock-unit name	Lithology	Shallowest opening	Deepest opening	Total open interval (feet)	Casing or open-hole diameter (inches)
	Wells completed in Carbonate Rock									
1	Prv. S23 E60 24BB	35 56 17	115 13 20	IP	Bird Spring	L	540	700	160	12
2	Prv. S23 E61 09BC	35 57 50	115 10 10	M	Monte Cristo	D	400	520	120	8
3	Prv. S18 E63 34CA	36 20 28	114 55 36	IP	Bird Spring	L	754	1,205	451	6
4	Prv. S17 E50 23BB2	36 27 54	116 19 02	∊	Bonanza King	D	0	140	140	14
5	NCAP S16 E58 23DD (SBH1)	36 32 12	115 24 03	O	Pogonip	L	654	694	40	6
6	NTS Tracer No.1	36 32 12	116 13 47	∊	Bonanza King, Carrara	D,L	625	830	205	9.9
7	NTS Tracer No.3	36 32 12	116 13 47	∊	Bonanza King, Carrara	D,L	620	807	187	5.5
8	NTS Tracer No.2	36 32 12	116 13 47	∊	Bonanza King, Carrara	D,L	659	828	169	6.2
9	NCAP S16 E58 14A (DR1)	36 33 32	115 24 40	D	Guilmette, Simonson	L,D	870	930	60	8
10	NTS S16 E56 08 (#2)	36 34 43	115 40 37	IP	Bird Spring	L	54	575	521	14
11	NTS TW-4 (66-75)	36 34 54	115 50 08	∊	Nopah	D	737	1,490	753	7.6
12	NTS Army 1 (67-68)	36 35 30	116 02 14	∊	Bonanza King, Nopah	L	785	1,946	1,161	10.7
13	NTS TW-10 (67-73)	36 35 31	115 51 04	∊	Bonanza King	L	1,020	1,301	281	8.6
14	Prv. S15 E67 09DD	36 38 19	114 29 43	pIP	--	L	360	420	60	8.6
15	NTS TW-F (73-66)	36 45 34	116 06 59	S	--	D	3,137	3,400	253	8.6
16	MX CE-DT-6	36 46 04	114 47 13	IP	Monte Cristo	L	457	937	480	12
17	NCAP S13 E65 28B (CSV2)	36 46 50	114 43 20	IP	Bird Spring	L	391	480	89	8
18	MX CE-DT-5	36 47 41	114 53 28	M	Monte Cristo	L	353	628	275	20
19	MX CE-DT-4	36 47 43	114 53 31	M	Monte Cristo	L	352	669	317	10
20	NTS TW-3 (75-73)	36 48 30	115 51 26	O	Pogonip	L	1,105	1,853	748	7
21	NTS UE25P#1 (75-57)	36 49 38	116 25 21	S	Lone, Robert Mtn.	D	4,255	5,922	1,667	6.7
22	MX CE-VF-2	36 52 27	114 56 51	IP	Bird Spring	L,D,C	860	1,009	149	10
23	NTS WW-C-1 (79-69)	36 55 07	116 00 34	∊	Carrara	L	1,545	1,650	105	16.7
24	NTS WW-C (79-69a)	36 55 08	116 00 35	∊	Carrara	L	1,544	1,701	157	10.8
25	NTS TW-E (83-69)	37 03 21	115 59 42	O	Pogonip	L	1,780	2,620	840	10.8

Table 1. Construction data and aquifer-test results for wells in carbonate-rock aquifers and noncarbonate (clastic) rocks of Nevada--Continued

Site No.	Site designation	Degrees, minutes, seconds: Latitude	Degrees, minutes, seconds: Longitude	Rocks tested: Age	Rocks tested: Rock-unit name	Rocks tested: Lithology	Well construction: Depth (feet below land surface): Shallowest opening	Well construction: Depth (feet below land surface): Deepest opening	Well construction: Total open interval (feet)	Well construction: Casing or open-hole diameter (inches)
26	NTS U3cn-5 (84-68d)	37 03 35	116 01 30	D	--	D,C	2,821	3,026	205	6
27	NTS UE-16D	37 04 12	116 09 51	IP	Tippipah	L	753	2,119	1,366	7
28	NTS TW-D (84-67)	37 04 28	116 04 30	M	Eleana LS, Shale	L,C	1,772	1,882	110	10.8
29	NTS TW-1 (87-62)	37 09 29	116 13 23	D	Devils Gate, Nevada	D	3,700	4,198	498	7.6
30	NTS WW-2 (88-66)	37 09 58	116 05 15	O	Pogonip	L	2,550	3,422	498	6.6
31	MX DL-DT-3	38 05 31	114 53 42	M	--	L	853	2,395	1,542	8.8
32	MX-CV-DT-1	38 07 58	115 20 46	D	Guilmette	D	803	1,837	1,034	10
33	MX N07 E63 14ABC	38 28 19	114 51 58	IP	--	L	230	435	205	10.8
34	prv. N08 E43 24AA	38 32 41	117 05 41	∈O	--	L,C	160	340	180	6
35	MX SV-DT-2	38 55 21	114 50 36	IP	Ely LS, Chainman	L,C	500	2,447	1,947	6
36	Prv. Fad Shaft	39 30 20	115 59 05	∈	Hamburg LS, Shale	L,C	1,025	2,465	1,440	120
37	Prv. N22 E57 25CD	39 44 27	115 30 43	D	Devils Gate	L	480	583	103	12.8
38	Prv. N36 E62 18	41 00 13	115 00 39	D	Guilmette	L	140	220	80	6
39	Prv. N37 E63 06BA	41 07 29	114 53 56	P	Ely LS	L	555	595	40	6
	Wells completed in Noncarbonate rock (clastic)									
40	NTS TW-5 (68-60)	36 37 46	116 18 22	∈	Carrara	C	735	800	65	7
41	NTS UE16F	37 02 08	116 09 24	M	Eleana	C	1,293	1,414	121	9.6
42	NTS UE-17A (84-64A)	37 04 25	116 09 58	M	Eleana	C	745	1,190	215	4.5
43	NTS UE-15D (89-68)	37 12 33	116 02 29	p∈	Johnnie	C	1,773	5,940	4,167	4.5

Table 1. Construction data and aquifer-test results for wells in carbonate-rock aquifers and noncarbonate (clastic) rocks of Nevada--Continued

Specific capacity: Estimated by dividing constant pumping rate by final drawdown, except values estimated by Winograd and Thordarson (1975), which are based on drawdown at 100 minutes.
Estimated transmissivity: From capacity: based on specific capacity using method of Theis and others (1963). From drawdown: based on regular measurements of drawdown in pumped well using method of Cooper and Jacob (1946). From recovery: based on regular measurements of recovery in pumped well using method of Cooper and Jacob (1946). From other data: based on other methods and data noted in footnotes.
Hydraulic conductivity: Value estimated from transmissivity divided by total open interval, followed by: C, transmissivity estimated from specific-capacity data used to calculate hydraulic conductivity; D, transmissivity estimated from drawdown data used; O, transmissivity estimated from other data used; R, transmissivity estimated from recovery data used.

Site No.	Rate pumped (gallons per minute)	Draw-down (feet)	Specific capacity (gallons per minute per foot)	Test duration (minutes)	Estimated transmissivity (feet squared per day): From capacity	From drawdown	From recovery	From other data	Hydraulic conductivity (feet per day)	Reference
					Wells completed in Carbonate Rock					
1	17	90	0.19	240	32	--	--	--	0.2	(C) Driller's report dated 11/81
2	121	91	1.33	120	270	--	--	--	2.2	(C) Driller's report dated 06/73
3	72	282	.26	480	53	--	--	--	.12	(C) Driller's report, permit 50316
4	537	40	13.25	1,350	3,700	--	--	[a]3,500	25	(O) Dudley and Larson, 1976, tables 3 and 4
5	24	9	26.7	600	7,600	(b)	37,000	--	940	(R) Present study
6	100	8	13	60	2,800	--	--	--	14	(C) Johnston, 1968, p. 21-32, 44
7	100	2	60	60	16,000	--	--	--	84	(C) do.
8	94	1	140	60	36,000	--	--	--	210	(C) do.
9	14.5	11	1.3	1,638	320	450	100	--	7.5	(D) Present study
10	500	50	10	--	2,100	--	--	--	4.1	(C) U.S. Corps of Engineers, written commun., 1942
11	154	40	4.5	2,000	530	1,500	3,000	--	2.0	(D) Winograd and Thordarson, 1975, table 3
12	455	85	6	3,000	800	5,200	11,500	--	4.5	(D) do.
13	400	91	4.8	3,000	1,100	2,700	7,100	--	9.5	(D) do.
14	225	137	1.64	960	400	--	--	--	6.7	(C) Drillers report dated 11/85
15	58	2	29	--	[c]8,000	--	--	--	30	(C) Winograd and Thordarson, 1975, table 3; Thordarson and others, 1967, p. 14
16	472	42	11.4	3,963	3,200	12,600	[d]53,000	--	26	(D) Present study
17	101	30	3.4	1,320	860	1,600	7,000	--	18	(D)
18	3,400	11	309	42,441	98,000	250,000	--	[e]100,000	900	(D) Berger and others, 1988, p. 30-39; Bunch and Harrill, 1984, p. 33
19	540	3	154	4,600	45,000	200,000	--	[f]760,000	630	(D) Berger and others, 1988, p. 24-29; Bunch and Harrill, 1984, p. 33; Morin and others, 1988, p. 587
20	30	48	.7	1,000	80	510	--	--	.7	(D) Winograd and Thordarson, 1975, table 3
21	500	49	10.2	6,080	3,500	[g]1,200	--	--	0.71	(D) Winograd and Thordarson, 1975, table 3
22	77	13	5.9	830	1,600	2,800	7,800	--	19	(D) Present study
23	300	59	5.1	100	800	--	--	--	8	(C) Winograd and Thordarson, 1975, table 3
24	456	.8	570	240	130,000	--	--	--	860	(C) Claassen, 1973
25	[h]12	130	.08	340	19	--	11	--	.01	(R) Winograd and Thordarson, written commun., 1965

Table 1. Construction data and aquifer-test results for wells in carbonate-rock aquifers and noncarbonate (clastic) rocks of Nevada--Continued

Site No.	Rate pumped (gallons per minute)	Draw-down (feet)	Specific capacity (gallons per minute per foot)	Test duration (minutes)	Estimated transmissivity (feet squared per day): From capacity	From drawdown	From recovery	From other data	Hydraulic conductivity (feet per day)	Reference
26	76	172	.4	3,000	90	320	--	--	1.6	(D) Winograd and Thordarson, 1975, table 3
27	570	43	13.3	1,440	3,700	--	8,600	--	6.3	(R) Dinwiddie and Weir, 1979, p. 4-6, 15
28	22	49	.45	89	80	--	11	[i]13	.11	(O) Thordarson and others, 1962, p. 31-37
29	98	135	.8	500	130	880	470	--	.94	(R) Winograd and Thordarson, 1975, table 3
30	60	180	.4	5,000	94	170	710	--	.35	(D) do.
31	106	2	53	6,400	17,000	--	--	--	11	(C) Bunch and Harrill, 1984, p. 36; Ertec Western, written commun., 1985
32	95	63	1.5	1,380	350	--	--	--	.34	(C) Bunch and Harrill, 1984, p. 32; Ertec Western, written commun., 1985
33	225	118	1.9	210	390	--	--	[j]2,400	1.7	(C) Bunch and Harrill, 1984, p. 31; driller's log 22581
34	35	4	8.75	10,080	2,700	--	--	--	15	(C) Driller's report dated 01/86
35	100	124	.8	200	190	130	530	--	.3	(R) Bunch and Harrill, 1984, p. 105; Ertec Western, written commun., 1985
36	3,600	270	13.3	43,200	3,200	2,200	2,100	[k]3,200	1.5	(D) Stuart, 1955, p. 2-4
37	550	560	.98	240	190	--	--	--	1.8	(C) Driller's log 22217
38	30	75	.4	180	80	--	--	--	1	(C) Driller's log 20511
39	15	80	.19	300	40	--	--	--	.9	(C) Driller's log 20972
							Wells completed in Noncarbonate Rock (clastic)			
40	<5	126	<.04	--	<7	--	--	--	<.1	(C) Thordarson and others, 1967, p. 14
41	--	--	--	100	--	--	--	[l]1	.01	(O) Dinwiddie and Weir, 1979, p. 16-19
42	20	493	.04	120	8	--	1.2	--	.006	(R) Weir and Hodson, 1979, p. 4, 6, 8, 11
43	78	294	.27	2160	40	80	--	--	.02	(D) Thordarson and others, 1967, p. 20

[a] Estimated from drawdowns at nearby well S17 E50 23BB1.
[b] Influence of barometric pressure was greater than drawdown.
[c] Estimate based on airline measurements. Estimated storage coefficient, 0.013.
[d] Pump has no foot valve, making recovery difficult to analyze.
[e] Estimated from drawdowns at MX well CE-DT-4 (site 19). Estimated from drawdowns and recoveries at several wells. Estimated storage coefficient, 0.14. Storage-coefficient estimates range from 0.0014 to 0.00075.
[f] Estimated from borehole flowmeter test during present study. Estimated from slug test. Recovery took 100 minutes.
[g] Galloway (1986) estimated storage coefficient of 0.0003 using tidal fluctuations of water levels in well.
[h] Drawdown may be influenced by caving of overlying tuffs.
[i] Estimated using method of Skibitzke (1963).
[j] Estimated from drawdown in nearby observation well.
[k] Estimated from drawdowns and recoveries at several wells. Storage-coefficient estimates range from 0.0014 to 0.00075.
[l] Estimated from slugtest. recovery took 100 minutes.

Table 2. Data from drill-stem tests on petroleum-exploration wells. Compiled from McKay and Kepper (1988, table 2, appendices A and B)

Age: ∈, Cambrian; D, Devonian; M, Mississippian; IP, Pennsylvanian; ρ, Permian; U, undifferentiated.
Lithology: C, predominantly noncarbonate clastics; D, predominantly dolomite; G, gypsum; L, predominantly limestone. Multiple abbreviations are listed in order of predominance.
Depth interval: Reported depth zone that was mechanically isolated for the test.
Duration of test: Final shut-in period. For initial shut-in time or flow times, see McKay and Kepper (1988, appendix B).
[--, no data available]

Site designation	Degrees, minutes, seconds		Rocks tested			Depth interval tested (feet below land surface)	Duration of test (minutes)	Transmissivity (feet squared per day)	Hydraulic conductivity (feet per day)
	Latitude	Longitude	Age	Rock-unit name	Lithology				
Wells completed in Carbonate Rock									
Virgin River USA 1-A	36 38 18	114 23 42	ρ	Kaibab	L,C,G	11,764-11,814	120	0.07	0.0014
Adobe Federal 19-1	38 01 03	115 17 07	M	Joana	L	7,500-7,706	120	820	4
DOC Federal 5-18	38 17 38	115 50 22	M	Joana	L	5,671-5,725	120	84	1.6
Lone Tree 1-14-43	38 22 42	115 38 09	D	Guilmette	L,D	4,372-4,430	120	6.2	.11
Adobe Federal 16-1	38 24 15	115 50 51	D	Guilmette	L,D	3,785-3,930	90	350	2.4
Grant Canyon 5	38 27 15	115 34 49	D	Guilmette	L,D	4,548-4,648	60	460	4.6
Grant Canyon 1	38 27 19	115 34 37	D	Simonson	D	4,340-4,441	60	8.5	.085
Grant Canyon 4	38 27 32	115 34 21	D	Guilmette	L,D	4,034-4,061	62	510	19
Grant Canyon 3	38 27 45	115 34 37	D	Guilmette	L,D	3,934-3,961	60	15	.56
Bacon Flat 1	38 27 51	115 35 35	D	Guilmette	D,L	5,315-5,346	--	4.2	[a].13
Bacon Flat 5	38 27 57	115 35 10	IP	Ely	L	5,595-5,795	120	.062	.00031
White River Valley 1	38 29 09	115 06 37	IP	Ely	L	4,490-4,578	120	.077	.0087
Dobbin Creek Fed A1-6	38 59 38	116 36 49	U	--	D	(b)	1,419	6.9	.056
Wells completed in Noncarbonate Rock (clastic)									
Bacon Flat 5	38 27 57	115 35 10	M	Chain-	C	6,228-6,276	180	.041	.0008
Soda Springs Unit 1	38 32 54	115 32 59	∈	man	C	7,699-7,796	120	0.72	.0072
				--					

[a] Transmissivity is from reservoir engineer's report. Reported hydraulic conductivity was 0.31 foot per day, but a transposition of numerals is suspected.
[b] Transmissivity and hydraulic conductivity are averages from three tests, in depth intervals 3,200-3,480, 3,600-3,660, and 3,650-4,034 feet.

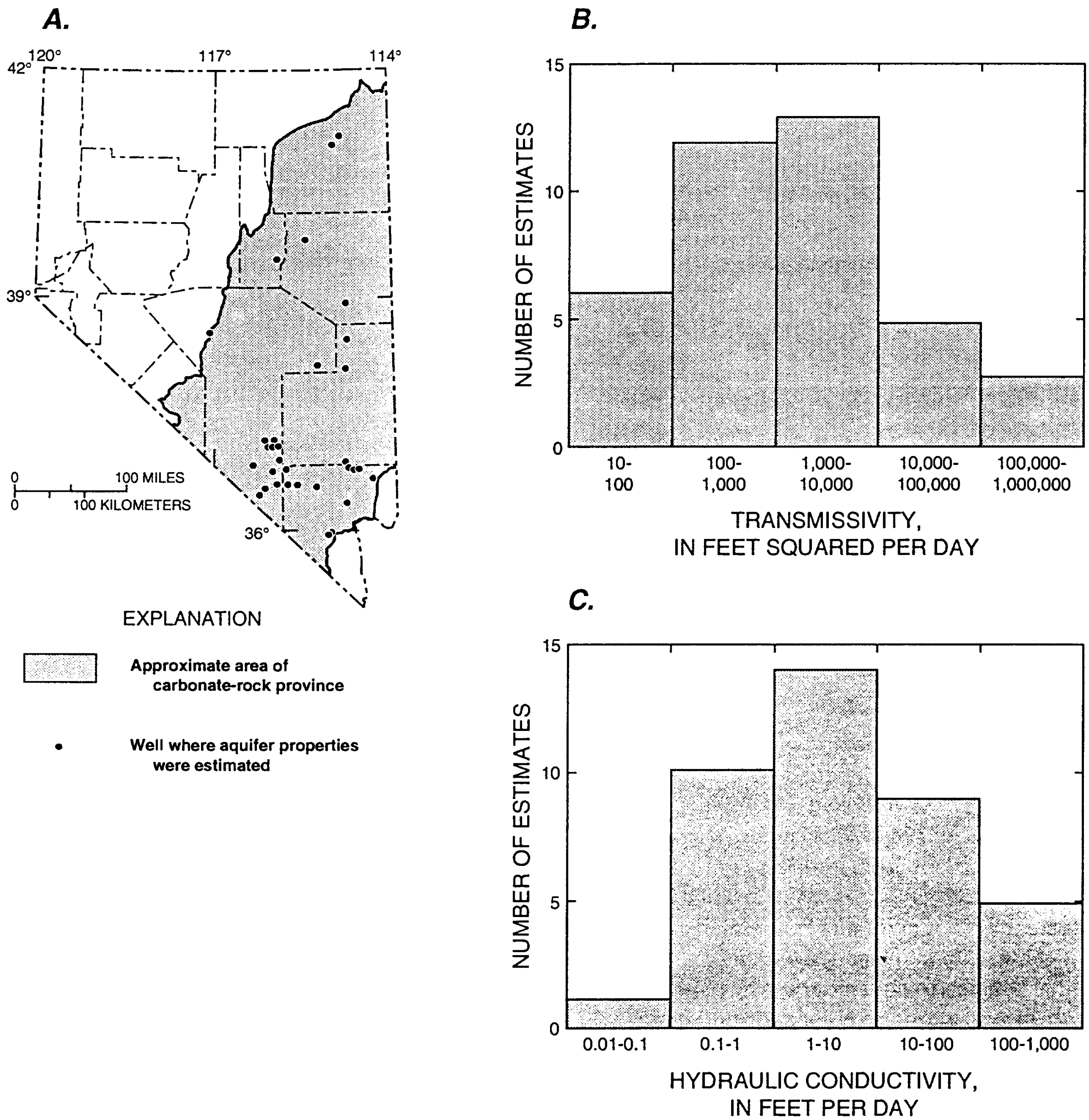


Figure 5. Estimated transmissivity and hydraulic conductivity of carbonate-rock aquifers in southern and eastern Nevada; (*A*) Location of wells at which test provide estimates of aquifer properties, (*B*) frequency distribution of estimated transmissivities, (*C*) frequency distribution of estimated hydraulic conductivities.

[Notably, the median is much less than the hydraulic conductivity at the MX wells in Coyote Spring Valley (about 900 ft ^{2}/d), and productivity of the MX wells is correspondingly higher (3,400 gal/min pumped with only 12 ft of water-level decline compared to 455 gal/min with 85 ft of drawdown at Army Well 1). In fact, the aquifer at the MX wells has a higher hydraulic conductivity than aquifers at 38 of the 39 sites at which test results are available.]

The median value of the conductivities estimated from the water-well tests is 430,000 times greater than the matrix conductivity of the rock. The practical importance of this difference between matrix conductivities and fractured-rock conductivities is suggested by the following example: a 500-ft deep, 12-in. diameter well penetrating fractured, water-saturated carbonate rock having a hydraulic conductivity equal to the median above would take only 21 minutes to refill to within 1 ft of the static water level after suddenly being bailed dry in comparison to the long time (17 years) necessary in unfractured carbonate rocks.

Hydraulic Characteristics of Associated Noncarbonate Rocks

Aquifer properties of intervening noncarbonate sedimentary rocks are somewhat less well known. These rocks are principally shale, siltstone, and quartzite. Shale commonly is relatively soft and deforms ductilly (bending rather than breaking) or by shattering into clay size particles. Quartzite is a brittle rock and is made up of tightly cemented or recrystallized quartz sand. Observations at outcrops indicate that quartzites commonly have been broken into very small fragments (Alan M. Preissler, U.S. Geological Survey, written commun., 1987). When fractured, these rocks are believed to be much less permeable than fractured carbonate rocks (Motts, 1968, p. 289; Winograd and Thordarson, 1975, p. C40). However, there are few data upon which to base this belief. Aquifer tests have been conducted at four wells tapping noncarbonate rocks at the Nevada Test Site (table 1). The median hydraulic conductivity determined from these tests is 0.015 ft/d (300 times smaller than the median conductivity of the carbonate-rock aquifers but still 1,500 times larger than that of the carbonate-rock matrix). Winograd and Thordarson (1975, p. C43) suggest that the few, low discharge springs present in the noncarbonate sedimentary rocks in southern Nevada also may indicate lower hydraulic conductivities.

Volcanic rocks, which were deposited about the same time as the basins were forming, are an important sequence of intervening rocks between the basin-fill deposits and the carbonate rocks beneath many basins of eastern and southern Nevada. Thick layers of these rocks are exposed also in many mountain ranges. The volcanic rocks have a wide range of permeabilities depending on their depositional history and range from excellent aquifers to barriers to ground-water flow (Winograd, 1971). In southern Nevada these rocks are less common than farther north, except near the Nevada Test Site, Caliente, and just north of Lake Mead (pl. 1).

Source, Occurrence, and Movement of Water

The water moving through and stored in the carbonate rocks is derived from precipitation—rain and snow—within the carbonate-rock province and on several mountain ranges adjacent to the province. Annual precipitation ranges from less than 3 in. in some of the southern valleys (for example, the Amargosa Desert and Death Valley [pl. 1]) to greater than 30 in. in some of the highest mountain ranges (for example, the Ruby Mountains [fig. 1]), and depends primarily on altitude (Hardman and Mason, 1949, p. 10). Virtually all the precipitation on the basin floors and most of the precipitation in the mountains is evaporated or transpired (used by plants) before the remainder recharges either the basin-fill aquifers or the carbonate rocks. Some precipitation may become surface runoff, which then either infiltrates to recharge ground water or is consumed by evapotranspiration.

The process through which water enters (recharges) the carbonate-rock aquifers is not completely understood. In some areas, for example, the Ruby Mountains in northeastern Nevada (Johnson, 1980, p. 17-18) and the Spring Mountains of southern Nevada (Winograd and Thordarson, 1975, p. C92), recharge to the carbonate-rock aquifers primarily is by downward percolation of water through the thin soil zone and into the carbonate rocks within the mountains. In other areas, water enters the carbonate-rock aquifers by leaking down through basin fill. This form of recharge is difficult to delineate because it occurs at depth beneath the basin fill and depends on aquifer properties and hydrologic conditions that are not adequately defined. The water involved in this interaquifer flow can easily be "double counted" (as part of the basin-fill resource AND as part of the carbonate-rock resource) unless interchanges between basin fill and the carbonate aquifers are well understood. Geochemical tracing of water has been used to good advantage in identifying recharge source areas in selected basins in southern Nevada (Emme, 1986; Lyles and Hess, 1988; Noack, 1988). Because of the aridity of the region and the mountainous terrain of the Basin and Range Province (fig. 1), recharge to the carbonate-rock aquifers at low altitudes, from direct leakage from overlying perennial streams, is rare in southern Nevada.

Once water infiltrates into the carbonate-rock aquifers it generally will flow downgradient to one or more discharge areas at rates of flow that vary considerably in space. Because ground water flows downgradient from areas of high head to areas of lower head (Mifflin, 1968, fig. 5) at rates that depend on the permeabilities of the rocks, the rate of flow through the carbonate rocks depends on the openings in the rocks and the hydraulic gradients, that is, the gravity and pressure forcing the water along. The path that water follows as it moves downgradient may be quite circuitous owing to geologic and hydrologic barriers; however, the paths are ultimately toward some area where water is discharging from the aquifers.

Water leaves the carbonate-rock aquifers by discharging at springs, by leaking into overlying and underlying aquifers, by transpiring through plants, by evaporating from areas where the water table is near the land surface (such as playas), and by discharging into rivers or streams (such as in the middle reaches of the Amargosa River [pl. 1]; Mifflin, 1968, p. 22). In some places, water leaves the carbonate rocks of Nevada by subsurface flow into adjacent States.

SUMMARY OF PROGRAM ACTIVITIES, 1985-88

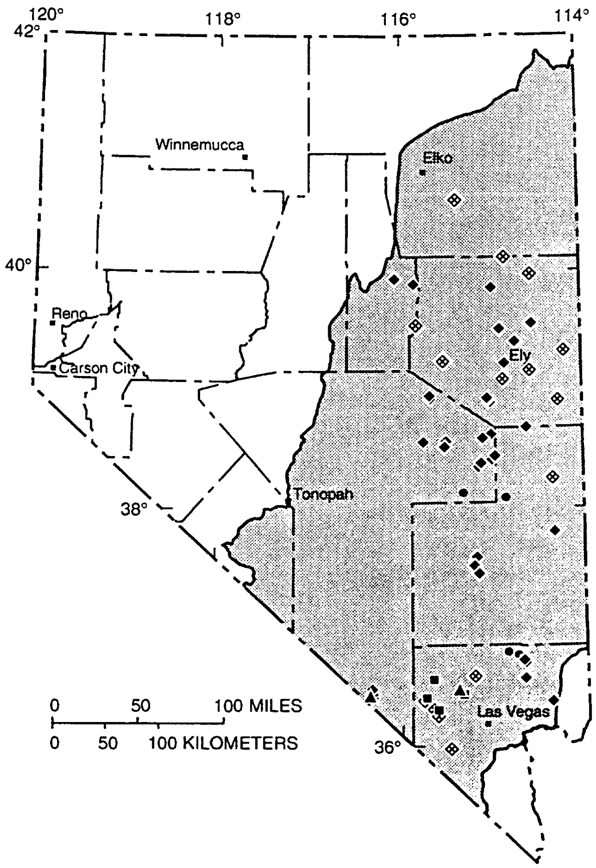
Activities during 1985-88 focused on determining the potential for development of the carbonate-rock aquifers in southern Nevada, largely north of Las Vegas. The activities included:

- **Collection of basic hydrologic data** such as high-altitude precipitation rates, ground-water levels in selected wells, and flow rates in selected springs and streams.
- **Geologic mapping** of the structure and stratigraphy of the carbonate rocks and younger basin-fill deposits.
- **Geophysical measurements and interpretations** employing measurement of the density, electrical, and magnetic properties of the rocks and sediments.
- **Geochemical sampling and inferences** characterizing ground water and flow paths using the isotopic composition and chemical constituents in the water.
- **Compilation of hydraulic properties estimated from available aquifer and drill-stem tests** in the carbonate rocks.
- **Drilling, logging, and hydraulic testing** of wells into the basin-fill and carbonate-rock aquifers.
- **Measurements of ground-water evapotranspiration rates** by native plants near key springs.
- **Synthesis** of the results of these specific activities, together with previous and concurrent studies.

Together these activities have increased our understanding of ground-water flow in the carbonate-rock aquifers of southern Nevada. This section summarizes the goals, accomplishments, and conclusions of each activity. The summaries are intended to describe the approaches and kinds of conclusions obtained by the activities. This section does not provide detailed descriptions of the work. For details or clarification, the interested reader should consult the separate reports describing these activities and results.

Basic-Data Collection

A network of gages and other monitoring sites provides information on key hydrologic parameters, and documents existing conditions in the carbonate-rock aquifers. The basic data network consists of 8 springflow gages (where flow is monitored continuously), 59 miscellaneous springflow measurement sites (where flow is monitored on a annual or semiannual basis), 4 observation-well recorder sites, 11 other wells used as observation wells for regular measurements of water level, and 15 high-altitude precipitation storage gages. Locations of all the monitoring sites are shown in figure 6. Results of this network are presented by Pupacko and others (1988, p. 45-50, 57-58, 60-61, 221, 226, 260) and Pupacko and others (1989, p. 44-47, 50, 55, 57, 187, 213-214, 216, 246). Results of monitoring spring discharge and ground-water levels in the carbonate-rock aquifers are summarized below as examples of the utility of these basic data.



EXPLANATION

Approximate area of carbonate-rock province

■ Springflow gage

◆ Miscellaneous springflow measurement site

● Observation well with water-level recorder

⊗ High-altitude precipitation storage gage

▲ Micrometeorological station for measurement of evapotranspiration

Figure 6. Sites where springflow, ground-water levels, high-altitude precipitation, and evapotranspiration have been monitored in carbonate-rock province of Nevada.

Spring Discharge

Continuous measurements (Pupacko and others, 1988, p. 48, 50, 61; Pupacko and others, 1989, p. 45-47, 57) indicate that the discharge from Muddy River Springs remains nearly uniform at levels reported by Eakin and Moore (1964) and Eakin (1964, p. 17) and that the discharge from Corn Creek Springs also is nearly uniform at about the rate measured during 1947-55 (Malmberg, 1965, p. 60). The locations of these springs are shown on plate 1. The observed long-term and short-term uniformity of discharge from these springs is typical of most regional springs that discharge from the carbonate-rock aquifers (fig. 7). The continuing uniformity of these discharges indicates that the springs have not been affected measurably by pumping of nearby wells. Short-term fluctuations in spring discharge are caused by changes in atmospheric pressure, earth tides, local precipitation, or other stresses. The basin-fill aquifers of the Upper Muddy River Springs area are currently (1989) experiencing increased pumping stress, and pumping from both the basin-fill and carbonate-rock aquifers in adjacent areas is expected to increase. Muddy Spring and Warm Springs West, both located in the area, have not yet shown long-term response to these pumping stresses. During the summer of 1987, discharge from Muddy Spring showed a slight decline that may or may not have been related to summer pumping. Similarly, the record of discharge from Corn Creek Ranch Spring, in northern Las Vegas Valley, indicates that the spring has not yet been affected by intensive pumping 11 mi farther south in the valley. Discharge from Rogers Spring, in a secluded part of the Black Mountains area near the Overton arm of Lake Mead, reflects only natural stresses.

Water Levels in Observation Wells

Measured static water levels in wells provide valuable information about conditions in an aquifer. For example, figure 8 shows water levels measured in a well (MX well CE-DT-4) that penetrates the carbonate rocks beneath Coyote Spring Valley, about 10 mi from Muddy River Springs (pl. 1). The water levels fluctuate about 0.2 ft seasonally with no apparent long-term trend of change. As of 1988, no water has been pumped from the carbonate-rock or basin-fill aquifers in the immediate vicinity, but nearby industrial pumping is planned for the near future. The nearest pumping is from another well into the carbonate rocks about 6 mi away (MX well CE-DT-6). The Moapa Valley Water Company has pumped this well during summers since 1986. More observations are needed to determine if the seasonal fluctuations measured in MX well CE-DT-4 are effects of this nearby pumping.

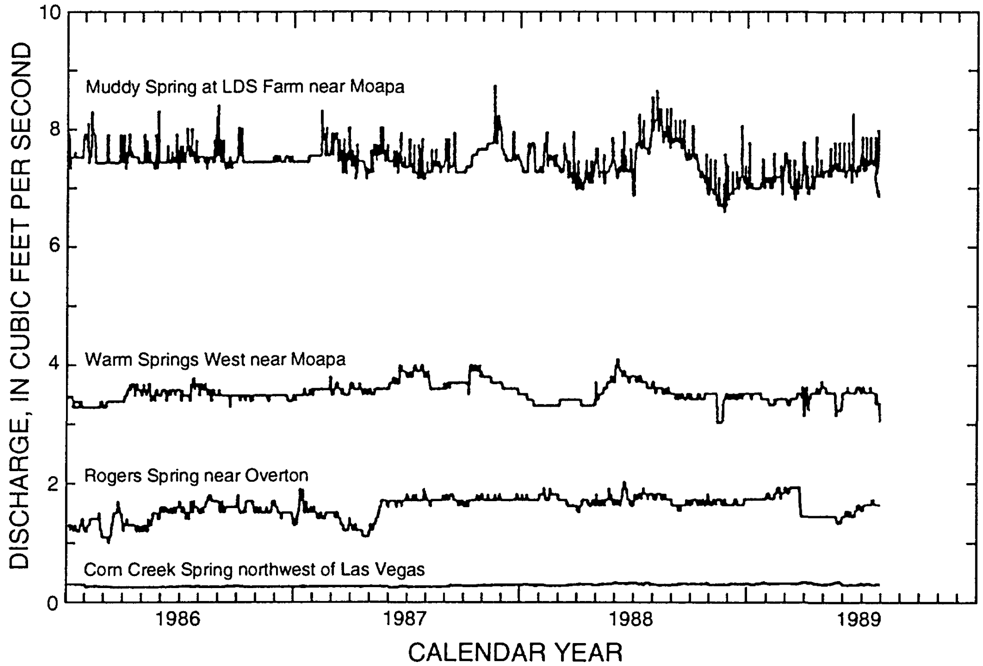


Figure 7. Flow rates of four springs that discharge from carbonate rocks in the study area, 1986-89. Spring locations are shown on plate 1.

Geologic Mapping Activities

Geologic studies in a 1,800-mi^2 area north of Las Vegas during 1985-88 included examination of the geologic literature, wide-ranging reconnaissance of the area, and detailed geologic mapping of areas selected to resolve known geohydrologic problems concerning past and present ground-water flow through the carbonate-rock aquifers. Geologic mapping and interpretations entail developing maps that show outcrops of rocks of all types and ages, together with structures that deform or disrupt those rocks. The history of the rocks and structures as well as their configurations at depth are inferred from observed field relations, previous mapping, and regional relations. Mapping is generally based on a combination of detailed field observations and correlation of observations with aerial photography and satellite imagery. Mapping was partly or fully supported throughout the area indicated in figure 9 (Guth, 1986, 1988; McBeth, 1986; Blank, 1988; Guth and others, 1988).

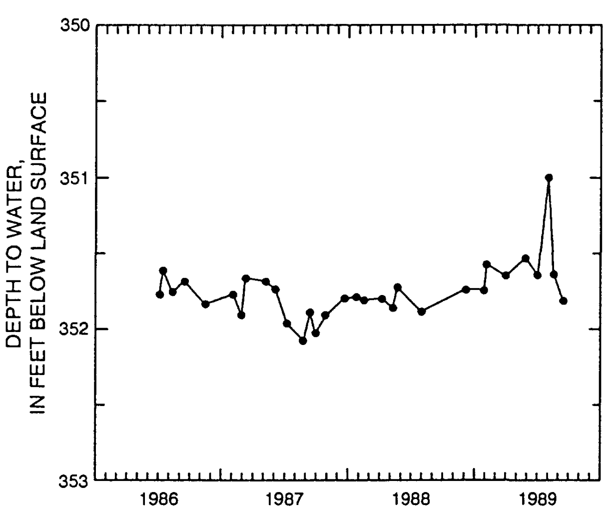
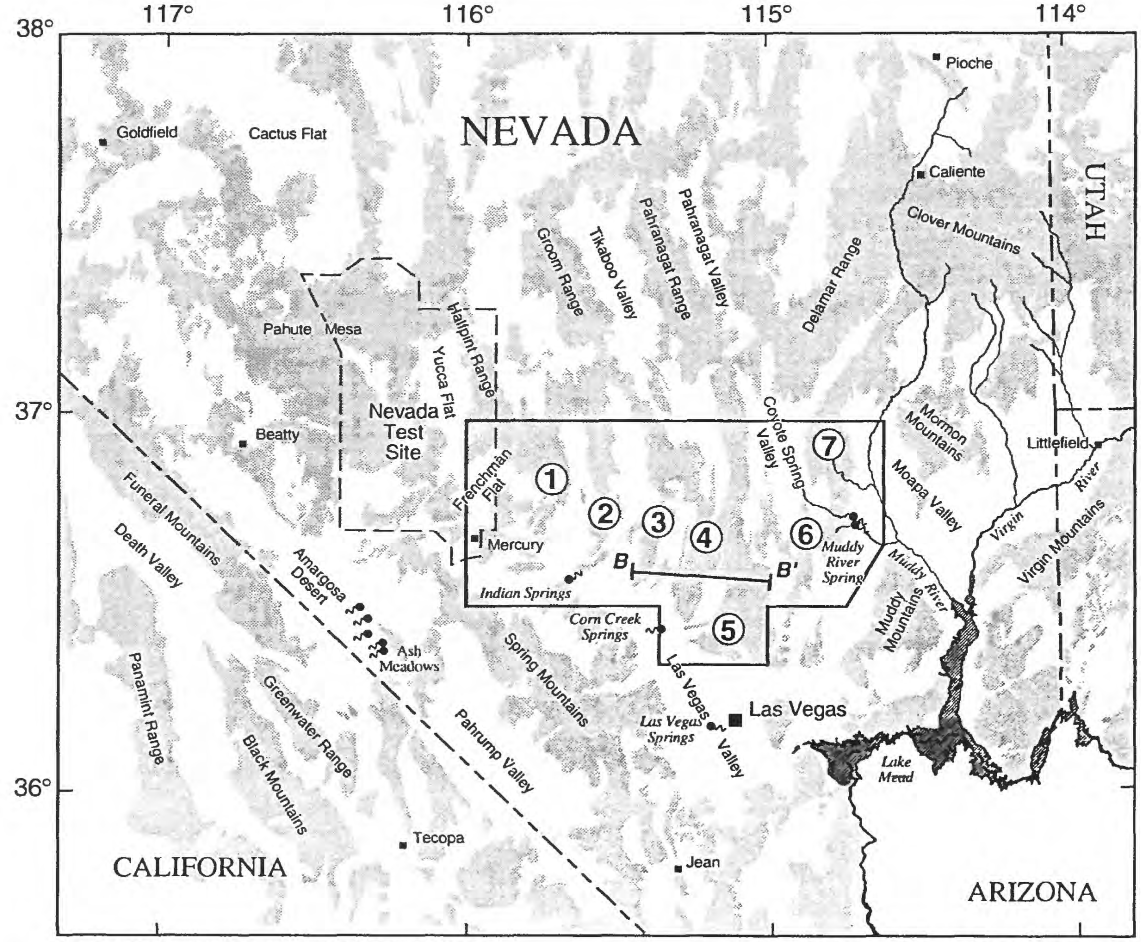


Figure 8. Water levels in MX well CE-DT-4, 1986-89. Well penetrates carbonate-rock aquifer beneath Coyote Spring Valley. Well location is shown in figure 36.

Geologic mapping with special attention to aquifer configurations has shown that structural deformation subsequent to deposition of the carbonate rocks in southern Nevada greatly complicated the originally flat-lying carbonate rocks and thereby greatly complicated the aquifer systems contained therein. Mapping west of the Sheep Range during 1986-87 indicated that many of the exposed (and buried) carbonate rocks were pulled apart along low-angle faults during the last 15 million years (Guth, 1986; Guth and others, 1988). Fault-bounded blocks of carbonate rocks have been juxtaposed against other blocks of rocks of lower



Base from U.S. Geological Survey digital data, 1:100,000, 1985
Universal Transverse Mercator projection
Zone 11

Geology modified from Plume and Carlton (1988), Stewart and Carlson (1978), and Wilson and Moore (1959). Geology in lower left and lower right corners of map area not shown

0 20 40 60 MILES

0 20 40 60 KILOMETERS

EXPLANATION

Basin fill

Consolidated rock

B—B' **Approximate line of geologic section in figure 10**

Extent of mapping

① **Mountain ranges in which mapping was fully or partly supported by this study —** 1, Spotted Range; 2, Pintwater Range; 3, Desert Range; 4, Sheep Range; 5, Las Vegas Range; 6, Arrow Canyon Range; 7, Meadow Valley Mountains

Spring or closely spaced springs

Figure 9. Area where geologic mapping was fully or partly supported by present study.

permeability (Guth, 1986). These forces were far more effective in pulling apart the exposed rocks in this area than in the area east of the Sheep Range (as previously noted in Wernicke and others, 1984, p. 489). The area east of the Sheep Range was mapped for this study mostly during 1985-86. The differences in extension and aquifer thickness between the highly deformed sections of rock beneath and west of Sheep Range and the less deformed sections farther east are suggested in figure 10. These differences are believed to have important hydrologic consequences (Dettinger, 1988; Dettinger and Schaefer, in press), and have been an important part of selection of sites for some of the exploratory wells drilled for this study.

The origin and configuration of individual structures also may affect ground-water flow. Extension of the rock masses resulted in innumerable small and large faults and widespread fracturing and shattering of the rocks. Field observations of fault zones and fractures in outcrops along the west side of the Sheep Range (and on Tucki Mountain in Death Valley) revealed that, in some instances, breakage of rocks was so severe that rocks were reduced to grain- to clay-size fragments, followed by alteration of the component minerals and subsequent reconsolidation of the rock along some faults. Examples of this brecciation and reconsolidation are reported by Guth (1981, p. 766). Such deformation and reconsolidation was found mostly adjacent to older, low-angle fault zones, and locally may have rendered many such fault zones impermeable to ground-water flow. Other fault zones, especially recently active, high-angle normal faults (such as those that form the steep edges of mountain ranges) were observed to form fractures that are more open and, consequently, might transmit ground-water flow more readily.

Geophysical Explorations

About 50 percent of the carbonate-rock aquifers lie buried beneath younger rocks and sediments that may be thousands of feet thick. Four kinds of geophysical measurements were made to provide information to estimate thicknesses of basin fill overlying the carbonate rocks and to locate faults deep beneath land surface. Estimates of depths to carbonate rocks and faults are helpful when choosing sites for exploratory drilling. The measurements used were gravity, seismic refraction, direct-current (DC) resistivity, and magnetotellurics. These measurements detect spatial variations in the density, strength, and electrical properties of rocks in the subsurface.

Measurements were made of Earth's gravitational field at about 200 sites on both sides of the Sheep Range. Figure 11 is a Bouguer gravity anomaly map of the area just north of Las Vegas based on these measurements. Thick sections of low-density basin fill (relative to the carbonate rocks) result in lower gravity anomalies. Thus, the areas underlain by such thick sections of basin fill are indicated on this map by gravity depressions (especially, the barbed ovals).

Seismic-refraction measurements were made at seven proposed drill sites to determine—on a local scale—the thickness of unconsolidated material overlying the carbonate-rock aquifers. Seismic waves—radiating from an explosion—travel much more slowly through basin fill than through carbonate rocks and this difference is detectable. Measurements were made of the time required for waves from an explosion to reach detectors at several distances from the explosion. The arrival times at several distances can be used to estimate the thickness and strength of the rock layers through which the waves pass.

Direct-current resistivity measurements were made at more than 60 sites on the west side of the Sheep Range. These measurements yield estimates of the electrical resistivity of rocks over a wide range of depths beneath the measurement equipment by inducing electrical currents in the Earth's crust and measuring the resulting voltage drops across the same area. Audiomagnetotelluric and magnetotelluric measurements also can be used to measure electrical resistivities of rocks at depth. These methods were applied both east and west of Sheep Range at locations shown in figure 11 (Pierce and Hoover, 1986, 1988). The methods infer electrical resistivities of buried rocks by measuring electrical and magnetic fields associated with naturally occurring electrical currents in the Earth's crust. When direct-current resistivity data are organized into a cross section such as the one in figure 12 (location shown in fig. 11) and conditioned on field geology and other geophysical measurements, variations in electrical resistivity of rocks at different depths can be inferred. Because different rock types (and different degrees of water saturation) can have different resistivities, such cross sections can be used to infer rock (and aquifer) configurations at great depths.

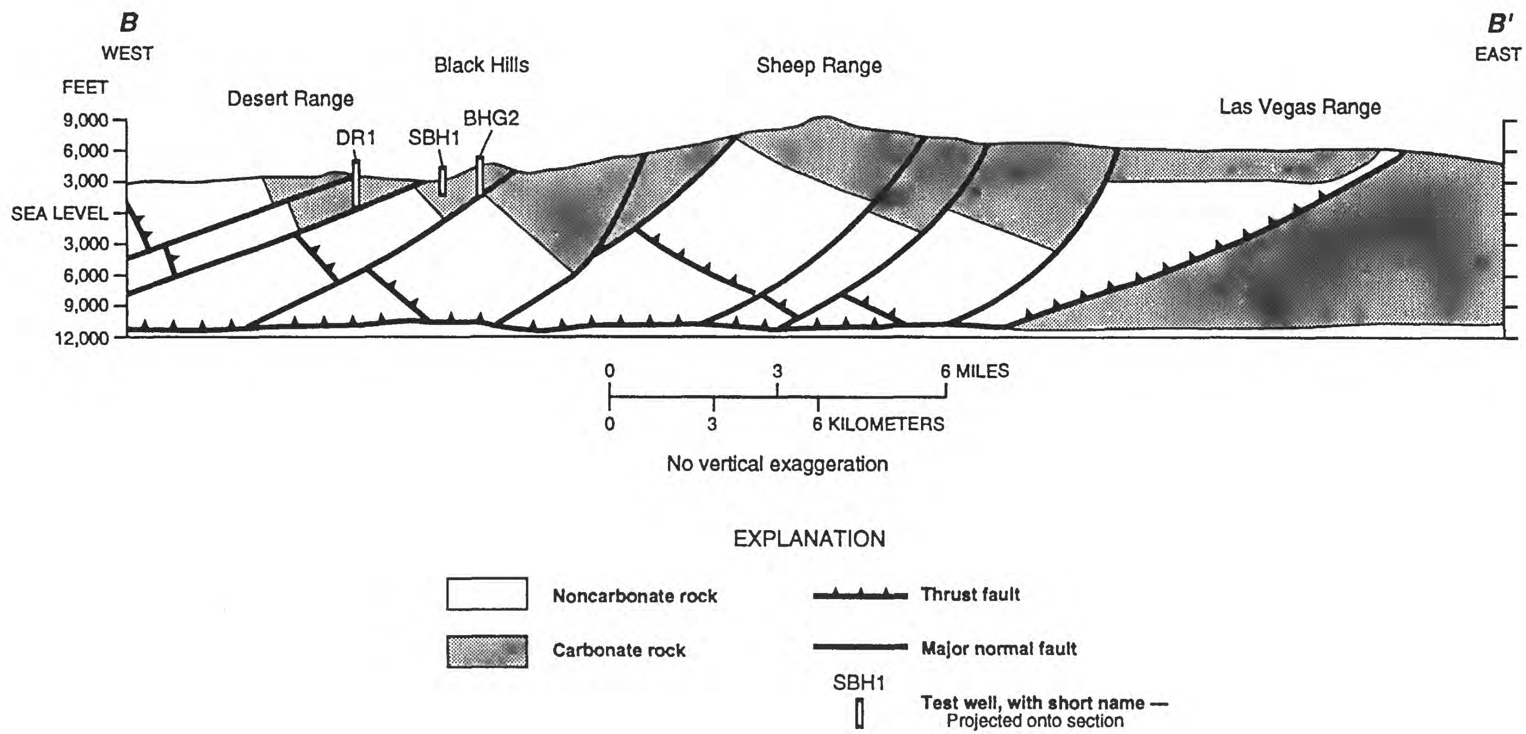


Figure 10. Schematic geologic section across Desert Range, Sheep Range, and Las Vegas Range, showing general location of test wells drilled in 1987-88. (Modified from Guth, 1981.) Line of section is shown in figure 9.

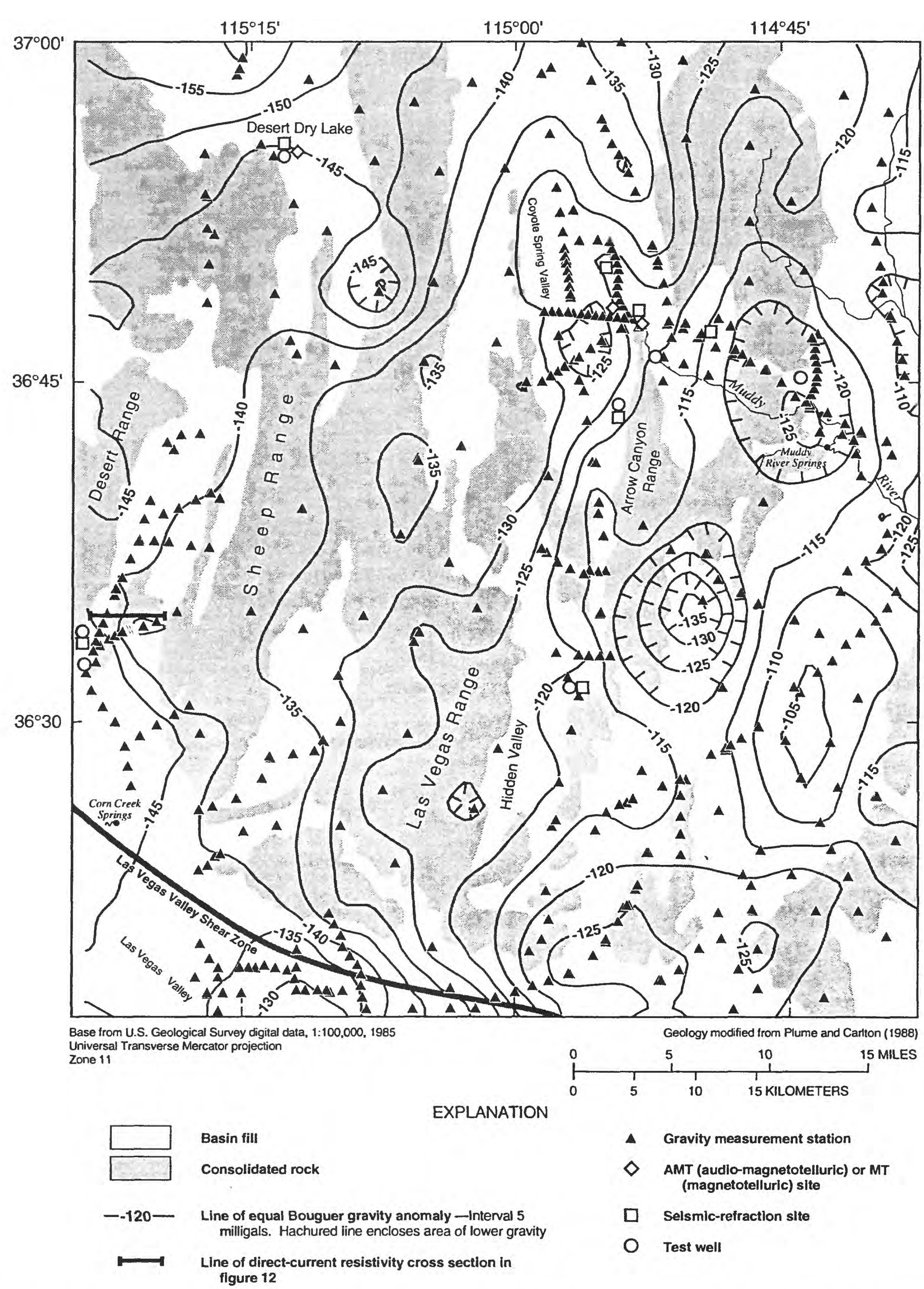
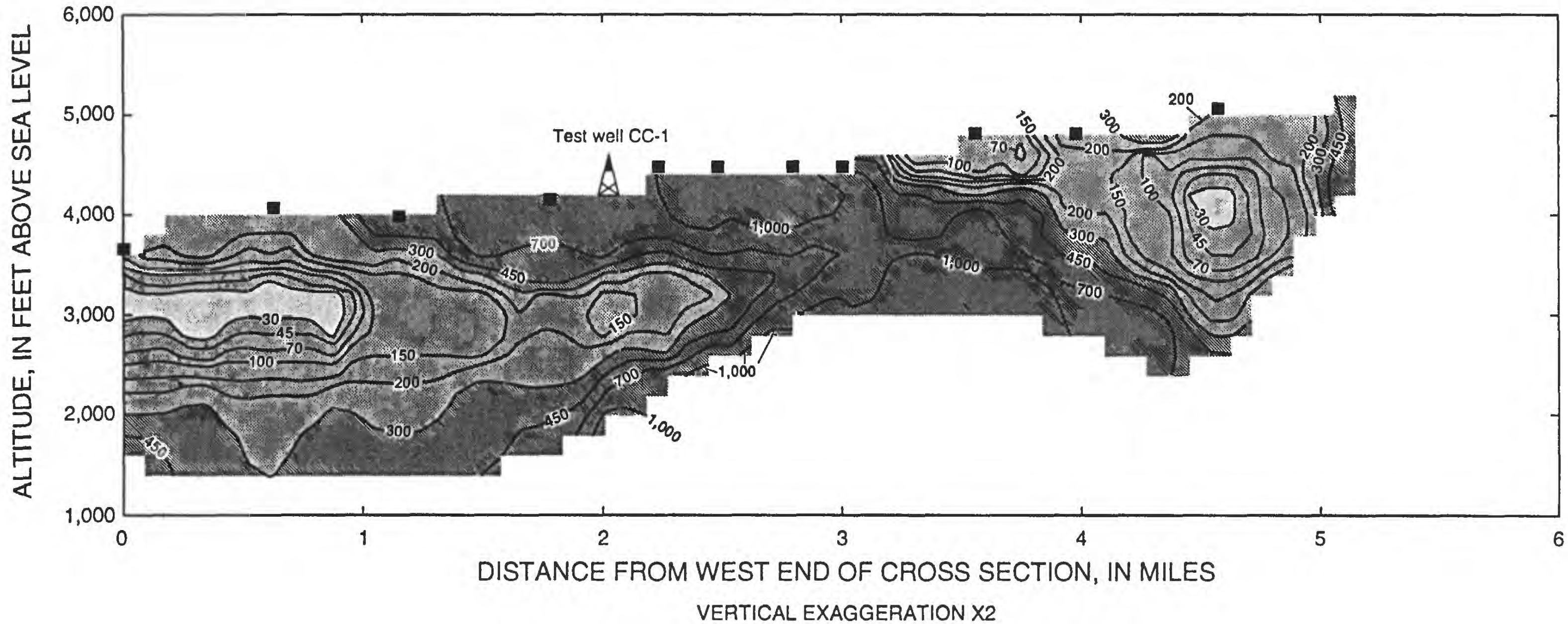


Figure 11. Bouguer gravity anomalies and location of geophysical measurement sites in south-central part of study area. Geophysics by Donald H. Schaefer, U.S. Geological Survey, Carson City, Nev.



EXPLANATION

RESTIVITY, IN OHM-METERS

1,200
300
30
0

Resistivity — Range from 300 to 1,200 ohm-meters probably is dense (unfractured and unsaturated) carbonate rock or coarse-grained, unsaturated fill. Range from 30 to 300 ohm-meters probably is highly fractured, saturated carbonate rock or basin fill (from fine-grained and unsaturated to coarse-grained and saturated). Range from 0 to 30 ohm-meters probably is saturated, fine grained basin-fill or basin fill saturated with poor-quality water

—70— **Line of equal resistivity** — Interval, in ohm-meters, is variable

■ **Direct-current measurement array**

Figure 12. Direct-current resistivity of rocks at depths between Desert Range and Sheep Range. Figure is based on direct-current geoelectrical profiles, but incorporates information from audiomagnetotelluric and magnetotelluric measurements and from geologic mapping. Line of section is shown in figure 11. Geophysics by Donald H. Schaefer, U.S. Geological Survey, Carson City, Nev.

Interpretation of a combination of these geophysical measurements indicates that thicknesses of basin fill overlying carbonate rocks range from less than 500 ft in Hidden Valley to about 1,000 ft in Coyote Spring Valley, and more than 6,000 ft beneath southern Desert Dry Lake Valley (Donald H. Schaefer and H.A. Pierce, U.S. Geological Survey, written communs., 1988). In the northernmost part of Las Vegas Valley (at the cross section in fig. 12), basin-fill deposits are probably about 2,000 ft thick (Pierce and Hoover, 1986, p. 363; Adel A.R. Zohdy, U.S. Geological Survey, written commun., 1986).

The geoelectrical measurements also showed that highly productive MX wells drilled in Coyote Spring Valley encountered a fault zone along the east edge of Arrow Canyon Range, rather than the more visible fault zone on the steep west side of the range (Pierce and Hoover, 1986, fig. 2). These measurements clarified the nature of structures that conduct water to those wells.

Geochemical Sampling and Interpretation

Water samples were collected and analyzed from 209 springs, streams, and wells in eastern and southern Nevada as a part of the carbonate-rock investigations during 1985-88. Locations of these sample sites are shown in figure 13. These new data were combined with other available data to determine sources and flow paths for water in the carbonate-rock aquifers in southern Nevada. These determinations were made using calculations of (1) chemical and isotopic mass balances, (2) the chemical saturation states of various constituents in the water with respect to minerals comprising the aquifers, (3) expected variations in chemistry of the ground water along flow paths in response to naturally occurring reactions, and (4) ground-water ages.

These geochemical efforts updated or evaluated regional-scale water balances in six parts of southern Nevada, including Las Vegas Valley, the Ash Meadows area, the Meadow Valley Wash area, and the Coyote Spring Valley-Muddy River Springs area (Emme, 1986; Hershey and others, 1987; Kirk and Campana, 1988; Lyles and Hess, 1988; Noack, 1988; Thomas, 1988). The studies (Emme, 1986; Schroth, 1987; Kirk and Campana, 1988; Thomas, 1988) generally verify the overall water budgets developed by previous investigators for regional flow beneath the White River drainage and Meadow Valley Wash area in east-central Nevada that provide inflow to southern Nevada (Rush, 1964; Eakin, 1966; Winograd and Friedman, 1972). Other results alter previous concepts of regional flow beneath southern Nevada in that most recharge from the Sheep Range is directed toward the Muddy River Springs rather than radially towards other adjacent valleys including Las Vegas (Thomas and Welch, in press).

The studies also addressed flow and recharge processes in and around the Spring Mountains that are the major local recharge area for southern Nevada (Hershey and others, 1987; Lyles and Hess, 1988; Noack, 1988; Thomas, 1988). Within the Spring Mountains, lithologic variations in the mountain block are directly associated with chemical variations in

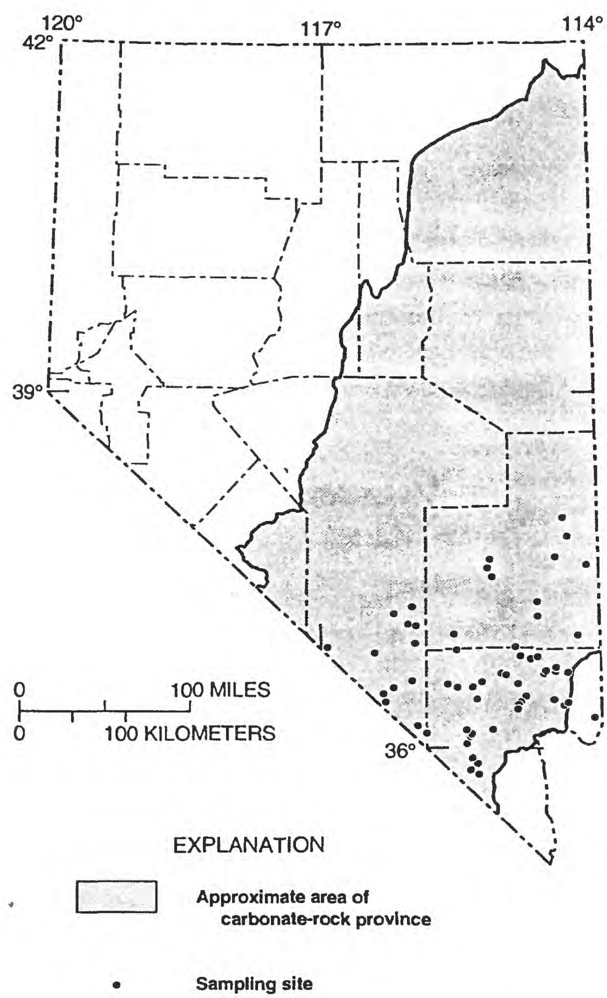


Figure 13. Springs, wells, and streams sampled for geochemical determinations in and adjacent to carbonate-rock province of southern Nevada.

ground water. Examples of this were observed in areas of dolomitized limestone (such as in Lee Canyon, pl. 1) where higher concentrations of magnesium are found in the water and near outcrops of Jurassic rocks (as in Red Rock Canyon, pl. 1) where sulfate becomes a dominant ion (Lyles and others, 1986).

Much of the effort around the Spring Mountains focused on the Las Vegas Valley shear zone—a complicated structure extending from the northeastern part to the northwestern part of Las Vegas Valley and nearly to Mercury. Flow in the basin-fill aquifers of the shear zone was shown to be impeded in some areas and enhanced in others, presumably by the influence of deeply buried geologic structures (Lyles and Hess, 1988). As a consequence, the ground water of Las Vegas Valley—in and south of the shear zone—is a mixture of water from different sources. Recharge from the Spring Mountains contributes significantly to basin-fill aquifers of Las Vegas Valley. One hypothesis developed from studies around the Spring Mountains is that, near the main well fields for the Las Vegas urban area and near the toe of Kyle Canyon alluvial fan (pl. 1), ground water may be a mixture of shallow circulating water that is clearly from the Spring Mountains and deep circulating water from areas to the north or west (including other parts of the Spring Mountains; Lyles and Hess, 1988, p. 51; Noack, 1988, p. iii). At the toe of the Kyle Canyon fan, for example, ground water is composed of a small amount of shallow circulating water discharging from Kyle Canyon and as much as 90 percent deep-circulating water (Lyles and Hess, 1988, p. 43).

The quantity of water entering southern Nevada as inflow from the carbonate-rock aquifers of east-central Nevada was addressed also in some detail. The White River regional flow system—an interbasin ground-water flow system that spans much of eastern Nevada from areas west of Ely in east-central Nevada to Moapa in southern Nevada— provides the principal (perhaps only) inflow from east-central Nevada. Kirk and Campana (1988) simulated the flow system using a "discrete-state compartment model," which is a sophisticated accounting of mixing of naturally occurring deuterium in the ground water along flow paths in the system. The model represented the flow system as two layers of mixing cells: a lower layer representing the carbonate-rock aquifers and an upper layer of basin-fill aquifers (fig. 14). The mixing of water with different isotopic compositions that results from the flow of water from cell to cell was simulated by the model. Calibrating the model allowed determinations of ranges of "reasonable" values for recharge, storage volumes, and ground-water ages in the flow system that are compatible with observed conditions (Kirk and Campana, 1988). The ranges reported are relatively large and uncertain but can be constrained somewhat by a simultaneous reevaluation of the southern White River flow system and Ash Meadows system reported by Thomas and Welch (in press). As noted previously, the efforts generally agreed with previous water budgets, but some sources of flow within southern Nevada were re-considered (notably, recharge from the Sheep Range).

Finally, a broad reconnaissance of water quality in several aquifers of southern Nevada demonstrated that aquifers beneath and east of Las Vegas Valley and elsewhere in southeasternmost Nevada are likely to contain water of a quality not suitable for public supply or most other uses (Lyles and others, 1986; Schroth, 1987, p. iii). This result will be discussed in greater detail in the section of this report titled "Where is water potentially available in carbonate-rock aquifers?"

Well Drilling, Geophysical Logging, and Aquifer Testing

Test wells were drilled to provide direct subsurface data on the carbonate-rock aquifers. Aquifer tests were done and geophysical logs collected. The wells also provided information on depths to water and chemistry of water in the aquifers. Data collected from the wells were used to test hypotheses developed in other studies and provided solid evidence—subsurface configurations of rock types and units, estimates of hydraulic properties, water levels, water chemistry, and measures of rock porosity—as to hydrologic conditions in the carbonate-rock aquifers.

The 16 wells drilled, rehabilitated, or otherwise used for collection of these kinds of data are described in table 3 and their locations are shown in figure 15. Descriptions of lithology, drilling rates, geophysical logs, and aquifer tests are described for eight of these wells by Berger and others (1988). The lithology of well BHG-2 is described by Schaefer and others (1992). Water levels in the Divide and Old Dry wells are described by Lyles (1987). Overall results of drilling, logging, and testing are summarized (with examples) in the following paragraphs.

Well Drilling and Rehabilitation

Nine wells were drilled during the studies in 1985-88. Lithologic samples, drilling records, and geophysical logs were available for five MX wells drilled during 1980-81, and were used in this study.

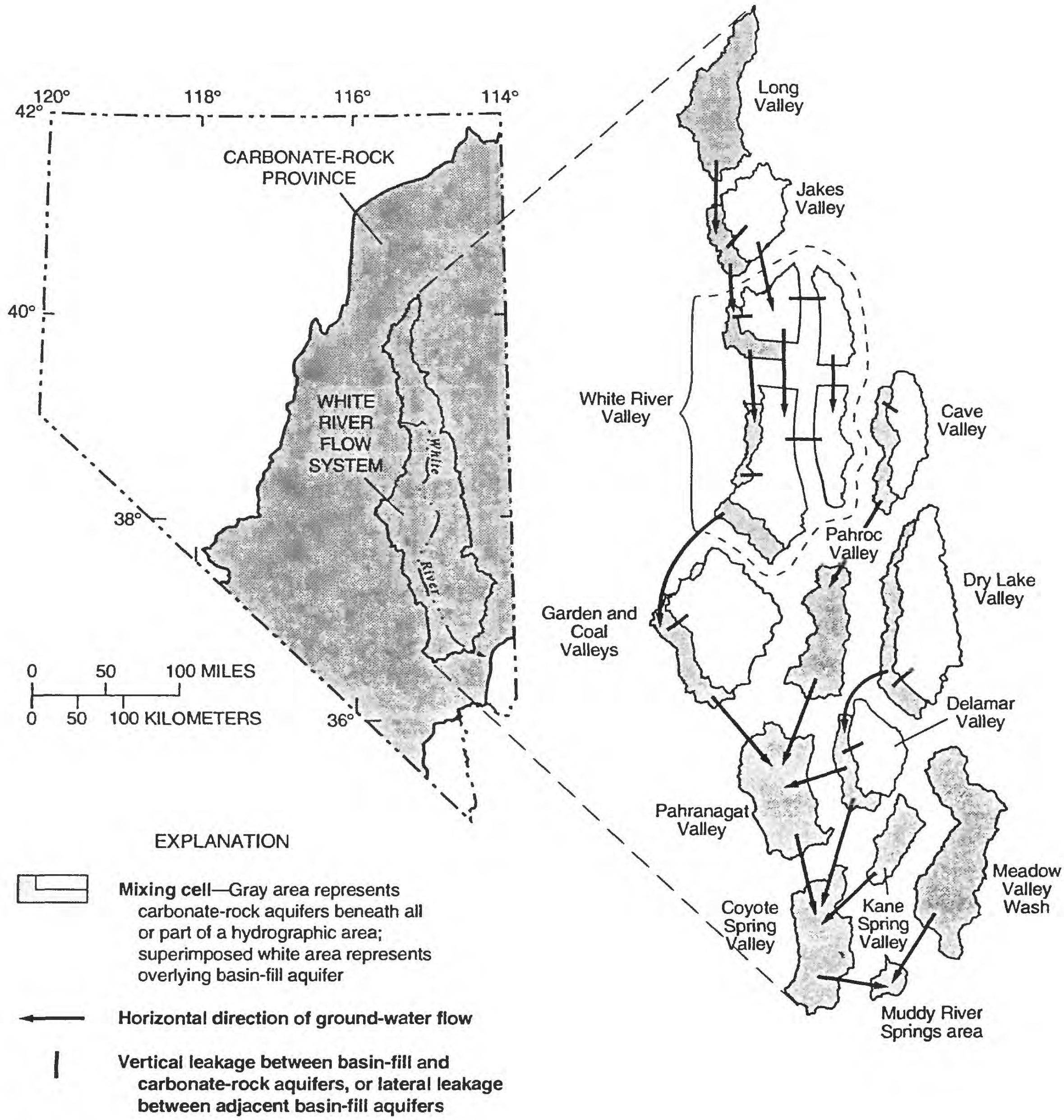


Figure 14. Schematic three-dimensional representation of mixing-cell model used to simulate flow and isotopic mixing in White River flow system (modified from Kirk and Campana, 1988, fig. 11).

Two abandoned stock wells in remote areas were reconditioned to provide inexpensive access to the subsurface. As a result, rock and sediment samples and drilling records are available from a total of 10,000 ft of drilling for this study (and the MX study) in the study area. Of this total, 4,500 ft penetrated basin fill and 5,500 ft penetrated carbonate rocks.

Some direct results from this drilling are access to the water-table for measurements of water-level altitudes and water samples that contributed to the geochemical interpretations. Zones of highly fractured carbonate rock that locally might be water-producing zones can be identified from penetration rates and rock samples collected during drilling. Finally, lithology encountered during drilling is a direct sampling of rock configurations beneath a well site, and thus might provide valuable inputs to geologic interpretations in the study area.

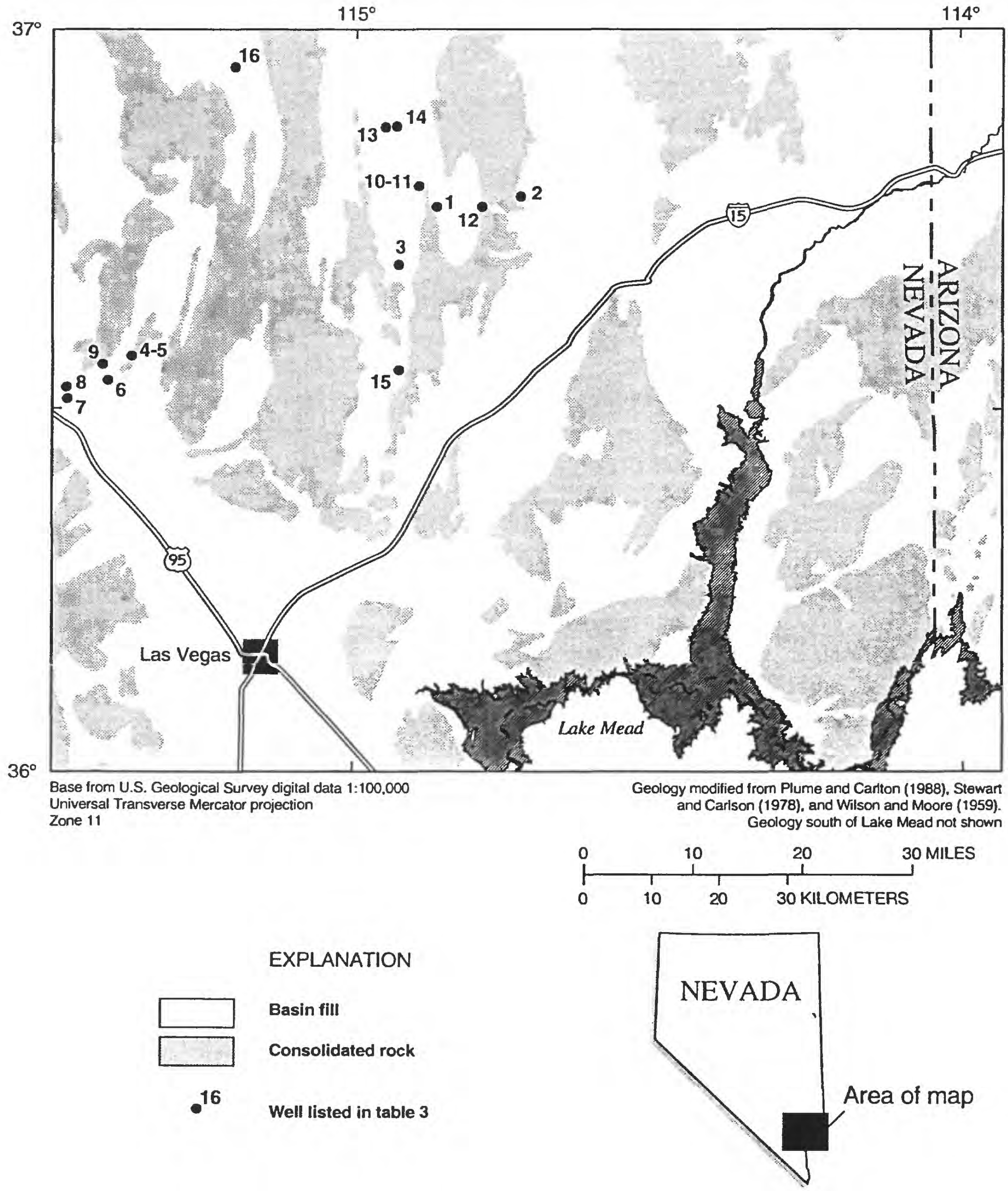


Figure 15. Wells used for measuring borehole geophysical properties, aquifer properties, water levels, and geochemical characteristics, 1984-88, in southeastern part of study area.

Borehole Logging

Geophysical logs of boreholes measure physical properties of rocks penetrated by a well as a function of depth (see descriptions of information that can be derived from logs in table 4). Zones of fractured rock commonly can be identified and hydrologic parameters can be estimated from the rock properties recorded. The several log types in different depth zones collected for this study total about 28,000 ft (Berger and others, 1988).

Geophysical logging in the wells indicated a wide range in the rock properties measured, which were dependent on primary porosity (open spaces between grains in the rocks) and secondary porosity (fractures and dissolution cavities). These porosities are important in determining the quantity of water contained in a given volume of aquifer material. The total porosities—primary plus secondary—determined from geophysical logging were in the same range as those reported from laboratory measurements of rocks

Table 3. Thickness of basin fill and carbonate rocks penetrated by selected wells

Site No. (fig. 18)	Well name	Thickness penetrated (feet) Basin fill	Carbonate rocks	Total well depth (feet below land surface)
Wells Drilled During Present Study				
1	CSV-1	765	0	765
2	CSV-2	17	461	478
3	CSV-3	780	0	780
4	BHG-1	380	40	420
5	BHG-2	142	1,258	1,400
6	SBH-1	60	634	694
7	DIVIDE	200	0	200
8	OLD DRY	210	0	210
9	DR-1	182	768	950
Existing Wells				
10	CE-DT-4	30	639	669
11	CE-DT-5	110	518	628
12	CE-DT-6	420	517	937
13	CE-VF-1	714	0	714
14	CE-VF-2	850	371	1,221
15	SHV-1	250	670	[a]920
16	DDL-1	420	0	420

[a] No drilling records available.

Table 4. Information acquired from various geophysical logs

[Modified from Keys and MacCary, 1971, table 1]

Geophysical log	Information acquired
Acoustic transit time	Primary porosity, fractures, lithology
Borehole televiewer	Fractures, construction of existing wells
Caliper	Diameter of hole, fractures, construction of existing wells
Electric	True resistivity, stratigraphic correlation
Gamma-gamma density	Bulk density of rocks or sediments, total porosity, water level, lithology
Natural gamma	Clay or shale content, stratigraphic correlations
Neutron	Total porosity, location of water level, lithology
Temperature	Ground-water temperature and temperature gradients, location of water level, movement of water in well

collected at the Nevada Test Site (Winograd and Thordarson, 1975, p. C17), which averaged about 5-6 percent. Secondary porosity as estimated from the logs in zones where many fractures were present locally might constitute almost half of that total (Berger, 1992).

Aquifer Testing

Properly conducted and monitored aquifer tests can provide estimates of the capacity of aquifers to transmit and store water. The hydraulic properties that characterize these capacities are the transmissivity and storage coefficient of the aquifer, respectively.

Aquifer testing involves lowering a pump into a well to a depth below the water level, pumping water from the well at a constant rate for long periods of time while recording water-level changes in the pumped well and, if available, in any nearby observation wells. As pumping continues, water levels generally decline in the well, and the rate at which the water level declines can be used to estimate the transmissivity. After the pump is turned off, measurements are made of the recovery of water levels in the wells. The rate of recovery is used to estimate transmissivity. Measurements of declining water levels in nearby wells can be used to estimate both the transmissivity and storage coefficient of the aquifer. Because of the high cost of drilling in the carbonate-rock aquifers, most aquifer tests in the carbonate-rock aquifers of Nevada lack nearby observation wells. This limits the accuracy of the estimates of transmissivity and precludes estimation of storage coefficient (Heath, 1983, p. 42).

Estimates of transmissivity (and storage coefficient for one example) calculated from aquifer tests made in some of the carbonate wells during 1985-88 are given in table 5. All estimates are based on the straight-line approximations described for well CSV-2 and data presented in Berger and others (1988) or collected since that report. To facilitate comparisons among well sites, the last column in table 5 presents a normalized response of the aquifer tested in each well to 1 week of pumping at 1,000 gal/min. The responses are normalized to reflect drawdown that would occur in a 24-in. diameter production well at each site if it tapped 500 ft of water-saturated rock. The storage coefficient is assumed to be 0.1. Projections of drawdown are made by using known and estimated aquifer properties at each well together with simple mathematical solutions for drawdown given in Theis (1935). Projected drawdowns are those that theoretically would develop in addition to the rapid drawdowns that develop in the first few minutes of pumping. These early drawdowns reflect well construction, pump configuration, and other installation specific properties and may amount to more drawdown than the long-term contributions.

Table 5. Data and results of aquifer tests done during 1985-88

[--, no estimate available]

Well	Pumping rate (gallons per minute)	Pumping duration (hours)	Maximum drawdown (feet)	Calculated transmissivity (foot squared per day)	Calculated storage coefficient (fraction)	Hypothetical drawdown (feet)
CSV-2	101	22	30.1	1,600	--	27
CE-DT-4	540	77	3.7	200,000	--	.9
CE-DT-5	3,400	326.3	11.8	250,000	0.14	.7
CE-DT-6	472	66	41.6	13,000	--	17
CE-VF-2	77	14	13.0	3,000	--	47
SBH-1	24	10	.9	37,000	--	1.6

Activities Using Data from Petroleum-Exploration Wells

As part of the studies, existing data from petroleum-exploration activities in Nevada, where applicable, were used to describe the hydrology of the carbonate rocks (McKay and Kepper, 1988). In Nevada, three types of data are available for estimating the hydraulic properties of carbonate-rock aquifers: aquifer tests at water wells, natural fluctuations of water levels in wells or flow from springs, and records from wildcat oil and gas exploration. Results from tests at 39 water wells penetrating carbonate-rock aquifers (including the aquifer tests described in the preceding paragraphs) were compiled (table 1). Only one example of the use of natural water-level fluctuations is available in the literature (Galloway, 1986). Beginning with the present study, measurements of natural water-level fluctuations were made and used to augment the aquifer tests and oil-exploration tests; see Kilroy (1992) for complete details. As of 1988, over 480 wildcat oil and gas wells have been drilled in Nevada, and many penetrate carbonate rocks. Some provide useful data about the properties of carbonate-rock aquifers.

Locations of all the oil and gas exploration wells in and adjacent to the carbonate-rock province of Nevada are shown in figure 16. Individual records for each well are on file at the Nevada Bureau of Mines and Geology. Ideally, a complete well file will contain the following: application forms and completion reports, all geophysical logs (if run), and drill-stem test (DST) reports (if run). In practice, few files are complete.

Drill-stem tests are specialized hydraulic tests used by the petroleum industry to determine aquifer properties of rocks penetrated by oil-exploration wells.

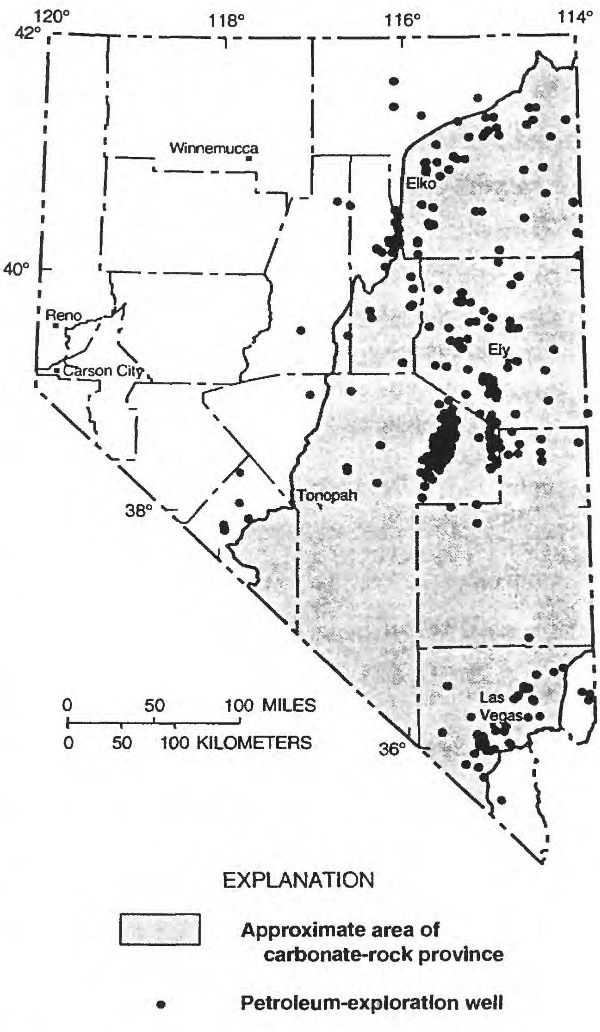


Figure 16. Distribution of petroleum-exploration wells in and adjacent to the carbonate-rock province of Nevada. Data from McKay and Kepper (1988).

By mechanically isolating a chosen interval in an oil well and then observing flow rates and pressures in the well as the isolated zone is vented to atmospheric pressure or closed off ("shut in"), three important characteristics of the subsurface formation may be obtained: pressure head, permeability, and fluid chemistry. By using a technique developed for the petroleum industry (but analogous to the Theis recovery method familiar to hydrologists [Bredehoeft, 1965]), hydraulic conductivities have thus far been estimated at 13 oil test wells drilled in carbonate rocks of Paleozoic age.

The estimates of aquifer properties derived from DST's in carbonate-rock aquifers are shown in table 2; estimates from two tests in noncarbonate rocks are shown also. The resulting conductivities are plotted against depth to the middle of the tested zone in figure 17, as are the hydraulic conductivities estimated from aquifer tests at water wells (from table 1). Note that moderate hydraulic conductivities (on the order of 4 ft/d) are estimated from tests as deep as 7,770 ft below land surface.

Combining the 13 estimates from DST's with 39 estimates from aquifer tests at water wells (table 2), the overall distribution of 52 measured hydraulic conductivities shown in figure 18 is achieved. If no distinction between DST estimates and water-well estimates is made, the 52 hydraulic conductivity estimates have a median value of 2.1 ft/d, a mean of 75 ft/d, and a standard deviation of 226 ft/d. The hypothesis that the distribution of hydraulic conductivities is a lognormal distribution (with those statistics) cannot be rejected at a 10-percent confidence level.

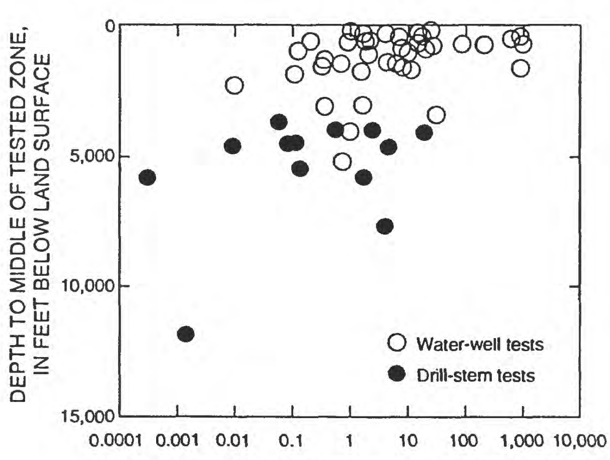


Figure 17. Relation between depth and hydraulic conductivities estimated from drill-stem tests at petroleum-exploration wells or aquifer tests at water wells in carbonate-rock aquifers of Nevada.

When the distinction is made between DST estimates and water-well estimates, DST values are as a group about an order of magnitude lower than the water-well estimates. In particular, the mean of the logarithm of the DST estimates is -0.7 whereas the mean of the logarithm of water-well estimates is +0.6. (Logarithms are used here to convert the lognormally distributed estimates to normal variates.) These two means imply that the central tendency of the DST distribution is 23 times less than the central tendency of the water-well estimates (the difference between means is significant at a 95-percent confidence level). Possible explanations for this difference between DST estimates and estimates from tests at water wells include the following:

1. DST's may have a greater tendency than the water-well tests to include insufficient flow periods during the test to allow for flushing of drilling fluids or for large parts of the aquifer to be "sampled."
2. The DST's generally test deeper rock zones than do the water-well tests and perhaps conductivities decrease with depth below land surface (although no such relation is apparent in fig. 17). For the test results in carbonate-rock

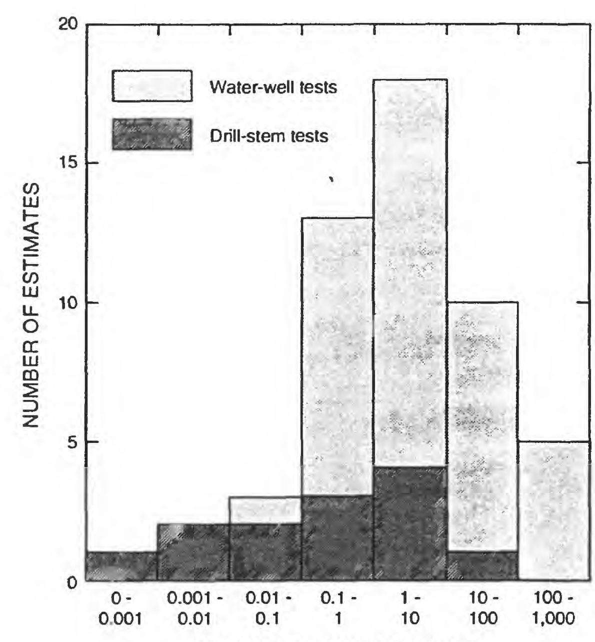


Figure 18. Frequency distribution of hydraulic conductivities estimated from drill-stem tests at petroleum-exploration wells or aquifer tests at water wells in carbonate-rock aquifers of Nevada.

aquifers (in tables 1 and 2), the median depth to the middle of the test interval for DST's is 4,500 ft; whereas, the median depth to the middle of the test interval for water-well tests is about 900 ft. The maximum depth of the middle of the interval tested by water-well tests is about 5,000 ft (minimum, 70 ft); whereas, the middle of the intervals of the DST's is about 3,600 ft (maximum, 11,800 ft). Thus, overlap in the depth distributions is relatively uncommon.

3. The DST's may more commonly test low-transmissivity zones. For example, DST locations near shale units also are common because exploration geologists often are searching for a transmissive reservoir rock (such as carbonate units) that is capped by a shaly formation to form a natural "trap" to catch oil and gas. That this placement of tests may influence the distribution of aquifer properties tested is shown by numerous outcrops in southern Nevada where fractures in the carbonate rocks have been filled with clays from nearby shale units.

4. Finally, significant violation of the assumptions underlying the mathematical interpretations of test results may be more common among the DST's (which commonly are done for much shorter periods of time than tests at water wells), and may systematically influence the general range of values estimated.

At present (1989), the difference between aquifer properties estimated from DST and water-well aquifer tests is poorly understood. More research is needed to make possible full use of the oil-industry records in studies of the carbonate-rock aquifers. Such research would be helpful because, aside from the Nevada Test Site area, oil wells commonly are the only deep wells and deep tests that have been made in the carbonate-rock aquifers. One result of uncertainty about the relation between the results of the two groups of tests is that, in this report, the distribution of conductivity estimates from water-well tests will be used wherever estimates of "characteristic" aquifer properties are required (to make estimates of drawdowns associated with development, for example). Development will cause stresses to the aquifers more like the stresses induced by water-well tests (long-term constant discharge, for instance) than like the stresses induced during DST's, and consequently the water-well estimates may be more representative of the properties that will control long-term impacts.

Evapotranspiration Measurement

Evapotranspiration (ET) is the total rate of direct evaporation from bare soil and free water surfaces plus transpiration by plants, with no attempt to distinguish between the two processes. Evapotranspiration together with springflow and subsurface leakage into other aquifers are the principal mechanisms by which water leaves the carbonate rocks. To better quantify the potential for spatially diffuse discharge of ground water from the carbonate-rock aquifers (as opposed to the localized flow of water from springs), measurements of evapotranspiration by native plants and bare soil evaporation were made during 1986 and 1987 and compared with previous studies in nearby arid regions. Previously, few measurements of actual ET (such as those of Czarnecki, 1986) had been made in the carbonate-rock province. Consequently, accurate quantification is difficult of the overall ET component in water budgets, as is quantification of that part of the ET component supplied by flow from the carbonate-rock aquifers.

Evapotranspiration rates have been calculated from data collected at special micrometeorological stations (fig. 6) at Ash Meadows and Corn Creek Springs. Data collected at the two sites between October 1, 1986, and September 30, 1987, included regular measurements or samples of air temperature, windspeed, relative humidity, precipitation, solar radiation, net radiation, soil heat flux, sensible heat flux, and latent heat flux. ET was calculated using two methods: the eddy-correlation method (Brutsaert, 1982) and the Penman combination method (Campbell, 1977, p. 138). The data collected (and some calculated results) are described by Johnson (1993), and summarized in the following paragraphs.

Typical conditions during 24-hour periods during summer 1987 at the two sites are shown in figure 19. The amount of solar radiation reaching the two sites was similar, but the fate of that energy differed depending on the hydrologic conditions at each site. Under relatively moist conditions at Ash Meadows, most of the total available radiation went to convert water to vapor.

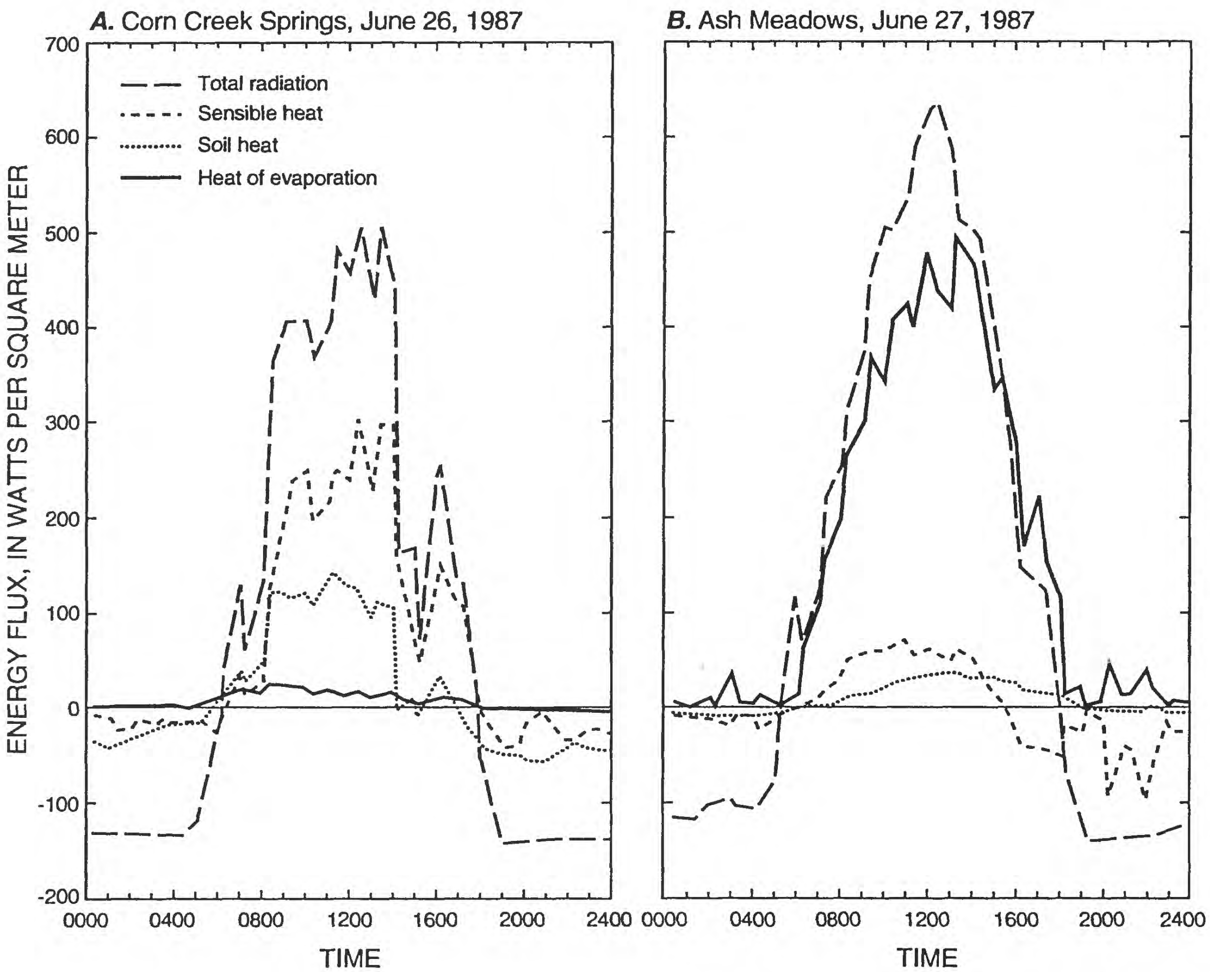


Figure 19. Energy flux during typical 24-hour, mid-summer periods at (*A*) Corn Creek Springs and (*B*) Ash Meadows. Micrometeorology by Michael J. Johnson, U.S. Geological Survey, Carson City, Nev.

At Corn Creek Springs, moisture was not as readily available for evaporation and so the available heat went mostly to raise soil and air temperatures.

The Ash Meadows ET station was located in a large meadow containing moist sub-soils; sparse, low-standing shrubs; and a dense, short grass ground cover. Depth to ground water generally was 4 to 8 ft. Ash Meadows is a regional spring discharge area with an estimated annual discharge of 17,000 acre-ft, and moist subsoils or shallow water tables are common within a radius of several miles from the springs. The measured daily rates (Johnson, 1993) imply an interstorm ET rate of about 30 in/yr.

In contrast, the Corn Creek Springs ET station was on bare, dry soils with a 25 percent coverage of low-standing shrubs. Depth to ground water is about 27 ft below land surface. Corn Creek Springs, with an annual discharge of about 220 acre-ft, discharges ground water that is recharged in the nearby Sheep Range (Thomas and Welch, in press). The small spring center at this site has an effect on ET only within a radius of about a quarter to half mile from the springs. Calculated daily ET rates for the area farther from the springs imply an interstorm ET total at this site of about 3 in/yr.

Synthesis

The preceding activities provided useful information describing how and where water is moving beneath specific areas of southern Nevada, but individually do not address some of the regional concerns that motivated the study. These regional concerns are addressed by synthesizing results from all parts of the present study, as well as from other ongoing (and many previously completed) hydrogeologic investigations in the area.

The following sections report on that synthesis in terms of the three basic concerns listed earlier: the location of water in the aquifers, the quantity of water in the aquifers, and the potential effects of development.

WHERE IS WATER POTENTIALLY AVAILABLE IN THE CARBONATE-ROCK AQUIFERS?

This question is best answered at two different scales or focuses. Regionally, the question "Where are the carbonate rocks present?" is not trivial and is basic to finding where water is in the rocks. More locally, the question "Where is the water concentrated within the rocks?" is also not trivial, and is basic to siting of exploratory wells and production wells. In addition, delineation of where the water in the carbonate-rock aquifers is likely to be of usable chemical quality is basic to determining where development may be pursued. This section will address each of these topics in turn.

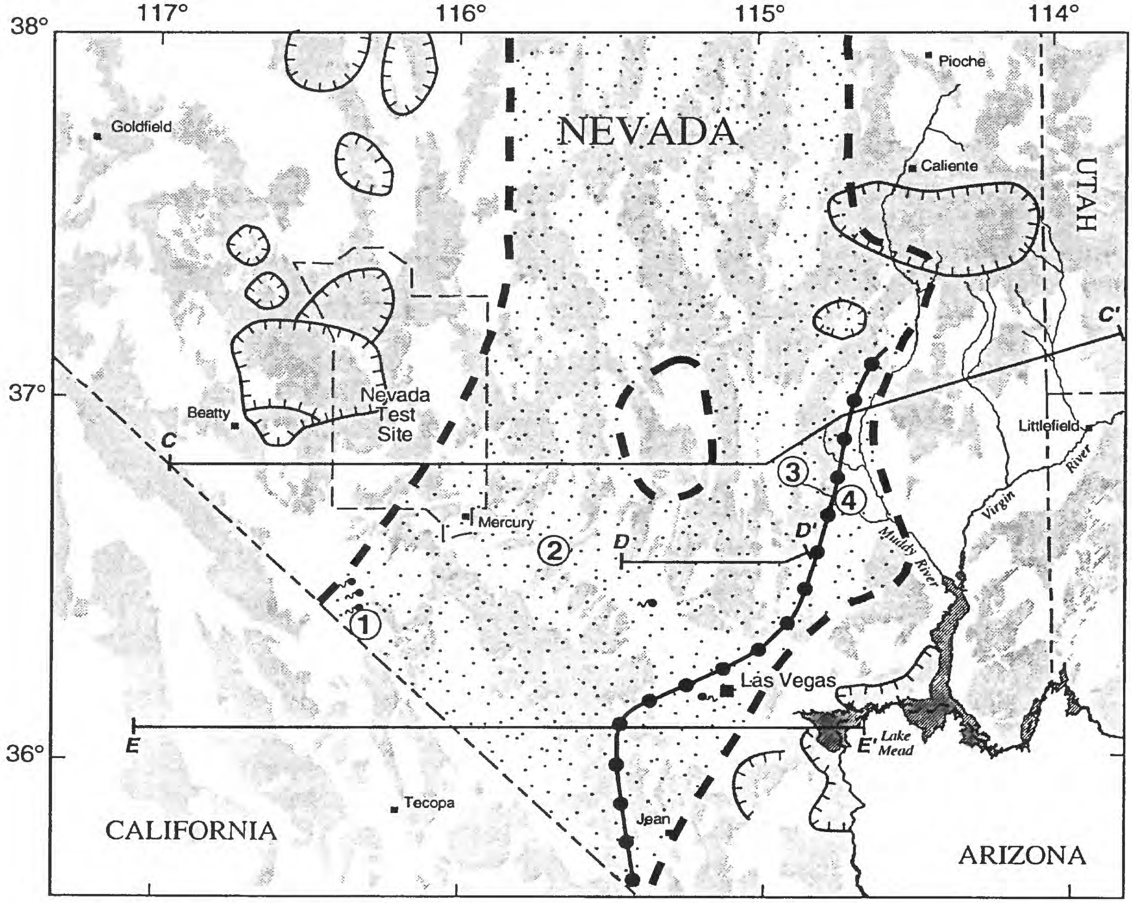
Distribution of Regional Carbonate-Rock Aquifers

In southern Nevada, over time, all geologic processes acting in the carbonate rocks including initial deposition and subsequent deformation have resulted in a broad zone of thick, laterally continuous carbonate rocks containing regionally significant aquifers (Dettinger and Schaefer, in press). This zone we refer to as the "central corridor" of the carbonate-rock province. Figure 20 shows the general boundaries of the central corridor south of 38°N. latitude.

On the east, the corridor is bounded by thin carbonate rocks east of Delamar Valley and the Meadow Valley Mountains. The carbonate rocks in these areas are thin as a result of original depositional thinning near the ancient seashores, extensional thinning, and erosion of much of the original sequence (Bartley and others, 1988). A large caldera (a volcanic collapse structure) and volcanic-rock complex protrudes into the eastern boundary in the vicinity of present-day Caliente (Ekren and others, 1977). Southward, the boundary probably runs west of the Mormon Mountains and east of Northern Muddy Mountains (Axen and Wernicke, 1989).

In the Mormon Mountains area (fig. 21, section *C-C'*), extension was extreme and results in thin, scattered, isolated blocks of carbonate rock lying on Precambrian igneous and metamorphic rocks at shallow depth (Wernicke and others, 1984, pl. 2; Smith and others, 1987, p. 386; Axen and Wernicke, 1989, p. 22-23). This shallow level of crystalline basement rock requires the corridor boundary to be west of the Mormon Mountains. The eastern boundary of the corridor continues along and around the north and west side of Lake Mead and then through the southeast quadrant of Las Vegas Valley and on past Jean toward the California border. North and west of Lake Mead, the carbonate rocks are overlain by Mesozoic sedimentary rocks containing evaporite minerals (gypsum, halite, and other natural salts) that render some unknown part of the ground water unsuitable for human consumption (more on this topic later in this section). The region south of the Muddy Mountains and east of Las Vegas and Jean contains few carbonate rocks (fig. 21, section *E-E'*); in fact, volcanic rocks mostly lie directly on crystalline rocks of Precambrian age (Bohannon, 1984, pl. 1b; Smith and others, 1987, p. 388 and 391). Although ground water has been inferred to flow through the volcanic rocks, flow rates and volumes are small (McKay and Zimmerman, 1983, p. 10-12).

The west side of the corridor (fig. 20) is positioned to coincide with a belt of Precambrian noncarbonate sedimentary rocks on the surface. Carr (1984) and Wernicke and others (1988) have suggested a thrust structural origin to bring these clastic rocks to and near the surface, but extreme extensional thinning of the Paleozoic carbonate rock section seems more likely to us. The belt largely isolates the locally thick carbonate rocks to the west from those of the central corridor. The area was greatly extended and the thickly deposited carbonate rocks (fig. 3, Nevada Test Site column) were greatly thinned (Maldonado, 1985, 1988; Carr, 1988a; Carr and Monsen, 1988, p. 50; Guth, 1988; Hamilton, 1988; Scott, 1988). A thick extensive cover of volcanic rocks and associated intrusive rocks west of the central corridor (Ekren and others, 1971; Byers and others, 1976; Carr and others, 1986) makes interpretation of the complex faulting of the carbonate rocks difficult. However, the low permeability of the Precambrian sedimentary rocks in the belt and the extensively thinned carbonate rocks probably constitute an effective western border to the central corridor along the Groom, Papoose, and Halfpint Ranges.



Base from U.S. Geological Survey digital data, 1:100,000, 1985
Universal Transverse Mercator projection
Zone 11

Geology modified from Plume and Carlton (1988), Stewart and Carlson (1978), and Wilson and Moore (1959). Geology in lower left and lower right corners of map area not shown

0 20 40 60 MILES

0 20 40 60 KILOMETERS

EXPLANATION

- Basin fill
- Consolidated rock
- **Central corridor of carbonate-rock aquifer in Nevada** — Area is underlain by thick sequences of carbonate rock; outside corridor, carbonate rock is thin, or present as isolated bodies
- **Outer margin of caldera or volcanic center** — From Ekren and others (1971), Stewart and Carlson (1976), Ekren and others (1977), Carr and others (1986)
- **Western limit of ground water generally too mineralized for most uses**
- C—C' **Location of hydrogeologic section in figure 21**
- ① **Other locations discussed in text** — 1, Ash Meadows; 2, Indian Springs; 3, MX wells in Coyote Spring Valley; 4, Muddy River Springs
- **Spring or closely spaced springs**

Figure 20. Central corridor of thick carbonate-rock sequences in Nevada part of study area that probably contains water of suitable quality for domestic and municipal use.

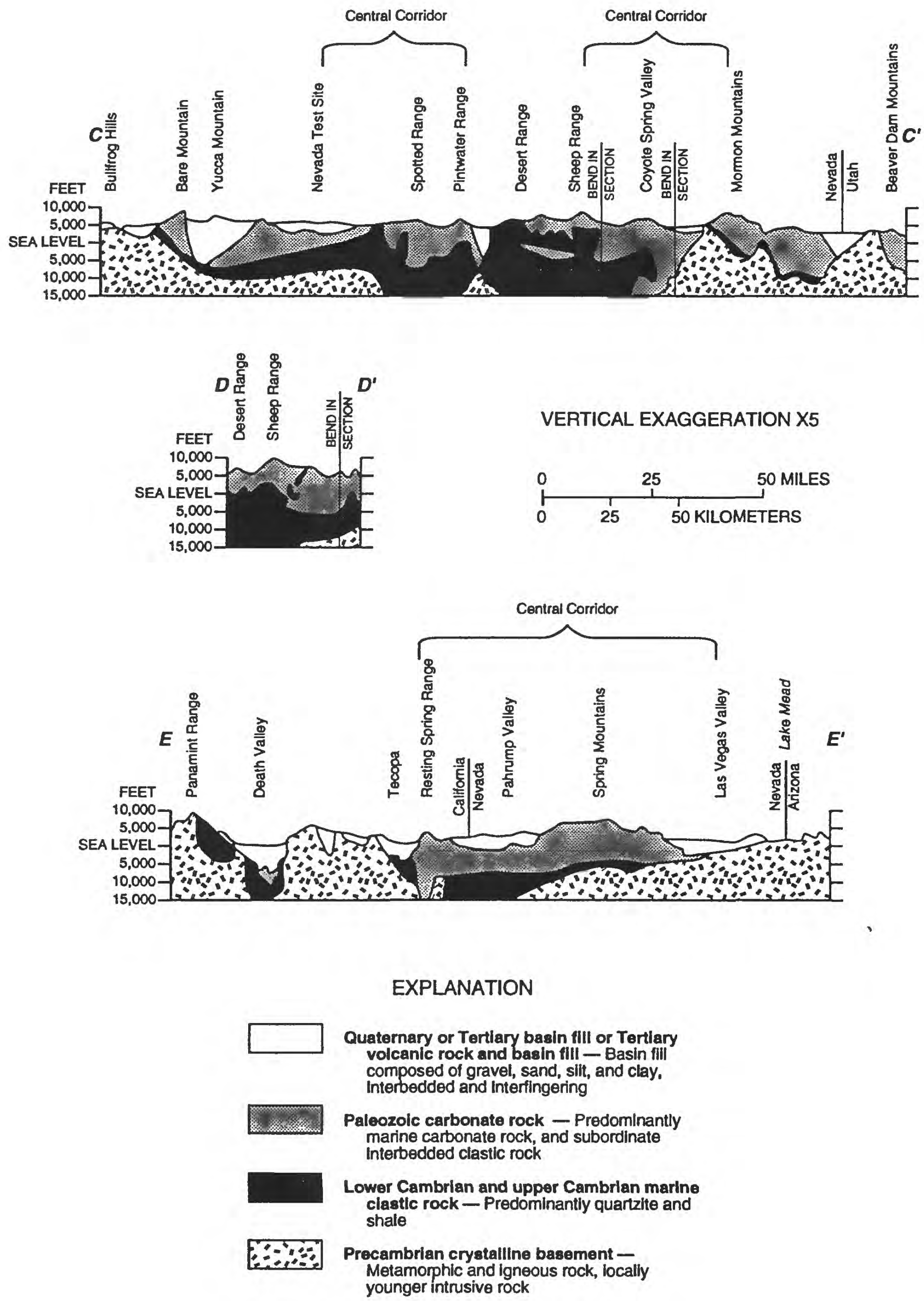


Figure 21. Hydrogeologic sections across southern Nevada. Section *C-C'* is based on work of Scott and Whitney (1987), Guth (1988), P.L. Guth (U.S. Naval Academy, written commun., 1988) and G.L. Axen (Harvard University, written commun., 1988). Section *D-D'* is modified from Guth (1980) and D.L. Schmidt (U.S. Geological Survey, written commun., 1986). Section *E-E'* is modified from Wright and others (1981) and Smith and others (1987). Lines of section are shown in figure 20.

South of the Nevada Test Site, the position of the western boundary of the corridor is uncertain but is assumed to run near the settlement of Amargosa Valley (Lathrop Wells) and west of Ash Meadows beneath the Amargosa Desert. The boundary then continues south along the western front of the Resting Spring Range in California and then east to the northern and eastern edges of the Kingston Range (Wright and Troxel, 1973, fig. 6; Wright and others, 1981; Burchfiel and Davis, 1988, figs. 9, 15, and 16). West of the southern part of the western boundary (fig. 21, section *E-E'*) are many complicated and hydraulically isolated blocks of carbonate rock, ranging from a veneer on the eastern slopes of the Panamint Range (Wright and others, 1981) to the thick plate of Paleozoic carbonate rocks at Bare Mountain (fig. 21, section *C-C'*) and the southern Funeral Range (Carr and Monsen, 1988, p. 51 and fig. 1). Interspersed between these carbonate rocks are abundant exposures of noncarbonate sedimentary rocks older than the carbonate rocks, Precambrian crystalline rocks, and plutonic rocks.

Plutonism and hydrothermal alteration associated with the volcanic centers both east and west of the corridor (fig. 20) may accentuate the overall low permeability of these bounding areas. Volcanic centers commonly are underlain by igneous plutons that, at depth, are probably extensive. These plutons displace, disrupt, and—through the action of associated hydrothermal fluids—greatly alter the surrounding sedimentary rocks (Blankennagel and Weir, 1973, p. B17; Byers and others, 1976, fig. 3; Ekren and others, 1977). The alterations commonly tend to reduce permeability in the sedimentary and volcanic rocks. As a result, although the hydrologic characteristics of the rocks within and around the volcanic centers are uncertain (Blankennagel and Weir, 1973), the volcanic centers of southern Nevada probably complicate and possibly impede regional ground-water flow through the carbonate rocks.

East and west of the central corridor are smaller blocks of carbonate rocks (west of Yucca Mountain and beneath the Mormon Mountains) that are thick but largely isolated from aquifers in other areas by noncarbonate, nonaquifer materials (Wernicke and others, 1985, fig. 15; Blank, 1988; Carr, 1988a; Hamilton, 1988; Scott, 1988; Wernicke and Axen, 1988b, fig. 2). The isolated carbonate-rock blocks, as a result, do not receive regional inflow and therefore transmit little water. In the areas outside the corridor, volcanic rocks may form the major (if not very extensive) aquifers where they are permeable enough. Otherwise, and more commonly, ground-water flow is concentrated in several basin-fill aquifers.

Within the central corridor, thicknesses and lateral continuity of carbonate rock are generally greater. Line *C-C'* (fig. 21) shows a nonuniform thickness of carbonate rocks at approximately the latitude of the Clark-Lincoln County boundary. Within the central corridor, two areas are underlain by thick and relatively continuous carbonate rocks connected to a similar thick carbonate-rock section described farther north by Bartley and others (1988, p. 1; Dettinger and Schaefer, in press); these are the Pintwater-Spotted Range area (Guth, 1988) and Coyote Spring Valley area (Guth, 1988; Wernicke and Axen, 1988a, p. 1749). These thick carbonate-rock areas probably contain the principal conduits for regional flow from east-central Nevada into southern Nevada, with the flow ultimately discharging at Ash Meadows and Death Valley and at the Muddy River Springs (Dettinger, 1987; Dettinger and Schaefer, in press).

Farther south, line *D-D'* shows the rocks beneath a short section just north of Las Vegas and shows thick carbonate rocks east of the Sheep Range (Guth, 1980, pl. 2). At moderate to great depths, the carbonate-rock aquifers beneath the Sheep Range are underlain by noncarbonate rock. The uppermost noncarbonate rocks are at high enough altitude along the west side of the range to impede westward flow by water recharging the mountains. These clastic rocks are exposed in the adjacent central and northern Desert Range (fig. 10). This barrier provides a geologic justification for geochemical balances developed during this study that indicate that nearly all the water recharging the Sheep Range flows to the north and east towards Muddy River Springs (Thomas, 1988; Thomas and Welch, in press).

Line *E-E'* shows a single, continuous corridor of thick carbonate rocks surrounded by noncarbonate rocks and a few small and isolated blocks of carbonate rock (as on the western edge of Death Valley). At this latitude the central corridor is centered on the Spring Mountains-Pahrump Valley area (Wright and others, 1981). The carbonate rocks beneath Las Vegas Valley are believed to thin abruptly to the east toward Lake Mead (Smith and others, 1987, p. 38). Water flowing through the corridor at this latitude is derived mostly from recharging snowmelt in the Spring Mountains. Water flows radially away from the high-altitude areas of the Spring Mountains to discharge near Tecopa, at Pahrump, at Indian Springs, and (in the past) at Las Vegas Springs (Hershey and others, 1987).

The sections in figure 21 show that even within the central corridor thicknesses are not always large. Compressional and extensional structures also thickened and thinned the carbonate rocks within the central corridor. Identifying extremely extended areas, where the carbonate rocks are thin, is important to understanding the hydrology of the area. Recent geologic interpretations of structures beneath the central Desert Range (Guth, 1989, p. 34-36) conclude that extension between the northern Sheep Range and northern Three Lakes Valley removed nearly all the carbonate rocks, and erosion has exposed a large area of Precambrian noncarbonate rocks (fig. 21, section *C-C'*). Within this area, which is shown in the center of the corridor in figure 20, ground-water flow probably is restricted primarily to basin-fill aquifers overlying the Precambrian rocks.

Elsewhere, the central corridor is characterized by irregularly thick carbonate rocks relatively uninterrupted by hydrogeologic barriers. Exceptions include a few small igneous plutons, intruding the carbonate rocks at depth (Blank, 1988), which locally might function as barriers to ground-water flow. In some areas, low-permeability noncarbonate sedimentary rocks are near land surface and have only a thin cover of carbonate rocks as inferred near Indian Springs by Winograd and Thordarson (1968). These blocks and layers of upthrown noncarbonate rock may be barriers to near-surface flow, as well as to deep flow in some settings. Finally, some structural zones (especially important shear zones such as the Las Vegas Valley shear zone [Winograd and Thordarson, 1968, p. 44-46; Lyles and Hess, 1988] and the Pahranagat shear zone [Thomas and others, 1986]) may directly influence flow patterns over large distances within the central corridor—impeding flow in some areas and enhancing it in others.

The corridor, as delineated in figure 20, is a region in which the carbonate rocks are thick enough to allow flow of ground water to great depths. Even in areas where vertical movements along faults isolate deeper parts of the aquifer, some shallow avenues for ground-water flow usually remain. Thus, at present (1989), the carbonate rocks are inferred to be laterally continuous within this area, forming regionally extensive aquifers. The central corridor is "where the rocks are" that comprise the regionally important carbonate-rock aquifers.

Distribution of Flow Within the Central Corridor

The central corridor comprises about 10,000 mi^2 in southern Nevada, and within that large of an area determining the "best" places to explore for or develop water supplies from carbonate-rock aquifers is difficult. The overall strategy for such determinations applied in this study involves locating areas where carbonate rocks have been broken by extensional forces, locating recently active fault systems, choosing sites with a reasonable probability of regional throughflow, and identifying sites with known and adequate sources of water to supply eventual production. This strategy is based on the hypothesis that although the carbonate rocks are fractured sufficiently to yield water to wells and to allow some flow nearly everywhere, locally, large flows are concentrated in long established conduits or in more recently established conduits where the rocks have been faulted relatively recently.

Hypotheses Concerning Transmissivity in the Central Corridor

The presence of highly transmissive zones within the central corridor is indicated by (1) large discharges of water from the Muddy River Springs and the Ash Meadow springs supplied by aquifers with nearly horizontal potentiometric surfaces and (2) geologic mapping of exposed remnants of large solution-modified flow tubes and conduits through the carbonate rocks (as old as about 15 million years; Barton and Hsieh, 1989, p. 15-16). Large areas underlain by nearly horizontal potentiometric surfaces are upgradient from the Ash Meadows and Muddy River Springs discharge areas, and the large volumes of water that discharge at these spring systems—together with the low-gradient surfaces immediately upgradient—imply that flow to the springs is at least locally through high-transmissivity zones. The configuration of water levels in the carbonate rocks of much of southern Nevada are poorly delineated and so this approach to delineating zones of high transmissivity is not commonly available. In addition, not all low-gradient areas reflect high transmissivities; some reflect restrictions to flow or low recharge. For instance, the water levels to the south and west of Muddy River Springs remain horizontal for about 30 mi in areas where preliminary exploration suggests low flow rates and a resource potential only of stored water.

A preliminary hypothesis that emerged from the present studies is that regional flow enhances high transmissivity at the same time as high transmissivity allows regional flow. Clearly, moderate to high transmissivities over long distances promote regional-scale integration of ground-water flow of the type found in southern Nevada. At the same time, speculation (as yet undemonstrated) suggests that faults and fractures through which ground-water flows stay open longer (and better) than isolated openings. This may be the result of slow dissolution or wall-coating on fracture walls that widen or add strength to the openings, or may be due to some as yet undiscovered process of fracture scouring (carrying away gouge and clays) or fracture stabilization. Regardless, this hypothesis seems the simplest explanation for the long-term presence of regional discharge points along specific structural zones identified while mapping ancestral aquifer systems near Muddy River Springs (Dwight L. Schmidt, U.S. Geological Survey, written commun., 1986). Assuming that the hypothesis is true, certain fracture zones along inferred regional flow paths become prime targets in which to seek highly transmissive zones. Analysis of aquifer tests at 39 carbonate wells in Nevada supports this conclusion in that wells located within 10 mi upgradient from regional springs are about 10-20 times more transmissive, on the average, than wells located farther away. Thus, aside from potential effects of developing water from the midst of regional flow paths (more on this later), the pathways appear to be the most likely locations for highly productive wells and also for wells with clearly defined sources of water.

Principal Flow Paths in the Central Corridor

Principal flow paths through the carbonate rocks of southern Nevada are shown in figure 22. Previous and current studies (Eakin, 1966; Winograd and Pearson, 1976; Kirk and Campana, 1988) have suggested that a large volume of ground-water flow north of about 37°30' N. latitude is concentrated in a regional flow system centered beneath the valleys of the White River surface drainage. South of this latitude flow splits to supply discharge at Muddy River Springs and Ash Meadows. South of these discharge areas no regional-scale flow systems have been identified. The large area underlain by noncarbonate sedimentary rocks in the middle of the central corridor may divert southward flow to the southeast and southwest. If so, the flow paths shown in figure 22 are located correctly. Farther south, deep, probably poorly permeable basin-fill deposits along the Las Vegas Valley shear zone and along Meadow Valley Wash and Moapa Valley may divert flow to Ash Meadows and Muddy River Springs. The principal flow paths are tentatively assumed to be zones of highest transmissivity. Areas outside the principal flow paths are expected to have lower transmissivity, ranging mostly from low to moderate. This hypothesized division between zones of high and low transmissivity is still highly speculative.

Local Controls on Transmissivity

At a more local scale, fault structures are of primary importance in the exploration for ground water in the carbonate rocks of southern Nevada. Fractures and other openings are formed along and near faults, and some of these fracture systems can conduct ground water. The number, size, and open spaces in fractures observed in outcrops decreases with distance from larger faults. Large fault zones can function as conduits where much of the flow through the rocks is concentrated. Smaller subsidiary fractures, which are distributed throughout the large volume of rocks between major faults, may function as collectors of ground water. Thus, the prospects for developing highly productive wells are expected to be increased by focusing on fault zones. Young, active faults are preferred for development because the fracture permeability of a fault decreases with age by rock consolidation and cementation (Chapman and others, 1981; de Marsily, 1985). Of the many different types of faults, observations at outcrops indicate that the most open, presumably permeable faults are high-angle normal faults, such as range-front, basin-and-range faults. These faults are responses to extensional forces and so tend to pull apart and form somewhat less gouge (fine rock particles broken from the walls during fault movement that can completely fill and greatly reduce the porosity and permeability of a fracture) than flat-lying normal faults or compressional faults. The range-bounding faults also are commonly the most recently active large structures in the carbonate-rock province of southern Nevada. Other types of faults, such as thrust faults and strike-slip faults, are much less likely to be permeable because they tend (in outcrops) to be filled with gouge.

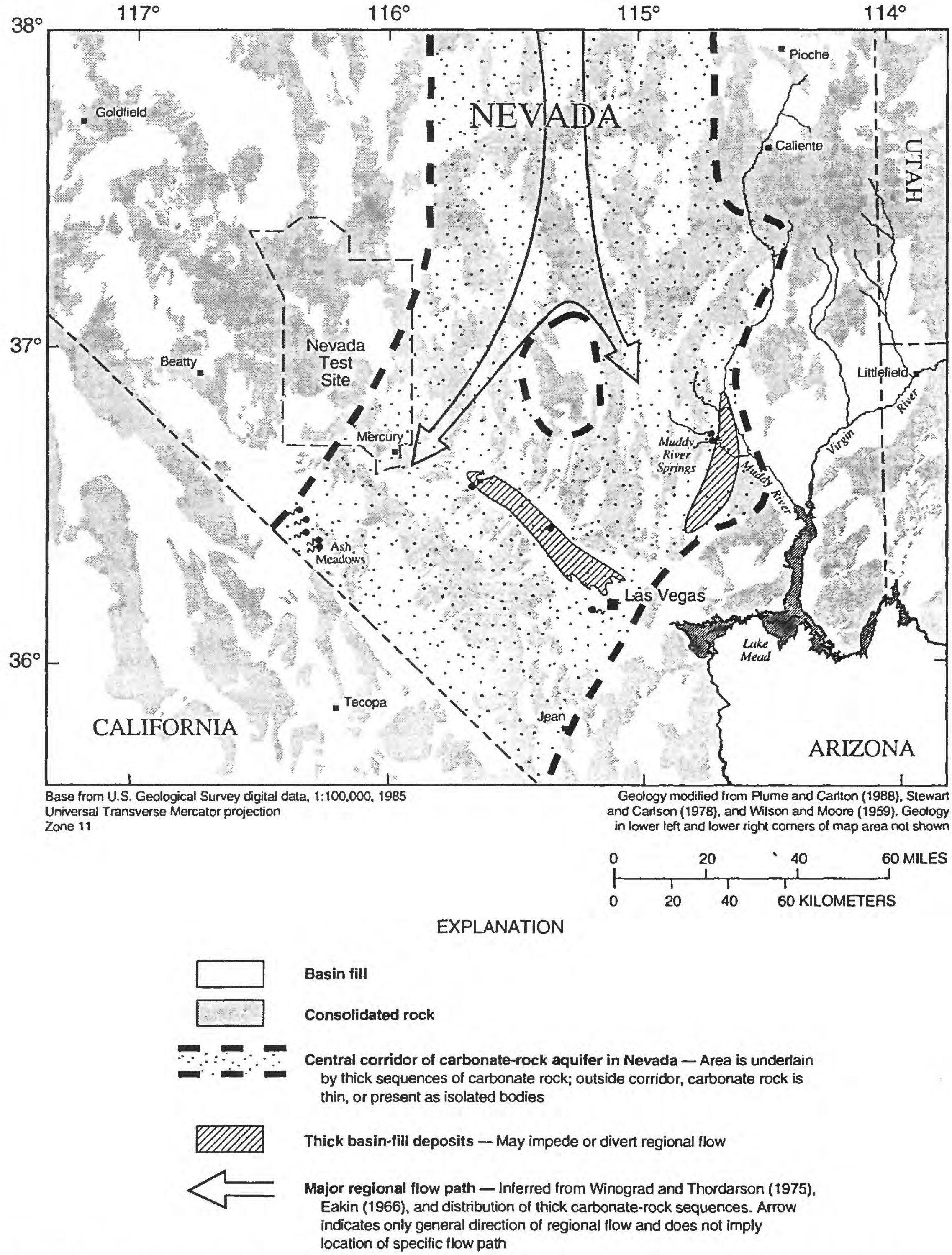


Figure 22. Principal paths of regional ground-water flow through carbonate rocks in Nevada part of study area.